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Using Blockchain Technology for Sustainability and Secure Data Management in the Energy Industry: Implications and Future Research Directions

Marianna Lezzi , Vito Del Vecchio and Mariangela Lazoi *

Department of Engineering for Innovation, University of Salento, 73100 Lecce, Italy; marianna.lezzi@unisalento.it (M.L.); vito.delvecchio@unisalento.it (V.D.V.)
* Correspondence: mariangela.lazoi@unisalento.it

Abstract: In the current era of digital transformation, among the plethora of technologies, blockchain (BC) technology has attracted attention, carrying the weight of enormous expectations in terms of its applicability and benefits. BC technology promises immutability, reliability, transparency, and security of transactions, using decentralized models to scale up existing Internet of Things (IoT) solutions while guaranteeing privacy. In the energy industry, BC technology is mainly used to secure distributed power grids, which have proven to be easily hackable by malicious users. Recognizing the need for a preliminary analysis of the literature investigating the role of BC technology for sustainability and secure data management in the energy industry, this study conducts a bibliometric analysis, identifying the implications and research directions in the field. Specifically, a performance analysis and scientific mapping are performed on 943 documents using the Scopus database and the VOSviewer software version 1.6.20. The result is the identification of seven thematic clusters and the most relevant implications as well as future research actions at the strategic, technical, regulatory, and social levels. This study extends the literature by suggesting potential sustainability opportunities regarding BC technology adoption in the energy industry; it also supports managers in identifying strategies to strengthen business sustainability by leveraging the development of new knowledge for secure asset management.

Keywords: blockchain; data protection; sustainability; Industry 4.0; energy; research directions

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1. Introduction

The digital transformation that has affected industry, including the energy field, has led to the emergence of advanced technologies dedicated to the gathering and sharing of big volumes of data, such as blockchain technology (BCT) [1]. BCT gains significant importance from both scholars and practitioners in terms of its applicability and benefits for business [2–4]. Indeed, blockchain (BC) technology can be defined as an immutable digital ledger technology, based on a distributed and decentralized infrastructure, that facilitates the management of data and transactions by leveraging encrypted and trusted mechanisms [5,6]. Compared to centralized models, the decentralized architectures that characterize BC technology have the potential to dramatically expand the scalability of existing industrial internet solutions while ensuring the security and privacy of network participants [7]. Moreover, BCT has attracted considerable attention for its ability to provide security, privacy, and traceability to systems, as well as data, within industrial contexts [8]. In fact, a strong relationship exists between BC technology and data security and traceability in industry [9]. In the energy industry specifically, BCT promises to bring about far-reaching changes, such as the simplification and automation of processes, increased transparency, and reduced transaction costs through disintermediation [10]. Furthermore, according to the study conducted in [11], BCT has the potential to improve the efficiency of current energy practices and processes and to accelerate the development of Internet of Things (IoT) platforms and digital applications while providing innovations in peer-to-peer (P2P) and decentralized generation. Finally, BCT can play a key role in mitigating some sustainability challenges and advancing the realization of the circular economy [12]. In this regard, it can promote green behavior, improve product lifecycle visibility as well as the efficiency of operations and systems, and encourage better sustainability reporting and monitoring [13].

According to [14], the business value generated by BCT will grow rapidly, reaching USD 176 billion by 2025 and USD 3.1 trillion by 2030. However, despite BCT being promising in terms of immutability, reliability, complete transparency, anonymity, integrity, and security of transactions without involving any third-party organizations [15–19], unlike other digital technologies, it seems to remain immature [20,21]. There are few studies in the literature that focus on the role of BC technology and its implications for data security and traceability in industrial contexts. For instance, ref. [2] described BCT without detailing its components or offering any suggestions about existing security solutions. Also, ref. [22] focused on defining different BC technology applications within Industry 4.0 but overlooked the technological impacts. In addition, refs. [11,23] explored some applications in specific target areas, but these studies lack generalizability. Furthermore, although some studies have explored the current status of BC technology research and applications in the energy industry through bibliometric analysis [24–27], none of them have focused on investigating the role played by BC technology in terms of sustainability and secure data management.

On the other hand, it is crucial to understand the implications of BC technology adoption for data security and traceability and for ensuring the sustainability of industrial business models. It is therefore insightful to intersect such fields in order to identify their knowledge boundaries [28]. Given these issues, this study employs a bibliometric review to fill the identified research gap by defining emerging lines of research related to the application of BCT in the energy industry in terms of sustainability and secure data management. Starting from these research gaps, a research question was designed with the intent to narrow the gaps and provide further knowledge to fill them. This paper aims to answer the following research question: what are the implications of BCT application for sustainability and secure data management in the energy industry? In order to answer this research question, a bibliometric analysis, using the Scopus scientific database and VOSviewer bibliometric analysis software version 1.6.20, is conducted on 966 documents in the knowledge area. In particular, a two-phase bibliometric analysis (i.e., performance analysis and science mapping) is adopted to increase the validity of the obtained results.

The analysis results reveal the recognition of seven clusters (i.e., using blockchain technology as a sustainable strategy in industry; blockchain technology for data traceability, security, and privacy; blockchain technology for lifecycle management; quality-oriented blockchain in the energy field; blockchain technology for healthcare; blockchain technology for human-centered solutions; and worldwide blockchain technology) as possible lines of research for comprehending BCT implications in the area of sustainability and secure data management in the energy field.

This study extends the frontiers of knowledge through the formulation of possible directions for future research in the energy industry and within an emerging technological field such as BC technology. Moreover, it supports managers in comprehending valuable practices for strengthening the sustainable nature of business, planning the use of BCT and leveraging the development of novel knowledge for secure asset management.

The remainder of this paper is organized as follows: Section 2 provides a literature overview on BCT and its applications for industrial data security and traceability, emphasizing sustainability aspects, especially in the energy industry. Section 3 describes the research method adopted in this study, while Section 4 highlights the results of the exploratory analysis, describing the clusters resulting from the bibliometric analysis and clarifying the emerging evidence in terms of implications and future research directions. Finally, Section 5 concludes the paper by addressing the key research findings and limitations.

2. Background

2.1. BCT Applications

Following the study conducted in [29] that allowed the first BC source code to be defined, BCT was officially introduced in 2009 to enable the use of digital currency (Bitcoin) through a dedicated platform. However, BC was soon implemented in many other applications, including those related to the industrial world and, specifically, the energy industry [11].

BC technology involves a distributed and ever-growing list (or chain) of concatenated data records, called blocks, which are protected through the use of cryptographic algorithms [30]. Two key elements underlying the effectiveness of such a list can be distinguished. The first element is related to the consensus required between the participating entities when adding a block; the second element depends on the links that are created between one block and the next, which make it difficult to change any block once it has been added to the list [3]. In this context, an entity represents any actor involved in a transaction that needs to be validated and recorded; it can be a person, a group of people, an organization, or a computing component (e.g., robot, intelligent device, sensor, or control device). On the other hand, a transaction is a record of the activity that is performed (whether financial, commercial, industrial, or system-related), whereas the list is a protected online register where certain transactions agreed upon and performed between different entities are recorded. Finally, the blocks, which store transactions, are usually timestamped, encrypted, and replicated across multiple sites and cannot be altered. This makes the security architecture underlying a BC robust and ensures data integrity and privacy [15,31].

The structure of the BC is divided into five layers [32,33]. The data layer is the lowest layer of BC architecture; it is used to store data and ensure their security. Specifically, this layer decrypts data in a decentralized manner with common algorithms and technologies (e.g., the hash algorithm and asymmetric cryptography). The network layer is instead a P2P network, where each node stores all transaction records in the form of a BC. This network uses distributed storage technology, and each node stores a copy of the complete data. Furthermore, the consensus layer hosts the consensus mechanism necessary to enable the management of BC data by all participating nodes. Currently, the mainstream consensus algorithm mainly includes Proof of Work (PoW), Proof of Stake (PoS), Delegated Proof of Stake (DPoS), and Practical Byzantine Fault Tolerance (PBFT) [11]. Another layer is the contract layer, which contains different smart contracts (SCs), consisting of different types of script code and algorithms [34]. Finally, there is the most superficial state, which contains the applications layer, in which practical applications of a BC, such as those related to the financial or health industry, are found.

BCT applications are often characterized by the need for disintermediation and decentralization [16,35]. According to [36], disintermediation is "the power of removing intermediaries in the distribution network", while the authors of [37] define decentralization as "the process of redefining and redistributing responsibilities, functions, and decision-making power within an organization so that stakeholder participation is more equitable and all power is not delegated to a central authority". Since a BC can guarantee reliable transactions between two unknown parties, eliminating the involvement of third parties, a large number of applications of this technology can be found in various sectors.

In addition to the well-known financial field of application, a use of BCT is in asset management, which allows for the history of assets to be tracked and their details to be stored efficiently [38]. BCT is also used in the healthcare sector for processing confidential medical data [39]. Furthermore, a strong expansion of the application of BCT has occurred in the pharmaceutical sector. Specifically, in this area, its application is aimed at drug supply chain management, drug quality assurance, and the prevention of drug counterfeiting [23].

BCT is also widely used in the energy sector, mainly to secure distributed power grids, which are easily hacked by malicious users [40]. In particular, the authors of [41] identified the following main application areas of BCT in the energy industry: decentralized storage and control in power grids; P2P energy trading in smart grids; electric vehicles; and carbon emission trading and green certificates. Moreover, the authors of [42] categorized the implementations of BCT in power systems into the following main categories: demand response, electric vehicles, decentralized energy management, energy trading, and distributed renewable energy. On the other hand, the study conducted in [11] summarized the key aspects of a business model that can be affected by BCT use in the energy industry. They fall into the areas of billing, sales and marketing, trading and markets, automation, smart grid applications and data transfer, grid management, security and identity management, the sharing of resources, competition, and transparency. Overall, BCT can reform the energy industry by eliminating energy monopolies and significantly reducing the price of renewable energy (RE) as well as the risk of RE system development [43].

Furthermore, the application of BCT is rapidly spreading in the food safety sector. Through its use, food chains are being tracked, verifying the origin of the product and its quality and ensuring that it reaches the recipient directly [6]. BCT is also being discussed in the government sector, where this technology could make services more efficient and transparent. Through the authentication of access, in fact, it will make it possible to request documents in real time without the need to undergo bureaucratic procedures [44]. A further area where the use of BCT is growing strongly is the technology sector. Here, its use enables device access control and efficient data management [45]. Furthermore, applications of BCT are known in the context of smart manufacturing [46], i.e., in the field of product lifecycle management (PLM). In this domain, the implementation of BCT enables increased data security and traceability, automated transactions, and decentralized consensus [47]. Finally, the study conducted in [22] mentions the drone, education, copyright, taxi, agriculture, and e-commerce and retail services sectors as new fields of application for BCT.

2.2. BCT for Industrial Data Security and Traceability

Since the first implementation of a BC as a public ledger for cryptocurrencies, BCT has evolved to create immutable systems that meet several criteria, such as reliability, anonymity, transparency, traceability, and, in general, a high level of security [48,49]. Thanks to these properties, BC technology has become an implementable technology in the context of the Industrial Internet of Things (IIoT) [50]. In fact, a BC is a distributed, traceable, and tamper-proof ledger [5]. In particular, its nodes share data and jointly maintain the ledger, and it uses consensus mechanisms to ensure data consistency. On the other hand, the encryption techniques used by a BC ensure secure data sharing between authorized users. Moreover, BC technology is more performant than cloud platforms and databases in general in terms of tamper proofing, privacy protection, and temporal ordering [51]. In fact, the immutability and traceability features of a BC enable it to guarantee the secure storage of data.

In the context of the IIoT, a certain number of BC-based frameworks have been defined to ensure the security and traceability of industrial data. The Compressed and Private Data Sharing (CPDS) framework proposed in [45] allows for data authentication, data access control, and a high level of data management efficiency. Three industrial entities operate within the CPDS, namely industrial participants, who process products and send product data to the BC; third-party users, who read product data from the BC; and access control managers, who define access policies to product data and assign keys to users. Moreover, ref. [44] proposed the privacy-preserving distributed access management framework (PDAMF), which utilizes the Ethereum BC platform for the management and utilization of shared resources between collaborating parties and resource access permissions. In particular, the PDAMF ensures (i) untraceability, whereby it is impossible to trace who requests access and under what conditions such access is granted; (ii) unlinkability, which makes it impossible to prove that transactions are sent from a specific sender or to prove the sender's real identity; and (iii) confidentiality policies, whereby sensitive access control policies are to be disclosed only to authorized parties.

In the context of the energy industry, the authors of [52] developed a BC-enabled smart energy trading platform using a permission BC network (i.e., Hyperledger Fabric), which allows the system administrator to manage the network and allows crowdsources to manage their accounts and perform energy transactions within the ecosystem. This platform consists of two modules: the BC-based energy trading module and the smart contract-enabled predictive analytics module. Specifically, the BC module enables peers to monitor energy consumption in real time and easily control energy trading, reward models, and immutable energy trading transaction logs. The predictive analytics module enabled by smart contracts aims to build a forecasting model based on historical energy consumption data to predict short-term energy consumption. Furthermore, the authors of [53] created a deep learning- and BC-based energy framework for the smart grid, titled DeepCoin, to protect the smart grid from cyberattacks. Specifically, the BC-based scheme consists of five phases: the setup phase, agreement phase, BC and consensus creation phases, and view change phase.

On the other hand, referring to the smart manufacturing domain, the framework proposed in [47] is applied in the context of PLM to cope with multi-party data management and security challenges. This framework considers the application of BC technology in four different PLM scenarios, such as (i) product design, (ii) product manufacturing, (iii) product utilization, and (iv) product recycling. Furthermore, the authors of [54] developed a BC-based life cycle assessment (BC-LCA) framework in which BC technology is implemented to secure and transmit inventory data from suppliers to manufacturers. Specifically, with the BC-LCA framework, specific data can be collected along the supply chain in real time while improving the availability, accuracy, privacy, and automatic updating of inventory data. Finally, the authors of [55] proposed a BC-based framework for an efficient logistics management system (named BFSELMS). The aim of BFSELMS is to provide secure transactions between supply chain actors through the integration of smart contracts into IoT systems. This framework aims to support IoT devices, privacy and security for customer and product information, and efficiency in the execution of logistics processes.

In the healthcare field, a BC-based electronic rehabilitation medical record (ERMR) sharing framework (BERMRSF) was developed to cover the processing phase of patient data. This framework was realized by using BC-specific technologies such as P2P network, BC data structure, asymmetric encryption algorithm, digital signature, and a consensus algorithm to achieve distributed storage, data security, privacy protection, data consistency, data traceability, and data ownership in the ERMR sharing process. In particular, a "partially decentralized" hybrid P2P network model was adopted. Moreover, the authors of [39] proposed a BC-based framework in response to the need for drug provenance information with the goal of preventing counterfeiting. This framework makes it possible to quickly trace back to the node where the problem occurred within the BC and correct it. Specifically, the underlying mechanism involves assigning an ID to the drug, which identifies it in the traceability system. After passing quality control at the manufacturing stage, the drug information is recorded on the BC, which will accompany the drug all the way to the end consumer. The architecture of the framework includes three parts: a BC network environment (characterized by a data layer, which is responsible for storing data about the drug, and a network layer that is the basis for transmitting the information); a smart contract that encapsulates the code that provides the functions of the system; and a web client that allows consumers and all participants in the process to interact with the BC, providing an indirect interface for user queries.

Finally, in the pharmaceutical industry, the authors of [56] proposed a framework for the secure transaction and tracking of drug information using the Ethereum distributed software platform. The proposed BC framework includes numerous agreements between different actors in the supply chain, namely between raw material suppliers and manufacturers, between manufacturers and distributors, and between distributors and retailers. Each agreement is bound by a smart contract, and each participant's transaction information is updated on the distributed ledger.

2.3. BCT for Sustainability

In the literature, there is a growing body of research on BC solutions that can be used to address sustainability [57,58]. In particular, it is noted that BCT plays a key role in P2P energy trading and the security of smart grids [59], as well as in supply chain management systems [60]. In the context of P2P energy trading, a BC enables direct and secure energy transactions, allowing smart grids to work to improve distribution efficiency. This approach promotes sustainability by improving the efficiency of energy consumption through decentralized dynamic pricing, consumption transparency, and the use of renewable energy [61]. Regarding supply chains, BCT can incentivize sustainability in terms of [13] (i) reducing product take-back and rework through its tracking capabilities; (ii) tracking the actual footprint of products and determining the amount of carbon tax to be charged to each company; (iii) improving recycling behavior; and (iV) enhancing the efficiency of emissions trading systems by reducing fraud and improving system fidelity. Specifically, BC-based supply chain management contributes to improve sustainability performances in the fields of environmental protection (through the environmental emission abatement, resource management, and waste management), social equity (by ensuring stable and unchanging information in supply chains), and economic/governance efficiency (by providing instant access to accurate and reliable information, solving the problem of information asymmetry through a smart contract and establishing trust and collaboration between the parties involved) [62].

According to [13], BCT provides opportunities to increase sustainability in four main areas, such as (1) designing incentive mechanisms and tokenization to promote green consumer behavior; (2) improving visibility across the product lifecycle; (3) increasing the efficiency of systems by reducing development and operational costs; and (4) promoting sustainability monitoring and performance reporting in supply chain networks. Furthermore, a BC can be considered an advanced tool that can help solve a number of problems related to climate change and clean energy transition. Specifically, these problems include popularizing green initiatives, reducing wasteful production and consumption, organizing sustainable investments, monitoring responsibilities in combating climate change and clean energy transition, and predicting climate change and clean energy transition [63].

In general, because of its nature as an open-source, peer-to-peer, and distributed system and its automation capabilities, a BC has the potential to create cleaner transactional economic processes and help achieve the necessary balance and harmony between the environment, economy, and society. In this sense, BCT contributes to the effective implementation of the circular economy and is in line with the Green Economy agenda [64].

3. Methodology

To determine the implications of using BCT for sustainability and secure data management in the energy field, it is useful to combine these topics and identify their knowledge boundaries [28]. Indeed, the aim of this paper is to answer the aforementioned research question: what are the implications of BCT applications for sustainability and secure data management in the energy industry?

To achieve this objective, a bibliometric analysis was designed and implemented starting from a pool of scientific contributions available in the literature. Scopus database was considered for collecting the pool of papers, as in [65]. Indeed, the Scopus database is the largest abstract and citation database, encompassing over 20,000 peer-reviewed journals across various disciplines, including science, technology, medicine, social sciences, and arts and humanities [66]. These journals come from major publishers such as Elsevier, Emerald, Informs, Taylor and Francis, Springer, and Inderscience [67]. As noted in [68], Scopus is considered more comprehensive than other databases, such as the Web of Science database, which is limited to ISI-indexed journals and only includes around 12,000 titles. Additionally, ref. [27] highlighted Scopus as a valuable source for peer-reviewed articles in the energy industry.

A bibliometric analysis allowed for investigating such data sample and provided an exploratory understanding of a BC as an emerging technology in the energy industry. Bibliometric analysis is indeed recognized as a fundamental methodology for exploring research of any disciplines and areas and highlighting their nature [69]. In particular, a two-phase bibliometric analysis approach was adopted (i.e., performance analysis and science mapping) for increasing the validity of the obtained results [70], as in [71–73]. While performance analysis allows for evaluating the impacts of scientific productions over time, science mapping enables the visual representation of data patterns and relationships.

As also suggested in [65,74,75], the reference methodology of this study consists of three main phases: (i) the definition of search schema and data sample; (ii) a preliminary analysis of the sample; and (iii) data analysis. Figure 1 details steps and sub-steps of the methodology.

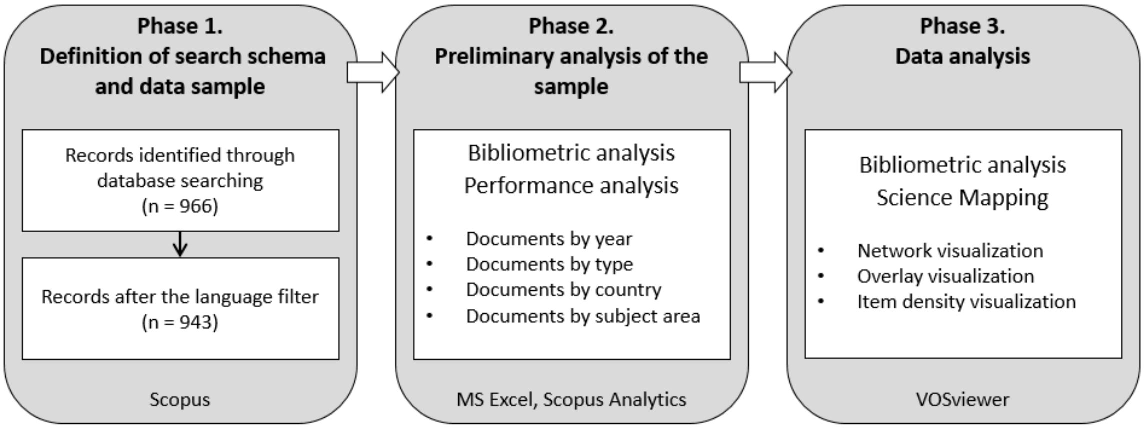

Figure 1. The steps of the research methodology.

3.1. Definition of Search Schema and Data Sample

In line with the objective of this study, the following keywords were selected to investigate the areas of interest:

- "Blockchain", "Block chain", "BCT", "Decentralized database", "Distributed ledger", "DLT", "Smart contract", "Consensus algorithm";
- "Data security", "Data protection", "Privacy", "Data insurance", "Information security", "Security of data", "Protection of data";
- "Traceability", "Trac* data", "Traceability links", "Traceability systems";
- "Energy industry", "Energy sector", "Electric power industry", "Power industry", "Power generation industry", "Smart grid*", "Power grid*", "Electrical grid*", "Electric grid*", "Electrical power network*", "Energy system*";
- "Sustainab*", "Green", "Circular econom*".

The choice of these keywords stems from considering similar concepts and synonyms as found in the theoretical background. In particular, the first group of keywords refers to BCT, the second focuses on the concept of data security, the third encompasses key terms related to data traceability, the fourth contextualizes the investigation in the energy sector, and the last introduces the concept of sustainability as a key emerging pillar in technology management. Specifically, the combination of these keywords was realized by means of mathematical logical connectives (i.e., Boolean operators). In this way, it is possible to create an appropriate pattern useful for selecting eligible papers for investigating the research question. Furthermore, in order to construct a homogeneous data sample useful for a bibliometric analysis, the language filter was used to only consider papers written in English. This selection criterion facilitated an integrated bibliometric analysis based on the terms' occurrence. The selection criteria are further explained in Table 1. The query was designed as follows:

Table 1. Selection criteria.

Criteria	Motivation
The paper must contain the selected keywords.	Because this study aims to investigate the intersection points of the fields of interest.
The paper must be written in English.	Because the bibliometric analysis is facilitated if a homogeneous set of terms refers to the same language.

("Blockchain" OR "Block chain" OR "BCT" OR "Decentralized database" OR "Distributed ledger" OR "DLT", "Smart contract" OR "Consensus algorithm") AND ("Data security" OR "Data Protection" OR "Privacy" OR "Data Insurance" OR "Information security" OR "security of data" OR "protection of data") AND ("Traceability" OR "Trac* Data" OR "Traceability Links" OR "Traceability Systems") AND ("Energy industry" OR "energy sector" OR "electric power industry" OR "power industry" OR "power generation industry" OR "smart grid*" OR "power grid*" OR "electrical grid*" OR "electric grid*" OR "electrical power network*" OR "energy system*") AND ("sustainab*" OR "green" OR "circular econom*") AND (LIMIT-TO (LANGUAGE,"English")).

Papers containing these terms in all document fields were searched in Scopus www.scopus.com (accessed on 27 June 2024), an important electronic scientific database recommended as a robust source of data.

According to the selection criteria (Table 1), the starting sample of 966 papers was further refined to 943 because of the language filter. The results were then exported into csv and txt files containing all of the information (e.g., title, authors, affiliation, abstract, and keywords) necessary to conduct the subsequent bibliometric analysis.

3.2. A Preliminary Analysis of the Sample

The second step of the methodology focuses on a performance analysis based on the statistical trend analysis of the contributions in the literature. MS Excel 2016 and Scopus Analytics 2024 were used for the analysis of the sample.

Figure 2 shows the trend in quantity of papers published over the years. As expected, it is interesting to observe that the conjunction of BCT for data security and traceability in the energy field with sustainable practices only started to be significant in recent years. Indeed, increasing attention being paid from both academics and practitioners can only be proven from 2019, with an approximated tax of production growth of 80% in 2020. Also, starting from 2020, a higher production of scientific studies can be observed (335% more in 2023). Indeed, as also confirmed in [76], BCT was still immature before 2018, and some applications appeared only recently.

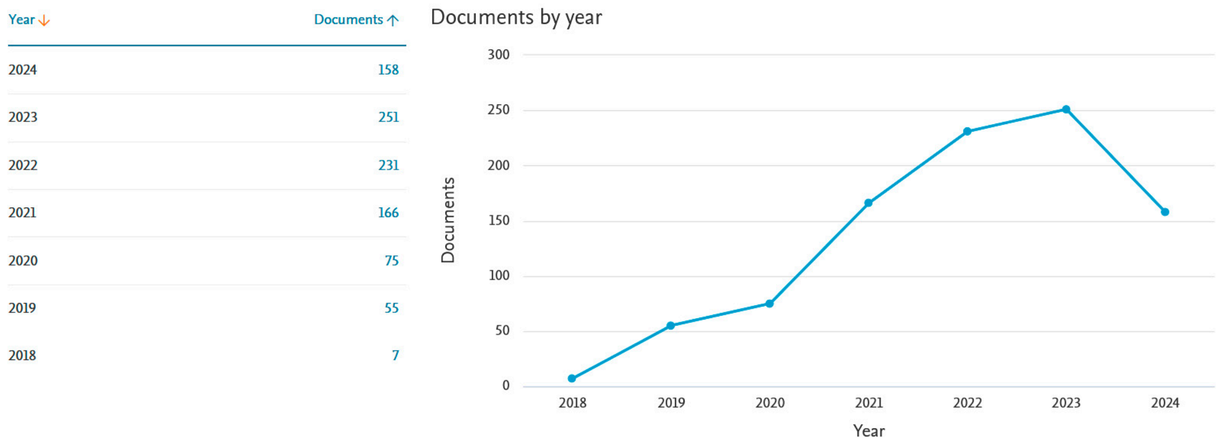

Figure 2. The publishing trend of papers over the years.

Furthermore, according to the Scopus classification (Figure 3), out of 943 documents, 56.6% represent journal articles, 18.7% are reviews, 12.7% are conference papers, and the rest are book chapters (8.8%), books (2.9%), and short surveys (0.2%). The large percentage of journal articles emphasizes the presence of consolidated studies in the field; on the other hand, the fair number of conference papers demonstrates the vibrancy of the research and provides an insight into possible growth trends.

Document type ↑	Documents ↓
Article	534
Review	176
Conference Paper	120
Book Chapter	83
Book	27
Short Survey	2
Retracted	1

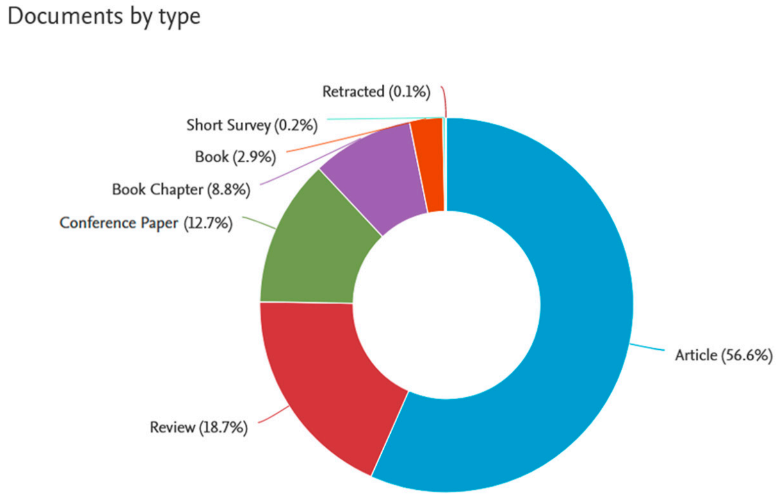

Figure 3. Document type distribution.

Interest in these fields and their relationship originates from all over the world (Figure 4). In fact, the top five countries that provided such studies are China (252 papers), India (215 papers), the United States (97 papers), the United Kingdom (86 papers), and Australia (68 papers). Italy appears at the eighth position with 42 papers. This view can also be interpreted as the diffusion trend in the interest in many different economies.

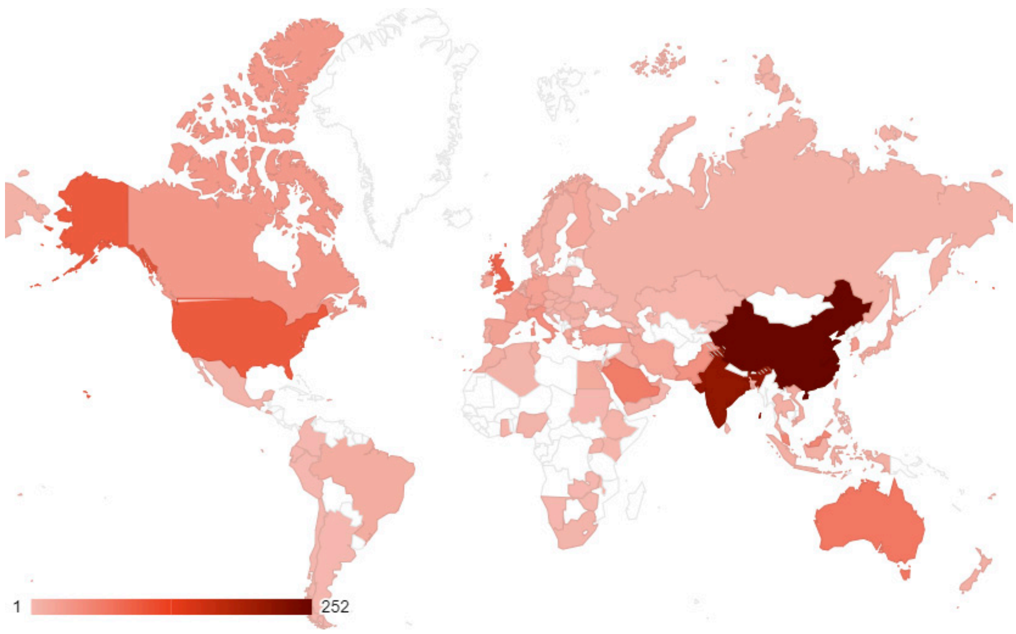

Figure 4. The distribution of papers around the globe.

Finally, Figure 5 reveals that there are several research areas that have turned their attention to BCT for data security and traceability in the energy field and with sustainable aspects. Particularly, the most important areas are represented by technical sources: "computer science" (30.4%), "engineering" (20.6%), "business, management and accounting"

(7.4%), "social sciences" (5.3%), "material sciences" (4.8%), "mathematics" (4.7%), and "decision sciences" (4.5%). It is important to note that only 4.3% of papers belong to the "energy" subject area, which is the focus of this study.

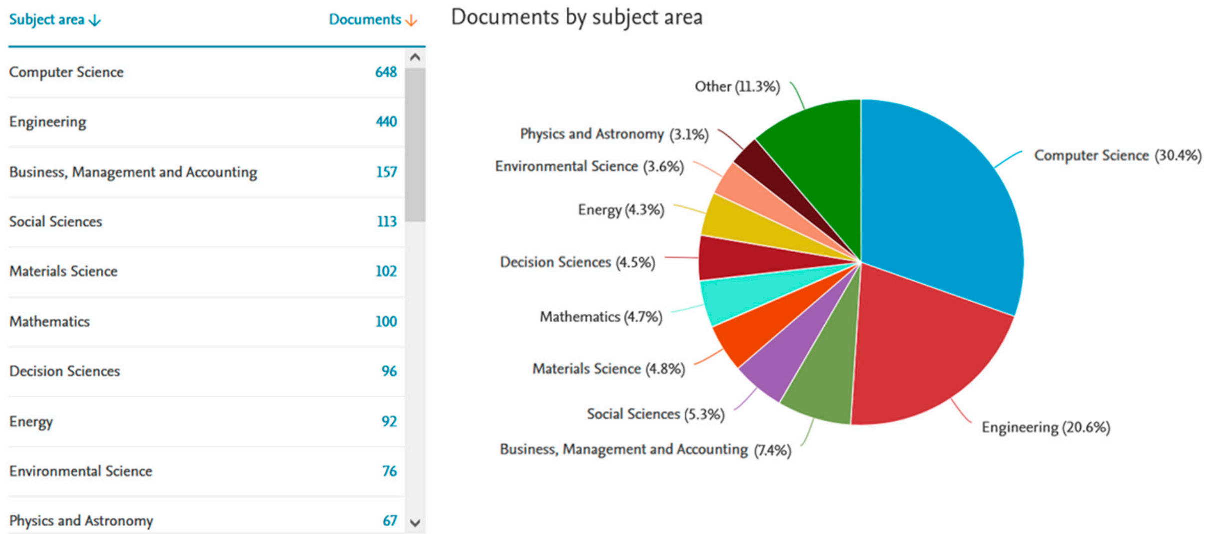

Figure 5. The distribution of papers by subject area.

3.3. Data Analysis

The third and last phases of the methodology focus on the science mapping of the bibliometric analysis based on the total amount of 943 documents. This approach has been applied over time in many research studies, such as in business strategy [77] and business management [78]. Such analysis is useful for a macro assessment of the most relevant topics related to the research fields, thus helping in defining the boundaries of knowledge of BCT in relation to sustainability and secure data management in the energy field. Therefore, a bibliometric analysis was conducted to (i) understand the recurring topics surrounding the areas of analysis; (ii) pinpoint their relationships; and (iii) outline upcoming topics and trends over time. A network analysis and graphical exploration of the textual data were performed to generate a co-occurrence map by means of the VOSviewer software. This tool targets the graphical rendering of bibliometric terms, which is functionally useful for visualizing large maps in an easy-to-interpret way [79,80]. The analysis was conducted following the suggestions provided in [67,69].

The analysis was performed by counting recurrent terms in the "title" and "abstract" with a frequency of at least 10. Out of 18,293 terms, 674 fulfilled the threshold. The next section provides a qualitative analysis.

4. Using BCT for Sustainability and Secure Data Management in the Energy Industry

To analyze whether BCT has implications for sustainability and secure data management in the energy field, bibliometric analysis proved to be a valuable tool for a general comprehension of the knowledge boundary. Particularly, the science mapping of the bibliometric review enabled a network analysis to be carried out using the co-occurrence of terms. As suggested in [81], it is probable that documents that refer to many common documents deal with a similar theme, and contrarily to other techniques, such as co-citation analysis that connects articles based on the received citations, co-occurrence aims at identifying the research front, that is, the historical trends.

The bibliometric analysis returned the co-occurrence map illustrated in Figure 6, which encompasses seven clusters of terms. Each recurrent term represents a node in the network that can be related not only to other nodes in the same cluster, but also to nodes in other clusters. The node size reflects the occurrence of the term; thus, the larger the nodes, the more frequent the terms in the analysis pool. Furthermore, the nodes' centrality is a mirror of the relevance for the cluster and for the entire network. The link between two nodes implies that those terms are embedded in the same article, and the thickness is proportional to the frequency of their use.

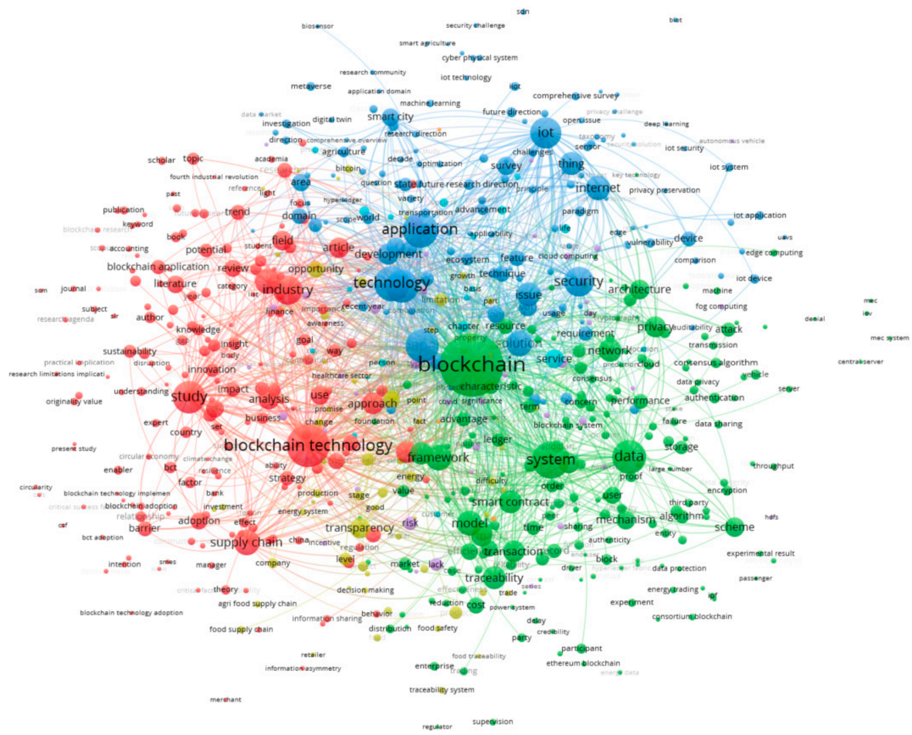

Figure 6. Network visualization.

The co-occurrence analysis revealed seven clusters, resulting in the identification of different colors. Generally, Figure 6 shows a first overview of the most important clusters, which are the green, red, and blue ones. The other clusters seem to be less impressive. By reading the cluster in detail, the following information can be derived:

- Cluster 1 (red) is composed of 195 terms (e.g., blockchain technology, study, industry, research, supply chain, strategy, adoption, barrier, approach, trend, use, management, operation, sustainability, artificial intelligence, database, logistic, blockchain application, capability, and insight), and it can be referred to the "using blockchain technology as a sustainable strategy in industry" topic. Therefore, the cluster seems to be focused on the adoption and integration of BCT as a useful strategical approach for enhanced industries, with a particular emphasis on supply chain and logistics management. Also, it informs the need to include the analysis of challenges and emerging trends, such as sustainability, and how to adopt such emerging technology from an operational point of view. Indeed, although previous studies analyzed the role of BCT in the energy sector (e.g., [24,25]), research focusing on the sustainability concept is scarce.
- Cluster 2 (green) is composed of 195 terms (e.g., blockchain, system, data, network, architecture, privacy, framework, model, information, transaction, efficiency, traceability, scheme, mechanism, process, smart contract, resources, attack, platform, and storage), and it can be referred to the "blockchain technology for data traceability, security and privacy" topic. This cluster deals with the technical aspects of BCT, encompassing system architecture, data management, and privacy. It also focuses on frameworks and solutions for the secure management of data, the preservation of information and systems, and the development of models against cyberattacks. This cluster is in line with previous studies concerning the role of the BCT for data security [2], but it also suggests the investigation of BCT for comprehensive, secure data management, including traceability and privacy issues.

- Cluster 3 (blue) is composed of 149 terms (e.g., application, technology, challenge, development, integration, solution, security, issue, perspective, domain, smart city, combination, requirement, environment, IoT, immutability, technique, use case, decentralization, and ecosystem), and it can be referred to the "blockchain technology for lifecycle management" topic. This cluster focuses on the design, development, and implementation of BCT solutions associated with the use of industrial internet. It also informs the need to build and integrate BCT while considering the specific requirements of use cases and managing all of the potential issues ranging from the conceptualization of the solution to the maintenance and disposal of the technology. Additionally, as the authors of [11,82] explored some applications in specific target areas, the cluster suggests the need to extend the application for generalizable findings [82].
- Cluster 4 (yellow) is composed of 66 terms (e.g., implementation, transparency, quality, energy, opportunity, investment, improvement, energy system, ledger technology, product, growth, limitation, property, safety, and production), and it can be referred to the "quality-oriented blockchain in the energy field" topic. This cluster focuses on the implementation of BCT in the energy sector as a promising solution to improve the quality of processes and products. It also suggests addressing technological investments for more efficient and sustainable energy systems. This cluster is in line with one of the most recent research streams [83] that has attempted to discover novel and greener solutions based on the use of technologies, such as the BC, for sustainable impacts in the energy sector.
- Cluster 5 (purple) is composed of 46 terms (e.g., risk, lack, government, healthcare, tool, individual, idea, policy, scenario, patient, functionality, healthcare system, cloud computing, data exchange, and health), and can be referred to the "blockchain technology for healthcare" topic. It considers the adoption of BCT and cloud technologies for the secure management of data in the healthcare sector. It also focuses on the government of patient data, suggesting the development of appropriate policies and regulations for data management, as in [84]. Indeed, the healthcare sector deals with a huge amount of sensible patient data, so they need to be carefully managed and governed.
- Cluster 6 (light blue) is composed of 19 terms (e.g., service, manufacturing, person, collection, execution, big data, blockchain integration, citizen, cybersecurity, life, progress, society, city, customer, and progress) and can be referred to the "blockchain technology for human-centered solutions" topic. The cluster concerns the impacts of BCT on society and how it affects individual life, societal progress, and city management. Therefore, this cluster considers the human factor as a novel valuable target to address in the future. Humans need to be factored into the design and development of BC solutions by considering their specific needs and expectations. Indeed, the human-centric concept, associated with the concept of sustainability and resilience, is one of the key pillars at the basis of the future industry [85].
- Cluster 7 (orange) is composed of four terms (e.g., detailed analysis, IoT, public blockchain, and widespread adoption) and can be referred to the "worldwide blockchain technology" topic as the potential value of BCT through private and public resources [86]. Also, as BCT will be more and more experimented and applied in different sectors [87], its maturity could increase over time, supporting integrated and transversal applications, solving critical issues, and providing BC solutions.

Furthermore, Figure 7 shows the overlay visualization of the term co-occurrence. It represents the same network map visualization, but within the temporal dimension, by using different colors (as shown in the color bar in the bottom right corner of the figure). The color represents the average year in which the terms appear. Older terms are in blue, newer terms are in yellow, and terms in the middle are in green. In order to observe a significant difference in colors, the reference time interval is from 2021 to 2023. In fact, before and after these years, no significant differences could be observed. Interestingly, the following main terms appear in recent times: algorithm, energy trading, insights, practice, interoperability, manufacturing, health, artificial intelligence, transition, resilience, behavior, effectiveness, access control, computing, cyber physical system, and investigation. Therefore, recent streams of the considered research fields seem to be focused on the association of BCT with Cyber-Physical Systems (CPSs), artificial intelligence (AI), and other enabling technologies for enhancing the quality of energetic applications.

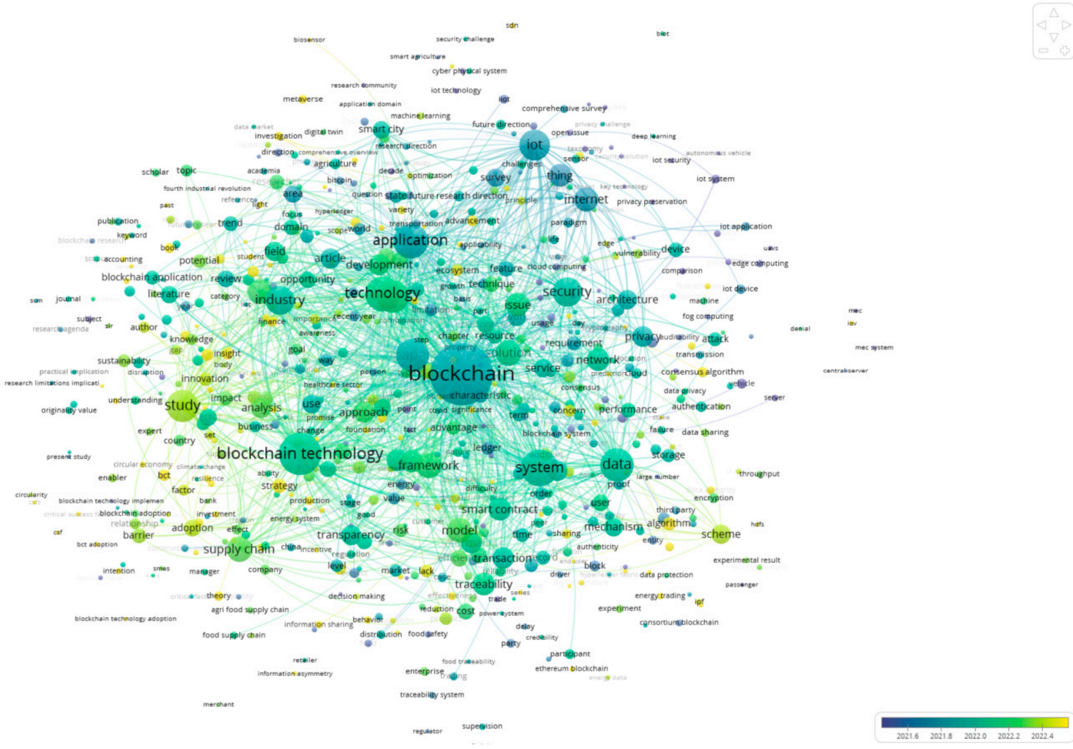

Figure 7. Overlay visualization.

On the contrary, older terms include IoT, value, consensus mechanism, ledger technology, survey, open issue, layer, and block. Therefore, the older literature seems to be more focused on investigating and defining BCT as a theoretical and conceptual paradigm.

In the middle, it is possible to find the following terms: development, data, system, efficiency, supply chain, security, network, smart city, trend, device, storage, and integrity. Therefore, starting from the recent past, the literature seems to be more focused on investigating BCT from the experimentation viewpoint.

In addition to the temporal dimension, the greater the distance of some nodes from the center of the network, the weaker their relationships with the key topics positioned at the center. Therefore, the overlay visualization suggests that despite some terms seeming to be investigated in the recent literature, those appearing at the boundary of the network could have a less relevant link with respect to some of the more central nodes.

Finally, in Figure 8, items are represented by their labels, similarly to the network visualization and the overlay visualization. However, the area around each term has a color that indicates the density of items at that point, including yellow, orange, and red. The larger the number of items in the neighborhood of a point and the higher the weights of the neighboring items, the closer the color of the point is to red. On the contrary, the smaller the number of items in the neighborhood of a point and the lower the weights of the neighboring items, the closer the color of the point is to yellow.

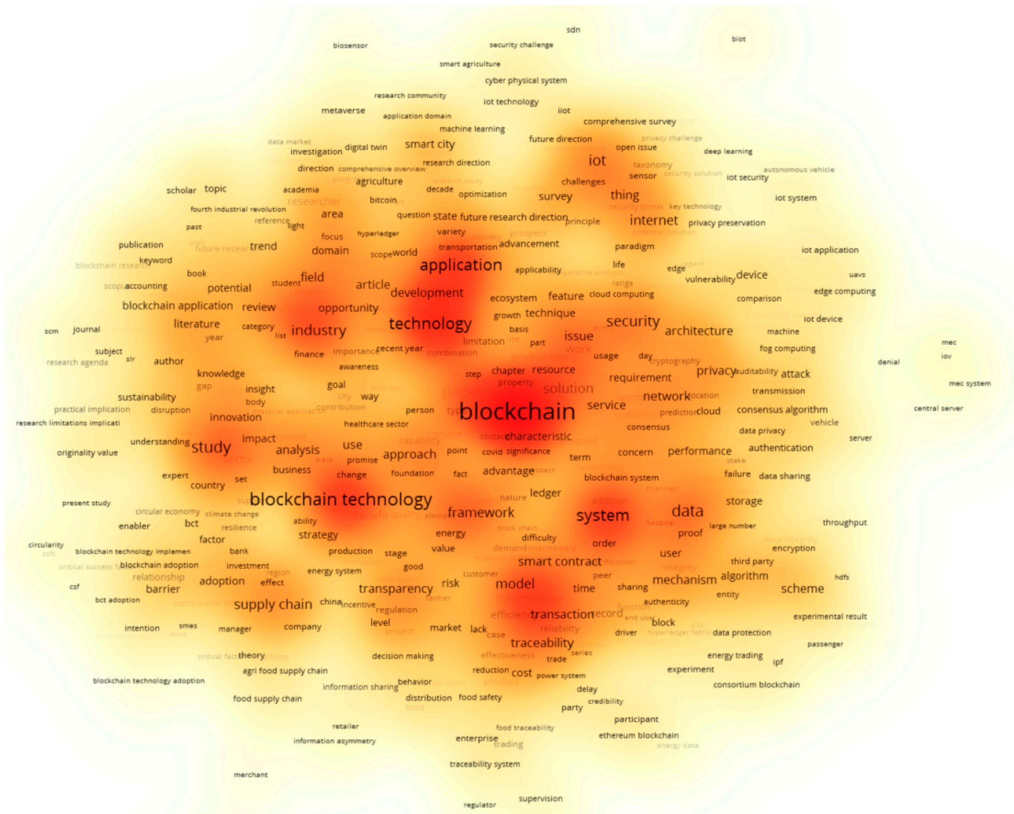

Figure 8. Item density visualization.

As shown in Figure 8, the most significant terms with the highest representative density are the following: BC, technology, system, application, and industry. Other important terms are data, security, supply chain, transparency, IoT, architecture, requirement, network, privacy, and service.

These terms suggest the most important topics in which the scientific literature has been concentrated over the years. It is important to note that, despite the key terms of this study being very considered (i.e., BC, data security and traceability), the terms "energy" and "sustainability" do not appear in the focus of the density distribution, thus suggesting potential future areas of research.

Implications and Future Research

The literature review revealed significant implications related to the adoption of BCT for sustainability and secure data management in the energy industry. In particular, a bibliometric analysis, which involves the use of statistical methods to analyze scientific publications, helped in assessing the influence, impact, trends, and hot topics within the research fields of interest. This approach assisted in constructing the main directions of future research, providing insights to guide strategic planning, funding decisions, and guiding the directions of scholars.

Based on the interpretation of the seven clusters identified above, Table 2 summarizes the most important implications of BCT and how it may influence future research actions in strategical, technical, regulatory, and social terms.

Table 2. Implications and future research in the field of BCT.

Cluster	Implication	Future Research Action	Reference
Using blockchain technology as a sustainable strategy in industry	Advancement of industrial scenarios in line with current technological frameworks	Understand how BCT enables novel business opportunities	[88]
	Integration of BCT in industry for sustainable management of data and systems	Identify benefits of using BCT with respect to secure data automation	[89]
	BCT integration with other enabling technologies	Ensure interoperability for transparent, accountable, and trustworthy technological solutions	[90]
	BCT solutions need to be considered with heterogeneous competences	Identify key stakeholders and discipline appropriate implementation protocol	[91]
	BCT correlation with environmental impact benefits	Analyze and monitor environmental impact of BC technology on basis of specific KPI (Key Performance Indicator) for sustainability	[92]
Blockchain technology for data traceability, security, and privacy	Novel approach for ensuring data traceability, security, and privacy	Conceptualize innovative frameworks that include BCT as key enabling driver	[93]
	Robust techniques and solutions for management of confidential data	Reengineer IT architectures and evolve towards decentralized and scalable structures	[94]
	Support confidential data transaction and transmission	Improve cryptography and anonymity without compromising regulatory and legal compliance	[95]
Blockchain technology for lifecycle management	BC technology has technical limitations and issues over time	Consider BCT challenges from design phase to its use, maintenance, and eventual disposal	[96]
	BCT is usually designed and implemented for specific and vertical applications	Move from specific use cases to generalized approaches and frameworks	[82]
Quality-oriented blockchain in the energy field	BCT helps to reduce energy consumption of computing resources	Empirically measure energy and cost savings in real BCT applications	[83]
	As a ledger technology, BC technology decentralizes and manages data and systems more effectively	Identify potential improvements of products and processes	[97]
	When associated with other enabling technologies (e.g., AI), BCT promises additional benefits	Design and develop new algorithms to improve performance and energy efficiency, energy trading, and renewable sources	[98]
Blockchain technology for healthcare	BCT helps in secure management of confidential patient data	Understand how patients can effectively benefit from use of BCT	[99]
	Distribution of data in decentralized technology structures places focus on privacy and data security	Design appropriate regulations in healthcare sector	[84]

Table 2. *Cont.*

Cluster	Implication	Future Research Action	Reference
Blockchain technology for human-centered solutions	Secure management of transactions worldwide	Include customers during entire lifecycle of BCT solution development starting from design phase	[100]
	BCT supports secure share and communication of personal data	Understand how BCT enables transactions without revealing sensible data	[101]
	BCT solutions are often less user-friendly	BCT solutions need to be designed and developed by focusing on human needs and expectations	[102]
	BCT ensures and disciplines smart contracts	Develop solutions for quick formal verification of smart contracts, data transmission correctness, and vulnerability prevention	[100]
	BCT is also related to social aspects	Analyze ethical, social, and educational impacts due to use of BCT	[103]
Worldwide blockchain technology	BCT solutions can rely on private and public infrastructure	Consider use of resources as a service	[86]
	Data ownership is not well defined	Design international data governance standard	[104]
	BCT regulates access to data	Design appropriate policy for enabling parallel access in real time by ensuring resilience	[105]
	BCT can be declined in different sectors	Push BC applications in smart logistics and supply chains smart grid, food, manufacturing, and healthcare sectors	[87]

Considering the derived insights from BCT implications and driving lines for future investigations, researchers may consider a contingent approach for supporting the alignment of technology innovation with organizational change [106]. Indeed, it is important to ensure not only the right adoption of BCT in the energy industry, which was revealed to be a scarce stressed topic in the literature, but also to guarantee a positive organizational response by managing an effective change process [107].

This type of research thinking may be used with an inter- or cross-cluster analysis. For instance, within the first cluster, "Using blockchain technology as a sustainable strategy in industry", the understanding of business opportunities related to BCT, the preliminary identification of benefits linked with the use of such technology, and the identification of the right stakeholders represent some issues that need to be considered before the development of technological solutions to ensure BCT interoperability and the analysis and monitoring of BCT's environmental impacts based on specific KPIs. Similar considerations could also be made for the other clusters. For example, in the "Blockchain technology for data traceability, security, and privacy" cluster, before the reengineering of IT architectures and the improvement of cryptography solutions, companies should conceptualize innovative and comprehensive frameworks that would consider the integration of BCT in their corporate environments.

On the other hand, prior issues need to be preliminary considered, such as the identification of potential improvements in products and processes, the inclusion of the right stakeholders and the analysis of their specific requirements, the classification of BCT challenges in its entire lifecycle, the design of appropriate policies and regulations, and the analysis of ethical, social, and educational impacts. After that, companies may invest in some other tasks, such as the design and development of novel algorithms to improve performance and energy efficiency, the introduction of solutions to enable transactions without revealing sensible data, and the effective development of human-centered BCT solutions.

In association with the contents that would be investigated in the future, some inferences may be derived with respect to the methodologies and techniques to adopt. The network visualization map shows that existing studies have mostly adopted literature reviews and surveys as reference methods to analyze the topic of BC technology in the energy sector. This phenomenon highlights how past research was mainly focused on more conceptual and theoretical studies instead of practical and empirical explorations. In fact, any studies were retrieved based on empirical experimentations of BCT or the execution of case studies that would recommend some evidence from real companies.

Finally, as anticipated by the clusters, the use of BCT implies some significant challenges and barriers that could limit the spread of such technology in the energy sector. For instance, guidelines, regulatory frameworks, or policies should be developed for a clear understanding of BCT and to reduce uncertainties [84,93]. Also, interoperability and scalability issues should be addressed [84,104]. The current potential of BC technology is limited in terms of its processing capacity, which may hinder high volumes of transactions from being carried out efficiently and may hinder integration with other complex systems and standards. In addition, the energy-intensive nature of BC technology, especially proof-of-work models, conflicts with sustainability goals. Lastly, the initial setup cost and some technical issues may discourage its widespread adoption [27].

5. Conclusions

Using a transparent and objective procedure, the bibliometric analysis revealed the distribution structure of the literature on the key fields of BCT from the perspective of sustainability and secure data management in the energy sector. In particular, the following seven key topics were identified as potential research directions: using blockchain technology as a sustainable strategy in industry; blockchain technology for data traceability, security, and privacy; blockchain technology for lifecycle management; quality-oriented blockchain in the energy field; blockchain technology for healthcare; blockchain technology for human-centered solutions; and worldwide blockchain technology.

These topics demonstrate an effective relationship between BCT and both the sustainability and secure data management concepts in the energy field. They suggest that with the development of increasingly high-performance applications, BCT has become a key technology capable of enabling secure, traceable, and tamper-proof transactions over the years. This makes it possible not only to securely manage the enormous amount of data that characterize IoT paradigm-based industrial environments (from the data collection phase to their transmission, storage, and use), but also to deploy resilient security solutions that respond effectively to cyber threats, preserving the security of critical industrial assets while ensuring business continuity. These suggestions contribute to extending corporate knowledge for the development of more sustainable business models.

Therefore, this paper, with the aim of guiding studies in the literature in the area of BC as a technology that ensures the principles of sustainability and those of data security and traceability, provides promising directions for future research (Table 2). In particular, these research actions need to be addressed with reference to the energy industry, where the literature still seems to be scarce. In fact, the clusters identified are in line with the gaps in the literature and suggest how to advance research to reduce missing knowledge. Finally, this study encourages future research to address the significant challenges and barriers that may limit the adoption of BC in the energy industry.

However, this study has some limitations that offer academics suggestions for future research improvement. In particular, the bibliometric analysis conducted was preliminary, relying on the Scopus database; in the future, further investigations could include an analysis of scientific papers from other sources such as Web of Science and

PubMed. Moreover, there exists a wide variety of methods for conducting a bibliometric analysis, and depending on the type chosen, the results may change. In this study, we used the keyword co-occurrence method for scientific mapping; however, other methods may be used in the future to map the knowledge area in the reference domain. On the other hand, the VOSviewer's adjustable parameters also affect the formation of thematic clusters. In this study, the most commonly adopted values for the parameters were used; however, future studies may include the use of other values. The keywords and search string used for data collection can also influence the results. Our approach was to be as inclusive as possible, so we defined five keyword groups and combined them to generate the main search string. Finally, the resulting interpretation of clusters could be biased by the subjectivity and backgrounds of the researchers; in the future, the content analysis could therefore be performed as a complementary method to improve research quality and reveal other insights.

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