Journal of Systems Science and Information
Jun., 2021, Vol. 9, No. 3, pp. 205–238
DOI: 10.21078/JSSI-2021-205-34

A Systematic Overview of Blockchain Research

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Abstract Blockchain has been receiving growing attention from both academia and practices. This paper aims to investigate the research status of blockchain-related studies and to analyze the development and evolution of this latest hot area via bibliometric analysis. We selected and explored 2451 papers published between 2013 and 2019 from the Web of Science Core Collection database. The analysis considers different dimensions, including annual publications and citation trends, author distribution, popular research themes, collaboration of countries (regions) and institutions, top papers, major publication journals (conferences), supportive funding agencies, and emerging research trends. The results show that the number of blockchain literature is still increasing, and the research priorities in blockchain-related research shift during the observation period from bitcoin, cryptocurrency, blockchain, smart contract, internet of thing, to the distributed ledger, and challenge and the inefficiency of blockchain. The findings of this research deliver a holistic picture of blockchain research, which illuminates the future direction of research, and provides implications for both academic research and enterprise practice.

Keywords blockchain; bitcoin; cryptocurrency; bibliometric analysis; co-citation network

1 Introduction

With the era of bitcoin, digital cash denoted as BTC makes it possible to store and transmit value through the bitcoin network[1]. And therewith, blockchain, the technology underlying

Received July 2, 2020, accepted February 24, 2021
Supported by the National Natural Science Foundation of China (71872171), and the Open Project of Key Laboratory of Big Data Mining and Knowledge Management, Chinese Academy of Sciences
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bitcoin, which adopts a peer-to-peer network to authenticate transactions, has been gaining growing attention from practices, especially Libra, a global currency and financial infrastructure launched by Facebook, and digital currency electronic payment. Currently, blockchain is also an increasingly important topic in the academic field. Blockchain research has considerably progressed, attracting attention from researchers, practitioners, and policy-makers[2–9].

Considering the huge potential benefits that blockchain would bring in various aspects of industries, for instance, finance and economy[10–12], internet of things[13–15], energy[16, 17], supply chain[18, 19], and other areas. It is often compared with the Internet and is even referred to as a new form of the Internet. As a result, the number of publications in the blockchain is growing rapidly. According to an initial search on the Web of Science Core Collection, over 2000 scientific papers published are related to blockchain.

Under the circumstances where the number of research publications in the blockchain is quickly increasing, although studies have tried to provide some insights into the blockchain research via literature reviews[20–24]. Comprehensive scientometric analysis of academic articles published in influential journals are beneficial to the further development of blockchain research. This research conducts a bibliometric visualization review and attempts to deliver an overview of the research in this fast-growing field.

The objectives of this research are as follows. First, we intend to build an overview of the distribution of blockchain-related research by time, authors, journals, institutions, countries (regions), and areas in the blockchain academic community. Second, we probe the key research topics of blockchain study, for which purpose, we conduct keyword co-occurrence analysis. Third, we picture the intellectual structure of blockchain study based on co-citation analysis of articles and author co-citation analysis. Finally, we identify the direction for the evolution of blockchain study. We adopt Citespace to detect and visualize emerging trends in blockchain study. To achieve these targets, we posed the following research questions:

Q1: What is the distribution pattern of blockchain publications and citations over recent years? Q2: Which are the main international contributing countries (regions) and institutions in blockchain research, and the collaboration network among them? Q3: What are the characteristics of the authorship distribution pattern? Q4: What are the key blockchain subjects based on the number of publications? Q5: Which are the major journals or conferences for blockchain-related research? Q6: Which are the most influential papers in blockchain research based on the number of citations? Q7: Who are the most influential authors in blockchain research according to the author co-citation network? Q8: What are the research trends in blockchain? Q9: What are the most supportive funding agencies for blockchain research?

Our intended contributions in this research are twofold. First, it is an attempt of adopting co-citation analysis to provide comprehensive and up-to-date developing trends in the lasted hot area, blockchain. Second, this study depicts a state-of-the-art blockchain research development and gives enlightenment on the evolution of blockchain. The findings of this research will be illuminating for both academic researchers, entrepreneurs, as well as policymakers.

The rest of the article is organized as follows. The literature review mainly summarizes related work. The “Data and methodology” section describes the data source and methodological process. The “Results” section presents the main results based on the bibliometric analysis

as well as statistical analysis. "Conclusions and implications" conclude this research provides answers to the aforementioned research questions and poses directions for further work.

2 Literature Review

Scientometric analysis, also known as bibliometric network visualization analysis has been widely adopted in numerous areas to identify and visualize the trends in certain fields. For instance, Bonilla, et al. analyzed the development of academic research in economics in Latin America based on a scientometric analysis[25]. Li, et al. conducted research on emerging trends in the business model study using co-citation analysis[26]. Gaviriamarin, et al. applied bibliometric analysis to analyze the publications on the Journal of Knowledge Management[27].

Since the birth of bitcoin, as the foundation of which, blockchain has gained an increasing amount of attention in academic research and among practices. The research papers focus on the blockchain are quite abundant and are continuing to emerge. Among a host of papers, a few studies investigate the research trend of blockchain-based on a bibliometric analysis[22, 23, 28–30].

Table 1 presents a summary of these bibliometric studies that summarized some findings on blockchain research, yet very few investigated the co-citation network and the evolution of popular topics in a timeline view. The number of papers these articles analyzed is relatively small, which may be because they used simple retrieval formula in searching blockchain-related articles, and it could pose a threat to bibliometric analysis. Therefore, this research aims to conduct a comprehensive analysis of the status of blockchain research, which is beneficial to future research and practices.

Table 1 An overview of existing bibliometric studies on blockchain research

ID	Year	First Author	Search Engine	Time Span	NP of analyzed	Main Findings
1	2019	Dabbagh M	WOS	2013–2018	995	Blockchain papers are mainly in Computer Science, followed by Engineering, Telecommunications, and Business Economics. National Natural Science Foundation of China has made sound investments in Blockchain research.
2	2018	Zeng S	EI; CNKI	2011–2017	473 (EI); 497 (CNKI)	Authors and institutes indexed by CNKI have higher productivity compared to EI. Researchers have shifted their attention from Bitcoin to the blockchain technology since 2017.

3	2018	Miau S	Scopus	2008–2017	801	There are three stages of blockchain research, namely, Bitcoin and cryptocurrencies, techniques of Blockchain and smart contract.
4	2017	Faming W	CNKI	2015–2017	423	Blockchain research system and the scientific research cooperation group of the author in China is yet to be formed.
5	2017	Mu-Nan L	WOS	1986–2016	220	Blockchains-related articles are highly correlated with Bitcoin's, Proceedings Papers account for 72% of the whole blockchain literatures.

Note: NP = number of publications; WOS = Web of Science Core Collection; CNKI = China National Knowledge Infrastructure Databases; EI = EI Compendex, an engineering bibliographic database published by Elsevier; Scopus = Elsevier's abstract and citation database.

3 Data and Methodology

This section elaborates steps to conduct a comprehensive bibliometric-based analysis: 1) data collection, 2) methodological process. The overall approach and methodology are shown in Figure 1, the details could be seen as follows.

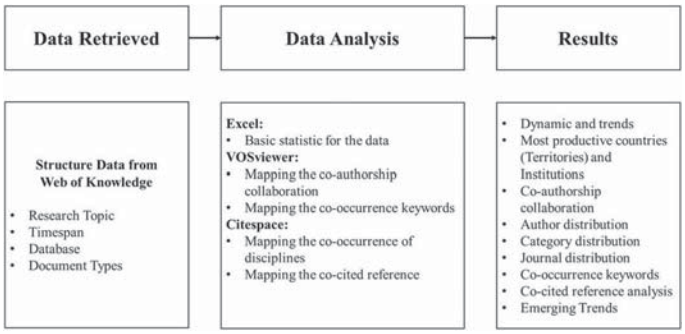

Figure 1 Research methodology

3.1 Data and Collection

As the leading database for science and literature, the Web of Science Core Collection has been widely used in bibliometrics analysis. It gives access to multidisciplinary information from over 18,000 high impact journals and over 180,000 conference proceedings, which allows for in-depth exploration of the complete network of citations in any field.

For the sake of acquiring enough articles that are relative to the blockchain, we select keywords from Wikipedia and industry information of blockchain, and some existing research literature[1, 20, 23, 30]. Moreover, in consideration of that, there are a host of blockchain research papers in various fields, in fact, although some papers use keywords in abstract or the main

body, blockchain is not the emphasis of the researches. Therefore, in order to get more accurate research results, we choose to conduct a title search instead of a topic search. Table 2 presents the retrieval results with different keywords in the titles, we find that among publications that are relative to the blockchain, the number of Proceeding Papers is the biggest, which is closely

Table 2 Blockchain research article characteristics by year from 2013 to 2019

ID	Retrieval Formula	Records	Document Type
1	TI = ("blockchain*")	1,506	P:793; A:683; R:40
2	TI = ("bitcoin")	606	P:333; A:272; R:5
3	TI = ("blockchain*" OR "bitcoin")	2,064	P:1,042; A:995; R:44
4	("blockchain*" OR "bitcoin" OR "ethereum*" OR "cryptocurrenc*" OR "smart contract*")	2,376	P:1,175; A:1,172; R:47
5	TI = ("blockchain*" OR "smart contract*" OR "smart-contract*" OR "distributed ledger" OR "hyperledger" OR "bitlicence" OR "chinaledger" OR "51% attack" OR "unspent transaction outputs" OR "segwit2x" OR "satoshi nakamoto" OR "dust transaction*" OR "cryptocurrenc*" OR "bitcoin*" OR "ethereum" OR "litecoin" OR "monero" OR "zerocoin" OR "filecoin" OR "crypto currenc*" OR "crypto-currenc*" OR "cryptocurrenc*" OR "encrypted currenc*" OR "on-ledger currenc*" OR "off-ledger currenc*" OR "cryptonote" OR "altcoin" OR "crypto token" OR "crypto crash" OR "cryptokitties" OR "bitpay" OR "mtgox" OR "bitfinex" OR "bitstamp" OR "okex" OR "okcoin" OR "huobi" OR "bitmex" OR "binance" OR "negocie coins" OR "bitforex" OR "coinbase" OR "poloniex" OR "fcoin" OR "gate.io" OR "initial coin offering" OR "initial miner offering" OR "initial fork offering" OR "initial bounty offering*" OR "initial token offering" OR "security token offering" OR "initial cryptoasset offering" OR "crypto-wallets" OR "soft fork" OR "hard fork" OR "cold wallet" OR "hot wallet" OR "core wallet" OR "imtoken" OR "decentralized autonomous organization*" OR "decentralized autonomus corporation*" OR "decentralized autonomus campany*" OR "ASIC mining" OR "application-specific integrated circuit miner" OR "FPGA mining" OR "GPU mining" OR "bitmain" OR "canaan creative" OR "BTC.com" OR "antpool" OR "SlushPool" OR "ViaBTC" OR "BTC.TOP" OR "F2Pool" OR "interplanetary file system")	2,451	P:1,212; A:1,210; R:49

Note: Document type include: Article(A), Proceedings Paper(P), Review(R); Timespan = 2013∼2019, download in May 31, 2019; Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI, CCR-EXPANDED, IC.

followed by articles, and a few reviews. Based on the comparison of five search results in Table 2. In addition, for accuracy and comprehensiveness, we manually go through the abstract of all the papers form conducting a title search, and choose papers that are related to blockchain. Finally, a dataset with 2451 articles is used in the subsequent analysis.

The dataset we choose has good representativeness, although it may not completely cover all papers on the blockchain, it contains core papers, and in bibliometric analysis, core papers are enough to provide a holistic view for a comprehensive overview of blockchain research.

3.2 Methodological Process

The bibliometric approach has received increasing attention in many research domains. In this study, the methodological process mainly includes three methods: 1) descriptive statistical analysis, 2) article co-citation, author co-citation, and cluster analysis on co-cited articles; 3) time-zone analysis on co-cited keywords.

Descriptive statistical analysis displays an overall status of the research development in the target field, which mainly presents an overview by publication years, document types, the research area of published journals, number of citations, and in terms of most cited paper, influential author, institutions and countries. Co-citation analysis helps to identify the frequency of co-cited papers and authors and provides crucial insights into the intellectual structure of certain research fields[31]. Time-zone analysis helps to understand the flow of information and research trends in the target area[32].

Various visualization tools have been designed and developed as computer software such as Citespace and VOSviewer. In this study, we use Citespace for co-citation analysis and time-zone analysis, VOSviewer is adopted for social network analysis and visualization, we also apply other tools such as Excel and Tableau for basic statistical analysis and the visualization of the bibliometric results. Notably, in Citespace, core nodes are displayed as "citation tree-rings", which contain abundant information of an article, for instance, the color of a citation ring denotes the year of corresponding citations, and the rule of colors in Citespace is the oldest in dark blue and newest in light orange with a spectrum of colors in between, the thickness of a ring is proportional to the number of citations in a time slice[33]. Figure 2 illustrates the details of the citation tree-rings. In addition, Citespace adopts a time-slicing mechanism to produce a synthesized network visualization[34].

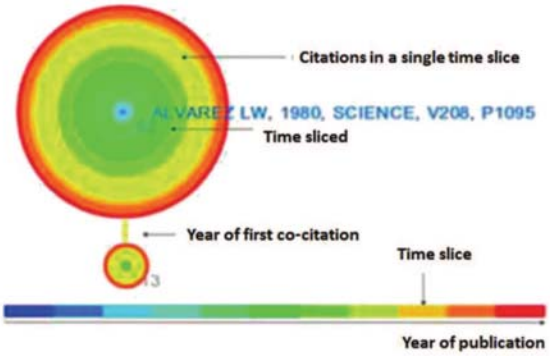

Figure 2 Citation tree-rings[33]

4 Results

4.1 Distribution by Publication Year

Table 3 illustrates several characteristics of blockchain-related publications sorted by the year of publication. The annual number of articles and countries has been growing continuously since the proposing of Nakamoto's paper in 2008[1], and the first blockchain research paper was published in 2013. By examining the published papers over time, there were only eight articles published in 2013. Afterward, with a continuous increase, a peak of 1,148 articles was published in 2018, and the number of publications is likely to grow ever since. Meanwhile, the annual number of countries taking part in blockchain research has also rapidly increased from 6 to 93 between 2013 and 2017, whereas the average number of Times Cited for single articles declined from 34.00 to 1.73 between 2013 and 2018. Over the observation period, 97 countries took part in the research on the blockchain with a sample of 44 in the H-index of our paper.

Table 3 Statistical description of Blockchain research article from 2013 to 2019

Publication Year	NP (%) of 2451 Papers	No.CO	AV.TC	H-index
2013	8 (0.33%)	6	34.00	4
2014	54 (2.20%)	26	16.98	17
2015	101 (4.12%)	37	14.88	19
2016	176 (7.18%)	48	14.19	25
2017	569 (23.22%)	65	5.00	26
2018	1,148 (46.84%)	93	1.73	19
2019	395 (16.12%)	72	0.29	4
Total	2,451 (100.00%)	97	4.12	44

Note: NP = number of publications; No.CO = number of countries; AV.TC = average number of Times Cited.

Figure 3 presents the cumulative numbers of published articles and citations from 2013 to 2019. There was a drastic increase in the number of papers published annually after 2016. As for the cumulative number of citations, there was no citation of blockchain literature before 2013, and 272 citations in 2013. By 2018, this number has grown over 10,000, which implies a widespread influence and attention of blockchain study in recent years.

The exponential growth is a typical characteristic of the development of research fields[35]. The model can be expressed as:

$$C = \alpha \mathrm{e}^{\beta Y},$$

where C is the cumulative number of articles or citations, Y is the publication or citation year, α, and β are parameters. In this study period, the cumulative articles and citations in the filed grow exponentially by $R^2_{\text{articles}} = 0.9463$ and $R^2_{\text{citations}} = 0.8691$ respectively. This shows that the research quantity curve of the blockchain is like an exponential function, which means the attention of academic circles on the blockchain has been increasing in recent years.

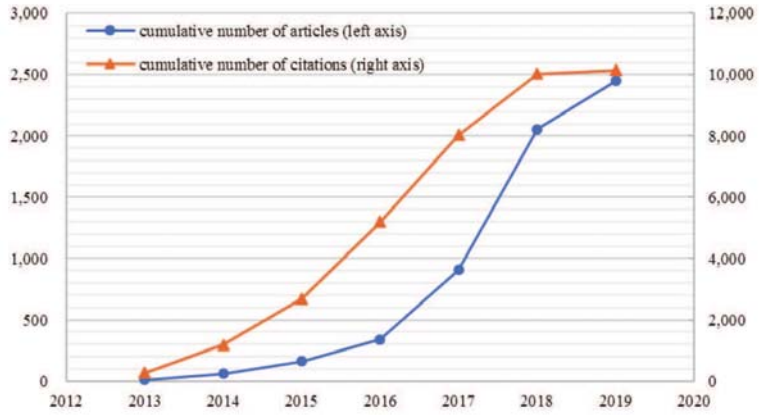

Figure 3 Cumulative growth in blockchain publications and citations, 2013–2019

4.2 Distribution and International Collaboration Among Countries/Regions

A total of 97 countries/areas have participated in blockchain research during the observation period. Table 4 shows the number of articles for each country (region) contributing to publications. Remarkably, an article may be written by several authors from different countries/areas, therefore, the sum of articles published by each country is large than the total number of articles. As can be seen from Table 4, the USA and China play leading roles amongst all countries/areas observed, with publications of 532 (20.94%) and 489 (19.24%) articles respectively, followed by the UK, which published 214 (8.42%) articles.

Table 4 Blockchain research country (region) ranked by number of articles (top 25)

Rank	Country (Region)	NP (%) of 2451 Papers	No.TC (%)	AV.TC	No.CA	H-index
1	USA	532 (20.94%)	3,709 (36.57%)	6.97	1,810	28
2	China	489 (19.24%)	1,357 (13.38%)	2.78	753	17
3	UK	214 (8.42%)	1,211 (11.94%)	5.66	658	17
4	Germany	121 (4.76%)	589 (5.81%)	4.87	437	13
5	Italy	120 (4.72%)	430 (4.24%)	3.58	335	11
6	Australia	118 (4.64%)	509 (5.02%)	4.31	372	13
7	France	105 (4.13%)	550 (5.42%)	5.24	376	13
8	South Korea	105 (4.13%)	451 (4.45%)	4.30	332	10
9	India	104 (4.09%)	178 (1.76%)	1.71	155	9
10	Canada	87 (3.42%)	390 (3.85%)	4.48	332	9
11	Japan	79 (3.11%)	165 (1.63%)	2.09	138	7
12	Spain	76 (2.99%)	396 (3.90%)	5.21	293	10
13	Russia	65 (2.56%)	61 (0.60%)	0.94	56	4
14	Switzerland	65 (2.56%)	416 (4.10%)	6.40	331	11
15	Singapore	55 (2.16%)	394 (3.88%)	7.16	313	11

16	Netherlands	47 (1.85%)	69 (0.68%)	1.47	66	4
17	Austria	43 (1.69%)	320 (3.16%)	7.44	280	8
18	Greece	42 (1.65%)	181 (1.78%)	4.31	171	5
19	Taiwan, China	39 (1.53%)	95 (0.94%)	2.44	78	6
20	U Arab Emirates	34 (1.34%)	144 (1.42%)	4.24	132	5
21	Brazil	32 (1.26%)	40 (0.39%)	1.25	39	4
22	Norway	31 (1.22%)	214 (2.11%)	6.90	172	7
23	Malaysia	30 (1.18%)	29 (0.29%)	0.97	27	4
24	Romania	27 (1.06%)	54 (0.53%)	2.00	52	3
25	Turkey	27 (1.06%)	65 (0.64%)	2.41	61	3

Note: NP = number of publications; No.TC = number of total Times Cited; AV.TC = average number of Times Cited; No.CA = number of Citing Articles.

From the perspective of citations, according to country/area distribution in Table 4, we also find that USA-authored papers were cited by 1,810 papers with 3,709 (36.57%) citations, accounting for 36.57% of total citations. Meanwhile, articles from the USA also have a very high average number of citations per paper with a frequency of 6.97, which ranks third among the top 25 countries/areas. Interestingly, the articles from Austria and Singapore appeared with the highest average number of citations per paper, with a frequency of 7.44 and 7.16 respectively, whereas the number of publications from these two countries was relatively low compared with the USA. The second was China, following the USA, papers were cited by 753 articles with 1,357 (13.38%) citations. Although the number of articles from China is close to the USA, the average number of citations per paper is lower with a frequency of 2.78. The subsequent countries include the UK, Germany, and Italy. The results indicate that the USA is the most influential country in blockchain.

International collaboration in science research is both a reality and a necessity[36]. A network consisting of nodes with the collaborating countries (regions) during the observation period is shown in Figure 4. The network is created with the VOS viewer in which the thickness of the linking lines between two countries (regions) is directly proportional to their collaboration frequency. We can see from Figure 4 that the USA has the closest collaborative relationships with China, the UK, Australia, Germany, and Canada. China has the closest collaborative relationships with the USA, Australia, Singapore, UK, and South Korea. UK has the closest collaborative relationships with the USA, China, France, and Switzerland. Overall, based on the collaboration network, collaboration mainly emerges in highly productive countries (regions).

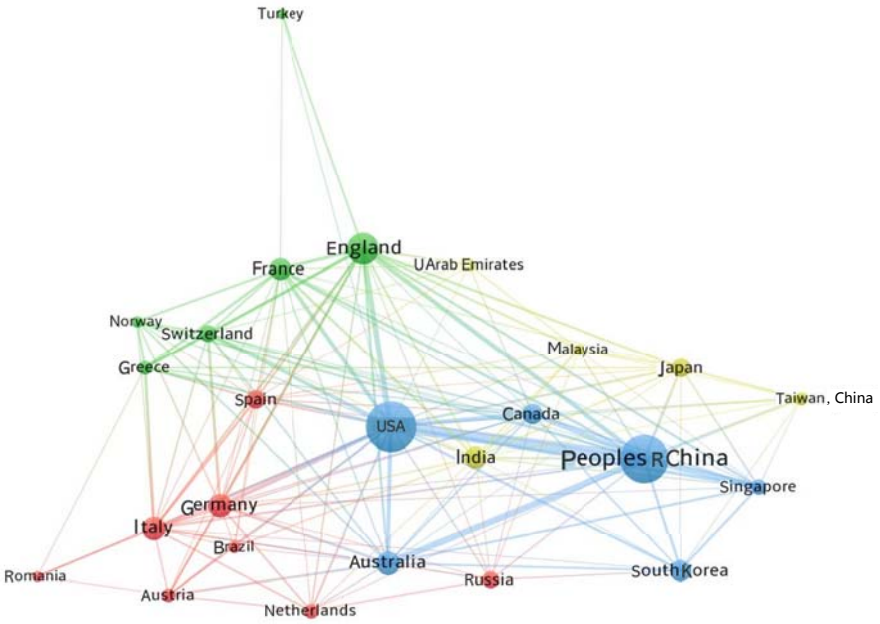

Figure 4 International collaboration network of the top 25 countries (territories), 2013–2019

4.3 Institution Distribution and Collaboration

A total of 2,190 institutions participated in blockchain-related research, and based on the number of publications, the top 25 of the most productive institutions are shown in Table 5. Chinese Academy of Sciences had the highest number of publications with 43 papers, followed by the University of London with 42 papers, and Beijing University of Posts Telecommunications ranked third with 36 papers. The subsequent institutions included the University of California System and the Commonwealth Scientific Industrial Research Organization (CSIRO). In terms of the number of total Times Cited, Cornell University is cited most with 499 citations, and the average number of Times Cited is 20.79. Massachusetts Institute of Technology followed closely with 407 citations and with an average number of Times Cited of 22.61. The University of California System ranks third with 258 citations and an average number of Times Cited of 8.06. ETH Zurich ranked fourth with 257 citations and an average number of Times Cited of 10.28. It is notable that the National University of Singapore also had a high average number of Times Cited of 12.56. These results indicate that most of the influential institutions are mainly in the USA and Europe and Singapore. The number of publications from institutions in China is large, whereas few of the papers are highly recorded in average Times Cited. Papers from the National University of Defense Technology China took the highest of average Times Cited of 7.79.

Table 5 Blockchain research country (territory) ranked by number of articles (top 25)

Rank	Institution	Country	NP (%) of 2451 Papers	No.TC	AV.TC	No.CA	H-index
1	Chinese Academy of Sciences	China	43 (1.75%)	136	3.16	117	6
2	University of London	UK	42 (1.71%)	132	3.14	123	7
3	Beijing University of Posts Telecommunications	China	36 (1.46%)	56	1.94	70	5
4	University of California System	USA	32 (1.30%)	258	8.06	233	8
5	Commonwealth Scientific Industrial Research Organization	Australia	28 (1.14%)	229	8.18	172	9
6	Beihang University	China	26 (1.06%)	43	1.65	38	4
7	University of Texas System	USA	26 (1.06%)	62	2.38	51	4
8	ETH Zurich	Switzerland	25 (1.02%)	257	10.28	208	9
9	University of Paris-Saclay	France	25 (1.02%)	85	3.40	82	5
10	Cornell University	USA	24 (0.98%)	499	20.79	387	10
11	International Business Machines	USA	24 (0.98%)	110	4.58	97	7
12	Peking University	China	23 (0.94%)	59	2.57	53	5
13	University of New South Wales Sydney	Australia	22 (0.89%)	171	7.77	147	6
14	University College London	UK	21 (0.85%)	87	4.14	82	5
15	University of Electronic Science Technology of China	China	20 (0.81%)	106	5.30	92	5
16	University of Sydney	Australia	20 (0.81%)	87	4.35	79	5
17	National University of Defense Technology China	China	19 (0.77%)	148	7.79	130	4
18	Shanghai Jiao Tong University	China	19 (0.77%)	46	2.42	42	3

19	University of Cagliari	Italy	19 (0.77%)	107	5.63	89	5
20	Massachusetts Institute of Technology	USA	18 (0.73%)	407	22.61	361	6
21	Nanyang Technological University	Singapore	18 (0.73%)	123	6.83	103	6
22	National University of Singapore	Singapore	18 (0.73%)	226	12.56	194	7
23	University of Chinese Academy of Sciences	China	18 (0.73%)	21	1.17	19	3
24	University of Texas At San Antonio	USA	17 (0.69%)	47	2.76	40	3
25	Xidian University	USA	17 (0.69%)	39	2.29	35	4

Note: NP = number of publications; No.TC = number of total Times Cited; AV.TC = average number of Times Cited; No.CA = number of Citing Articles.

To further explore data, the top 186 institutions with at least 5 articles each are chosen for collaboration network analysis. The collaboration network map is shown in Figure 5, the thickness of linking lines between two institutions is directly proportional to their collaboration frequency. As seen from the cooperation network in the Chinese Academy of Sciences, Cornell University, Commonwealth Scientific Industrial Research Organization (CSIRO), University of Sydney, and ETH Zurich cooperated widely with other institutions. This shows that collaboration between institutions may boost the research of blockchain which echoes with extant research that proposes with-institution collaboration and international collaboration may all contribute to article quality[37].

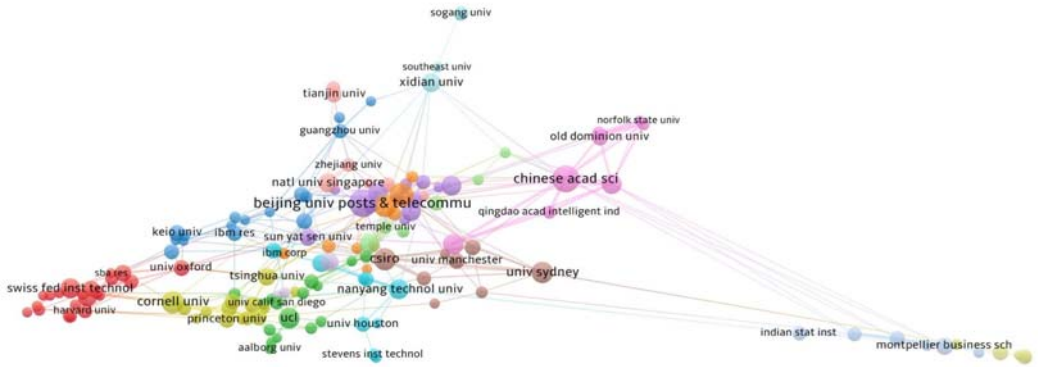

Figure 5 Collaboration network for institutions, 2013–2019

4.4 Authorship Distribution

The total number of authors who contribute to the publications of blockchain is 5,862. Remarkably, an article may be written by several authors from different countries (regions) or

institutions. Therefore, the total number of authors is bigger than the total number of articles. In fact, during the observation period, the average number of authors per paper is 2.4 articles. Reveals the distribution of the number of authors with different numbers of papers. As seen from the results, most of the authors had a tiny number of papers, i.e., among 5,862 authors, 4,808 authors have only one paper, 662 authors have two papers, and 213 authors have three papers.

According to the participation number of articles, the most productive author in the blockchain is Choo, Kim-Kwang Raymond from Univ Texas San Antonio, who took part in 14 articles in blockchain, followed by Marchesi, Michele from Univ of Cagliari, who took part in 13 articles related to blockchain. The third most productive author is Bouri, Elie from the Holy Spirit University of Kaslik, and David Roubaud from Montpellier Business School. Miller, Andrew, Shetty, Sachin, and Xu, Xiwei ranked fourth, who took part in 10 articles related to blockchain.

Table 6 The distribution of number of author with different numbers of articles

No.AU	No.AR	Full Name	Institution
1	14	Choo, Kim-Kwang Raymond	Univ Texas San Antonio
1	13	Marchesi, Michele	Univ of Cagliari
2	11	1. Bouri, Elie; 2. David Roubaud	1. Holy Spirit Univ Kaslik; 2. Montpellier Business School
3	10	1. Miller, Andrew; 2. Shetty, Sachin; 3. Xu, Xiwei	1. Univ of Illinois System; 2. Old Dominion Univ; 3. CSIRO
5	9	1. Bonneau, Joseph; 2. Kiayias, Aggelos; 3. Njilla, Laurent; 4. Salah, Khaled; 5. Shi, Elaine	1. New York Univ; 2. Univ of Edinburgh & IOHK; 3. US. Air Force Research Laboratory; 4. Khalifa Univ; 5. Cornell Univ
9	8	Du, Xiaojiang; Eyal, Ittay; Gupta, Rangan; Leung, Victor; Liang, Xueping; Moore, Tyler; Selmi, Refk; Tsai, Wei-Tek; Wang, Pengfei	-
15	7	-	-
25	6	-	-
44	5	-	-
74	4	-	-
213	3	-	-
662	2	-	-
4,808	1	-	-

Note: No.AU = number of author; No.AR = number of articles.

Figure 6 displays the collaboration network for authors. The thickness of the linking lines between the two authors is directly proportional to their collaboration frequency. As we can see from Figure 6, it indicates the most productive authors cooperate widely with others.

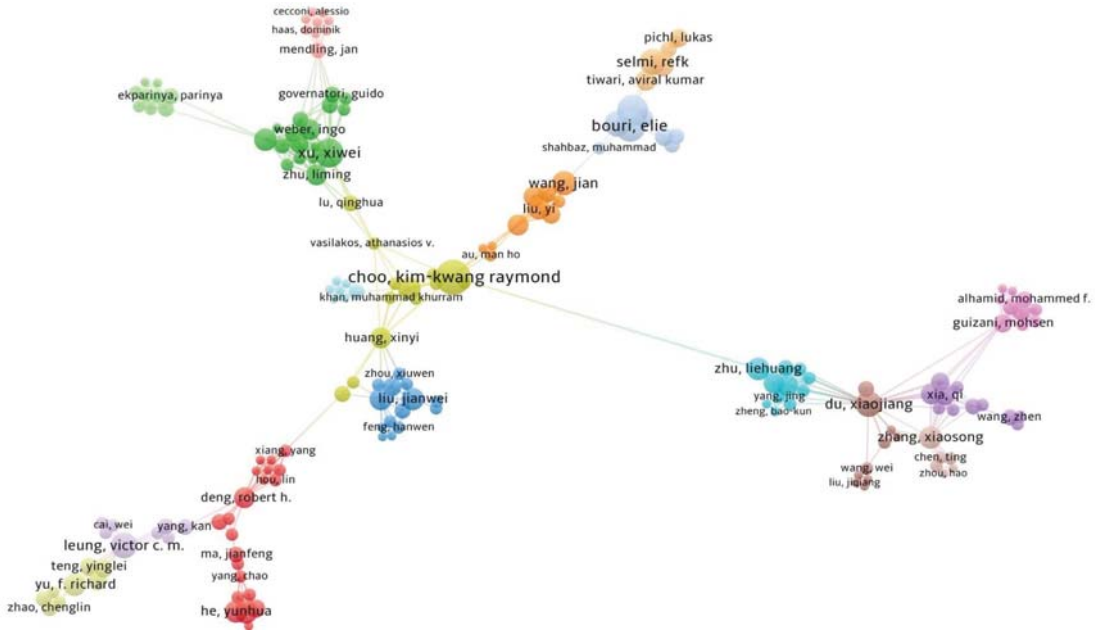

Figure 6 Collaboration network for authors, 2013–2019

4.5 Distribution of Subject Categories

Table 7 presents the top 25 blockchain categories ranked in terms of the number of articles published. As can be seen from Table 7, among the top 10 categories, six are related to the Computer Science field, which indicates that blockchain-related researches are more abundant in the field of Computer Science compared with other research fields. Besides, there are also publications in the category of Business & Economics with 385 records.

Figure 7 illustrates the betweenness centrality network of papers of the above categories by using Citespace after being simplified with Minimum Spanning Tree network scaling, which remains the most prominent connections. We can see from Figure 7, the centrality of Computer Science, Engineering Electrical Electronic, Telecommunications, Engineering, and Business & Economics are notable.

4.6 Journal Distribution

The research of blockchain is published in 1,206 journals (conferences), the top 25 journals (conferences) are displayed in Table 8. Blockchain research papers are concentrated in these top journals (conferences) and with a concentration ratio of nearly 20%. The major blockchain research journals include Lecture Notes in Computer Science, IEEE Access, Economics Letters, Future Generation Computer Systems, and Finance Research Letters, with more than 20 articles in each one. Meanwhile, the major blockchain research conferences include IEEE International Conference on Hot Information-Centric Networking, International Conference on Parallel and Distributed Systems Proceedings, International Conference on New Technologies Mobility, and Security, and Financial Cryptography and Data Security, with at least 14 articles published in each of these.

Table 7 The top 25 blockchain categories ranked by the number of publications

Rank	Web of Science Categories	Records	% of 2451
1	Computer Science	1326	54.10%
2	Engineering	724	29.54%
3	Engineering, Electrical & Electronic	666	27.17%
4	Computer Science, Theory & Methods	613	25.01%
5	Computer Science, Information Systems	608	24.81%
6	Telecommunications	410	16.73%
7	Business & Economics	386	15.75%
8	Computer Science, Software Engineering	219	8.94%
9	Computer Science, Interdisciplinary Applications	196	8.00%
10	Computer Science, Hardware & Architecture	184	7.51%
11	Economics	175	7.14%
12	Business, Finance	174	7.10%
13	Computer Science, Artificial Intelligence	134	5.47%
14	Government & Law	105	4.28%
15	Law	94	3.84%
16	Science & Technology — Other Topics	89	3.63%
17	Business	58	2.37%
18	Multidisciplinary Sciences	52	2.12%
19	Energy & Fuels	51	2.08%
20	Automation & Control Systems	44	1.80%
21	Management	41	1.67%
22	Physics	41	1.67%
23	Information Science & Library Science	39	1.59%
24	Operations Research & Management Science	36	1.47%
25	Green & Sustainable Science & Technology	34	1.39%

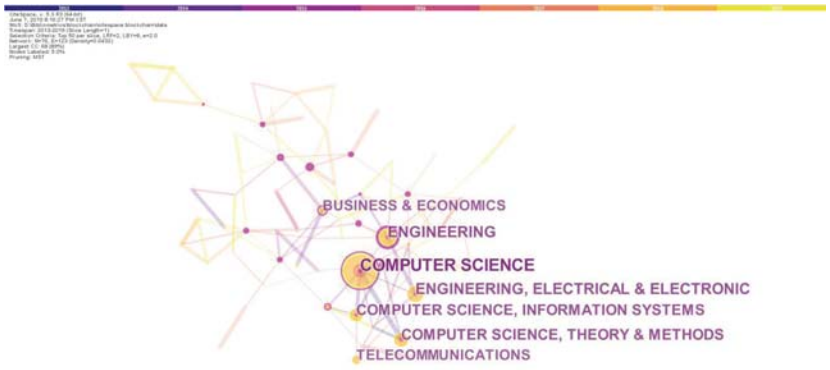

Figure 7 Categories involved in blockchain, 2013–2019

Table 8 The top 25 blockchain publication journals (conferences)

Rank	Source Title	NP (%) of 2,451	Country	No.TC
1	Lecture Notes in Computer Science	120 (4.89%)	Germany	1253
2	IEEE Access	102 (4.16%)	USA	639
3	Economics Letters	33 (1.35%)	Netherlands	555
4	Future Generation Computer Systems	22 (0.90%)	Netherlands	124
5	Proceedings of 2018 1st IEEE International Conference on Hot Information Centric Networking HOTICN	22 (0.90%)	-	2
6	Finance Research Letters	21 (0.86%)	Netherlands	307
7	ERCIM News	20 (0.82%)	-	1
8	Physica A: Statistical Mechanics and Its Applications	20 (0.82%)	Netherlands	101
9	International Conference on Parallel and Distributed Systems Proceedings	18 (0.73%)	-	4
10	Sensors	17 (0.69%)	Switzerland	66
11	PLoS One	16 (0.65%)	USA	283
12	Sustainability	15 (0.61%)	Switzerland	22
13	2018 9th IFIP International Conference on New Technologies Mobility and Security NTMS	14 (0.57%)	-	2
14	Advances in Intelligent Systems and Computing	14 (0.57%)	Germany	29
15	Financial Cryptography and Data Security FC 2016	14 (0.57%)	-	141
16	International Conference on New Technologies Mobility and Security	14 (0.57%)	-	2
17	Financial Cryptography and Data Security Fc 2014 Workshops Bitcoin and WAHC 2014	13 (0.53%)	-	142
18	Journal of Medical Systems	13 (0.53%)	USA	127
19	Proceedings 2018 IEEE 11th International Conference on Cloud Computing Cloud	13 (0.53%)	-	5
20	2018 IEEE 24th International Conference on Parallel and Distributed Systems ICPADS 2018	12 (0.49%)	-	0
21	Communications of the ACM	12 (0.49%)	USA	80
22	International Journal of Advanced Computer Science and Applications	12 (0.49%)	UK	7
23	Journal of Risk and Financial Management	12 (0.49%)	-	27
24	Strategic Change Briefings in Entrepreneurial Finance	12 (0.49%)	-	52
25	Computer Law Security Review	11 (0.45%)	UK	30

Note: NP = number of papers; No.TC = number of total Times Cited; Italic represents conference.

4.7 Intellectual Structure of Blockchain

Since the notion of co-citation was introduced, there are a host of researchers have adopted the visualization of co-citation relationships. The work is followed by White and Griffith[38], who identified the intellectual structure of science, researches then broaden the unit of analysis from articles to authors[39, 40]. There are two major types of co-citation analysis, namely, article co-citation analysis and author co-citation analysis, which are commonly adopted to visualize the intellectual structure of the research field. In this study, we explore the intellectual structure of blockchain by using both article co-citation analysis and author co-citation analysis. We apply Citespace to analyze and visualize the intellectual structure[41].

In this study, mining spanning trees was adopted to present the patterns in the author co-citation network, a visualization of the network of author co-citation is demonstrated in Figure 8. In the visualization of the co-citation network, pivot points are highlighted with a purple ring, and landmark nodes are identified with a large radius. From Figure 8, there are six pivot nodes and landmark nodes: Nakamoto S, Buterin V, Eyal I, Wood G, Swan M, Christidis K. These authors truly played crucial roles during the development of blockchain research. Table 9 shows the ranking of author citation counts, as well as their prominent publications.

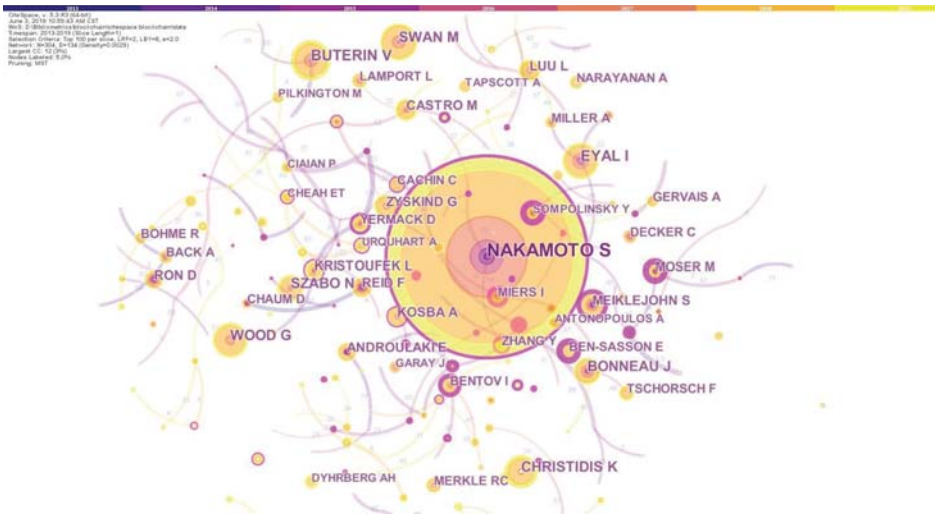

Figure 8 Network of author co-citation, 2013–2019

Nakamoto S, as the creator of bitcoin, authored the bitcoin white paper, created and deployed bitcoin's original reference implementation, is not surprised at the top of the co-citation count ranking, and has 1,202 citations in our dataset. Buterin V, a Russian-Canadian programmer, and writer primarily are known as a co-founder of ethereum and as a co-founder of Bitcoin Magazine, follows Nakamoto S, receives 257 citations. Eyal I, an assistant professor in technion, is a third of the ranking, with a representative article is "majority is not enough: Bitcoin mining is vulnerable". Wood G, the ethereum founder, and free-trust technologist ranks fourth with 244 citations. The other core author with high citations includes Swan M, Christidis K, Bonneau J, Szabo N, Zyskind G, Castro M, and Meiklejohn S, with more than 150 citations of each person, and the typical publications of there are present in Table 9.

Table 9 The top 15 co-cited author ranked by citation counts

Rank	Citation Counts	First Author	Article Title, Publication Year
1	1202	Nakamoto S[1]	Bitcoin: A peer-to-peer electronic cash system, 2008.
2	257	Buterin V[42]	A Next-generation smart contract and decentralized application platform, 2014.
3	251	Eyal I[43]	Majority is not enough: Bitcoin mining is vulnerable, 2014.
4	244	Wood G[44]	Ethereum: A secure decentralised generalised transaction ledger, 2014.
5	235	Swan M[2]	Blockchain: Blueprint for a new economy. 2015.
6	223	Christidis K[45]	Blockchains and smart contracts for the internet of things, 2016.
7	182	Bonneau J[46]	Sok: Research perspectives and challenges for bitcoin and cryptocurrencies, 2015.
8	176	Szabo N[47]	Formalizing and securing relationships on public networks, 1997.
9	164	Zyskind G[48]	Decentralizing privacy: Using blockchain to protect personal data, 2015.
10	154	Castro M[49]	Practical byzantine fault tolerance and proactive recovery, 2002.
11	153	Meiklejohn S[50]	A fistful of bitcoins: Characterizing payments among men with no names, 2013.
12	145	Kosba A[51]	Hawk: The blockchain model of cryptography and privacy-preserving smart contracts, 2016.
13	144	Reid F[52]	An analysis of anonymity in the bitcoin system, 2013.
14	143	Luu L[53]	A secure sharding protocol for open blockchains, 2016.
15	140	Ron D[54]	Quantitative analysis of the full bitcoin transaction graph, 2013.

To further investigate the features of the intellectual structure of blockchain research, we conducted an article co-citation analysis, using cluster mapping of co-citation articles networks to complete a visualization analysis of the evolution in the research field of blockchain. According to the article co-citation network, we adopted Citespace to divide the co-citation network into several clusters of co-cited articles. The visualization of clusters of co-cited articles is displayed in Figure 9.

As we mentioned earlier in the "Data and Methodology" section, the colors of citation rings and links are corresponding to the different time slices. Therefore, the deeper purple cluster (Cluster #1) is relatively old, and the prominent clusters (Cluster #0 and #2) are more recent. Cluster #0 is the youngest and Cluster #1 is the oldest. Cluster labels are identified based on burst terms extracted from titles, abstracts, keywords of bibliographic records[26, 41]. Table 10 demonstrates six predominant clusters by the number of members in each cluster.

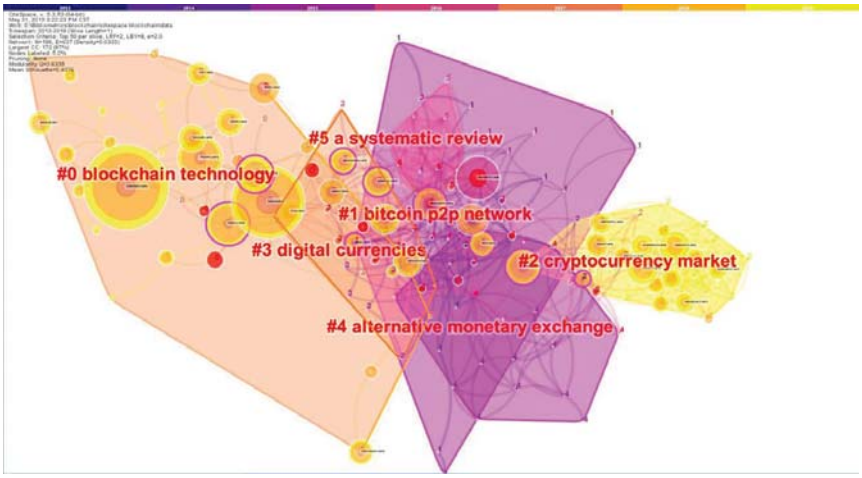

Figure 9 Clusters of co-cited articles, 2013–2019

Results show that the research priorities of the clusters keep changing during the observation period. From the earlier time (Cluster # 1), bitcoin and bitcoin network are the major priorities of researchers, then some researchers changed the focuses onto cryptocurrency in blockchain research. Notably, more researchers are most interested in blockchain technology and public ledger recently.

According to the characteristics of pivot nodes and landmark nodes in the co-citation article network. The landmark and pivot nodes in co-citation articles are shown in Figure 10, Five pivot nodes are Nakamoto S[1], Wood G[44], Kosba A[51], Eyal I[12] and Maurer B[55]. The main landmark nodes are Christidis K[45]. Swan M[2], Zyskind G[48] Nakamoto S[1], Kosba A[51], Notably, some nodes can be landmark and pivot at the same time.

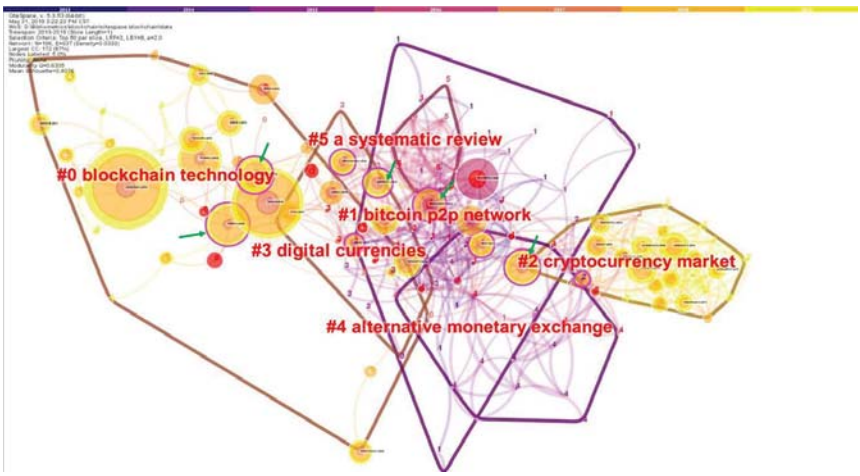

Figure 10 Landmark and pivot nodes, 2013–2019

Table 10 Summary of the largest 6 blockchain clusters

ID	Size	Label (LLR)	Label (TF*IDF)	Label (MI)	Mean Year
0	36	blockchain technology; service system; open issue; structured literature review; early standardization; blockchain application; blockchain research framework; future trend; health care application; blockchain.	internet; things; vehicular network; public ledger; pharmaceutics; e-agriculture; urban sustainability; nudge theory; cyber-security; smart contract.	public ledger; security infrastructure; online dispute resolution; public/private key; attention-driven investment; speculative bubble; iot applications; unconditional frequency domain analysis; measurement; distributed agreement; wald-wolfowitz test.	2016
1	34	bitcoin p2p network; risk scoring; bitcoin transaction; bitcoin; anonymity; bitcoin network; extracting intelligence; alternative monetary exchange; digital economy; bitcoin transversal; digital currencies.	cryptocurrency; virtual currency; digital money; mining pool; cryptocurrencies; supply; cryptocurrencies; double spending; electronic money; authorization; exchange rate.	blockchain technology; bitcoin p2p network; using p2p network traffic; public/private key; attention-driven investment; speculative bubble; unconditional frequency domain analysis; measurement; shangai stock market; central bank regulation.	2012
2	27	cryptocurrency market; industrial average; dow jone; bitcoin market; financial asset; systematic analysis; semi-strong efficiency; dynamic relationship; other financial asset; bayesian neural network; bitcoin price; blockchain information.	cryptocurrency; Markov chain monte carlo; non-linear time series models; vector autoregression; fluctuation behavior; investor attention; exact local whittle; random walk hypothesis; bsgvar model; google search volume index; cryptocurrencies.	public ledger; security infrastructure; online dispute resolution; public/private key; attention-driven investment; speculative bubble; iot applications; unconditional frequency domain analysis; measurement; distributed agreement.	2015

3	20	digital currencies; technical survey; scalable blockchain protocol; research perspective; off-blockchain bitcoin transaction; cooperative game; theoretic analysis; bitcoin mining pool; blockchain; bitcoin.	smart contracts; payment channels; orchestration; blockchain games; mining pool; asymmetric information; service resistance; client puzzles; emerging market currency; cryptocurrencies; digital currencies; consensus.	blockchain technology; distributed agreement; sharding; outlier; secure and correct systems; business process; orchestration; markets; choreography; jointcloud; anomaly; trustless.	2014
4	19	alternative monetary exchange; digital economy; bitcoin transversal; bitcoin; money; cryptocurrency; digital money; cloud mining; profitability; digital currencies; cryptocurrency.	cryptocurrency; digital currency; technology adoption; electronic payment; information share; price discovery; profitability; to-peer network; pedagogy; online dispute resolution; cryptocurrencies; digital currencies; consensus; profitability.	online dispute resolution; cost of transaction; arbitration; enforcement; public ledger; security infrastructure; public/private key; attention-driven investment; speculative bubble; iot applications; unconditional frequency domain analysis.	2013
5	11	a systematic review; current research; blockchain technology; bitcoin; tutorial; distributed consensus; altcoins; survey; digital currencies; blockchain; cryptocurrencies.	cryptocurrency; emerging market currency; emerging market transactions; fraud detection; rating fraud; reputation systems; smart contracts; blind signatures; off-chain transactions; scalability; emerging technologies; to-peer network; digital money; financial services.	blockchain technology; service system; open issue; structured literature review; bitcoin; early standardization; blockchain application; blockchain; cryptocurrency market; industrial average.	2014

Table 11 Details of the largest cluster (Cluster #0, top10)

Counts	First Author	Year	Publication Title	Source Title
214	Christidis K[45]	2016	Blockchains and smart contracts for the internet of things	IEEE Access
187	Swan M[2]	2015	Blockchain: Blueprint for a new economy	O'Reilly
119	Zyskind G[48]	2015	Decentralizing privacy: Using blockchain to protect personal data	IEEE Security and Privacy Workshops
112	Kosba A[51]	2016	Hawk: The blockchain model of cryptography and privacy-preserving smart contracts	IEEE Symposium on Security and Privacy
99	Tschorsch F[56]	2016	Bitcoin and beyond: A technical survey on decentralized digital currencies	IEEE Communications Surveys and Tutorials
85	Wood G[44]	2014	Ethereum: A secure decentralized generalized transaction ledger	Ethereum Secure Decentralized
77	Radziwill N[57]	2018	Blockchain revolution: How the technology behind bitcoin is changing money, business, and the world	The Quality Management Journal
75	Azaria A[58]	2016	MedVec: Using blockchain for medical data access and permission management	International Conference on Open and Big Data (OBD)
72	Yli-Huumo J[21]	2016	Where is current research on blockchain technology? — A systematic review	PLoS One
71	Narayanan A[59]	2016	Bitcoin and cryptocurrency technologies: A comprehensive introduction	Bitcoin Cryptocurrency

Table 12 Details of the largest cluster (Cluster #1, top10)

Counts	First Author	Year	Publication Title	Source Title
115	Nakamoto S[1]	2008	Bitcoin: A peer-to-peer electronic cash system	-
91	Ron D[54]	2013	Quantitative analysis of the full bitcoin transaction graph	International Conference on Financial Cryptography and Data Security
90	Meiklejohn S[50]	2013	A fistful of bitcoins: Characterizing payments among men with no names	Internet Measurement Conference
73	Reid F[52]	2013	An analysis of anonymity in the bitcoin system	International Conference on Social Computing

56	Miers I[60]	2013	Zerocoin: Anonymous distributed e-cash from bitcoin	IEEE Symposium on Security and Privacy
23	Ober M[61]	2013	Structure and anonymity of the bitcoin transaction graph	Future Internet
22	Moore T[62]	2013	Beware the middleman: Empirical analysis of bitcoin-exchange risk	International Conference on Financial Cryptography and Data Security
21	Androulaki E[63]	2013	Evaluating user privacy in bitcoin	International Conference on Financial Cryptography and Data Security
20	Barber S[64]	2012	Bitter to better — How to make bitcoin a better currency	International Conference on Financial Cryptography and Data Security

Table 13 Details of the largest cluster (Cluster #2, top10)

Counts	First Author	Year	Publication Title	Source Title
97	Böhme R[65]	2015	Bitcoin: Economics, technology, and governance	Journal of Economic Perspectives
80	Cheah E T[66]	2015	Speculative bubbles in bitcoin markets? An empirical investigation into the fundamental value of bitcoin	Economics Letters
78	Urquhart A[67]	2016	The inefficiency of bitcoin	Economics Letters
64	Dyhrberg A H[68]	2016	Bitcoin, gold and the dollar — A GARCH volatility analysis	Finance Research Letters
62	Ciaian P[69]	2016	The economics of bitcoin price formation	Applied Economics
60	Kristoufek L[70]	2013	BitCoin Meets Google Trends and Wikipedia: Quantifying the relationship between phenomena of the internet era	Scientific Reports
57	Dwyer G P[71]	2015	The economics of bitcoin and similar private digital currencies	Journal of Financial Stability
52	Nadarajah S[72]	2017	On the inefficiency of bitcoin	Economics Letters
51	Katsiampa P[73]	2017	Volatility estimation for bitcoin: A comparison of GARCH models	Economics Letters
49	Bouri E[74]	2017	Does bitcoin hedge global uncertainty? Evidence from wavelet-based quantile-in-quantile regressions	Finance Research Letters

Table 14 The top 10 cited blockchain articles

Rank	Title	First Author	Source Title	Year	TC	AV.TC
1	Blockchains and smart contracts for the internet of things	Christidis K[45]	IEEE Access	2016	266	66.50
2	Decentralizing privacy: Using blockchain to protect personal data	Zyskind G[48]	IEEE Security and Privacy Workshops	2015	169	33.80
3	Hawk: The blockchain model of cryptography and privacy-preserving smart contracts	Kosba A[51]	IEEE Symposium on Security and Privacy	2016	138	34.50
4	Bitcoin: Economics, technology, and governance	Böhme R[65]	Journal of Economic Perspectives	2015	128	25.60
5	Bitcoin and beyond: A technical survey on decentralized digital currencies	Tschorsch F[56]	IEEE Communications Surveys and Tutorials	2016	118	29.50
6	Zerocoin: Anonymous distributed e-cash from bitcoin	Miers I[60]	IEEE Symposium on Security and Privacy	2013	110	15.71
7	Zerocash: Decentralized anonymous payments from bitcoin	Sasson E B[75]	IEEE Symposium on Security and Privacy	2014	108	18.00
8	Majority is not enough: Bitcoin mining is vulnerable	Eyal I[43]	Financial Cryptography and Data Security	2014	102	17.00
9	Sok: Research perspectives and challenges for bitcoin and cryptocurrencies	Bonneau J[46]	IEEE Symposium on Security and Privacy	2015	99	19.80
10	The bitcoin backbone protocol: Analysis and applications	Garay J[76]	International Conference on the Theory and Applications of Cryptographic Techniques	2015	98	19.60

As seen from Table 10, Cluster #0 is the largest cluster, containing 36 nodes, for the sake of obtaining more information about these clusters, we explored the details of the largest clusters. Table 11 illustrates the details of the Cluster 0#.

We also explored Cluster #1 and #2 in more detail. Table 12 and Table 13 present the details of Cluster #1 and Cluster #2 respectively, it is notable that the most active citation in Cluster #1 is "bitcoin: A peer-to-peer electronic cash system", and the most active citation in Cluster #2 is "bitcoin: Economics, technology, and governance". The core members of Cluster #1 and Cluster #2 deliver milestones of blockchain research related to the bitcoin system and cryptocurrency.

Table 14 lists the first 10 most cited blockchain research articles indexed by the Web of Science. These articles are ranked according to the total number of citations during the observation period. Among these articles, the publication of "blockchains and smart contracts for the internet of things" by Christidis is identified as the most cited paper of 266 citations. The paper also has the highest average number of citations per year.

4.8 Keywords Co-Citation Analysis

According to Callon, et al.[77] co-word analysis is a useful way of examining the evolution of science. In our study, among 2,451 articles related to blockchain, we obtained 4,834 keywords, 594 keywords appeared 3 times, 315 keywords appeared 5 times, and 130 keywords appeared 10 times. Table 15 presents the most important keywords according to frequency. As seen, 'blockchain' ranks first with an occurrence frequency of 1,105, followed by 'bitcoin' of 606. The other high occurrence frequency keywords include: 'cryptocurrency', 'smart contract', and 'iot' (internet of thing).

Table 15 The top 25 keywords ranked by frequency

Rank	Frequency	Keywords	Rank	Frequency	Keywords
1	1105	blockchain	14	49	trust
2	606	bitcoin	15	50	distributed ledger
3	288	cryptocurrency	16	44	thing
4	270	smart contract	17	44	model
5	82	iot	18	49	inefficiency
6	149	security	19	44	economics
7	117	internet	20	44	management
8	110	ethereum	21	42	system
9	89	privacy	22	42	digital currency
10	78	internet of thing	23	40	authentication
11	60	technology	24	38	network
12	51	volatility	25	34	consensus
13	51	blockchain technology			

For the sake of further exploration of the relation amongst the major keywords in blockchain research papers, we adopted the top 315 keywords with a frequency no less than 5 times for co-occurrence network analysis. The keywords co-occurrence network is illustrated in Figure 11. In a co-occurrence network, the size of the node represents the frequency of the keywords co-occurrence with other keywords. The higher the co-occurrence frequency of the two keywords, the closer the relationship between them.

We can see from Figure 11, the size of blockchain and bitcoin are the largest among all keywords. This means, in general, blockchain and bitcoin have more chances to co-occurrence with other keywords. Besides, blockchain is closer with a smart contract, iot, Ethereum, security, internet, and privacy, whereas bitcoin is closer with digital currency and cryptocurrency.

Figure 12 displays the time-zone view of co-cited keywords, which puts nodes in order from left to right according to their years being published. The left-sided nodes were published in the last five years, and on the right-hand side, they were published in recent two years. Correspondingly, some pivot nodes of keywords are listed in the boxes. We hope to show the evolution of blockchain in general and the changes of focuses in blockchain study.

The results suggest that, in 2013, when blockchain research begins to surface, bitcoin dominated the blockchain research field. Reasonably, the bitcoin is the first cryptocurrency based on blockchain technology, and the influential essays include quantitative analysis of the full bitcoin transaction graph[54]; a fistful of bitcoins: Characterizing payments among men with no

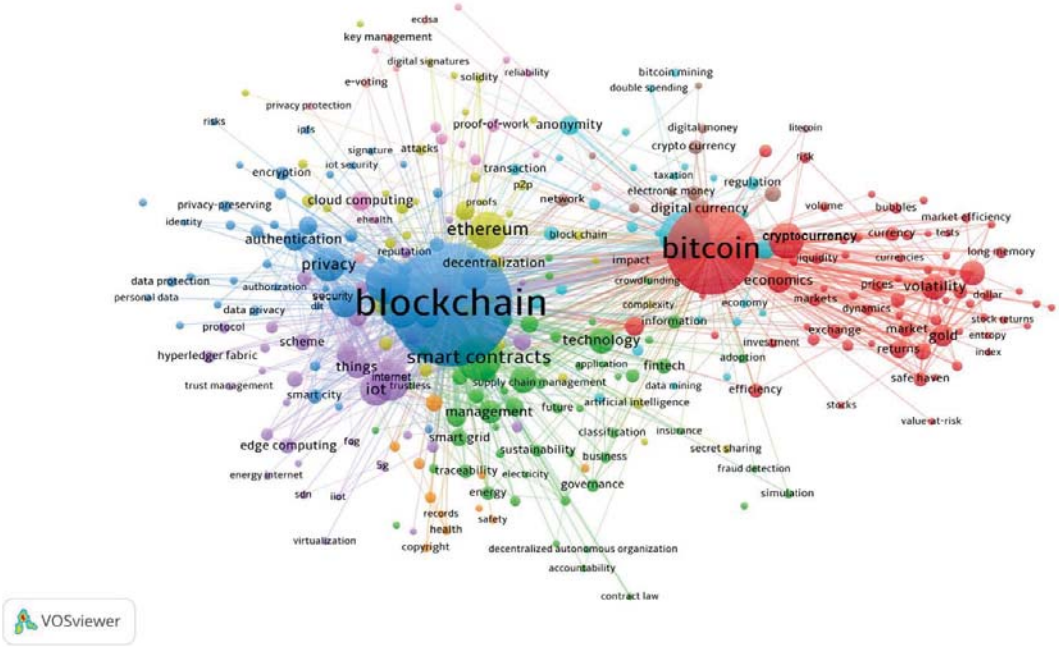

Figure 11 The keywords co-occurrence network, 2013–2019

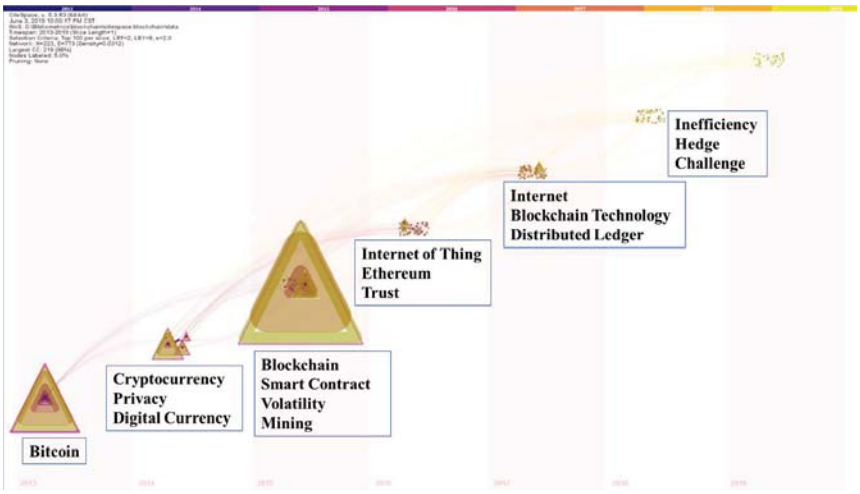

Figure 12 The time-zone view of co-cited keywords, 2013–2019

names[50]; and bitcoin meets google trends and Wikipedia: Quantifying the relationship between phenomena of the internet era[69]. Afterward, as various altcoins appeared, cryptocurrency and digital currency are widely discussed in blockchain-related research. The high-citation article is Zerocash: Decentralized anonymous payments from bitcoin[74] and privacy, which is the prominent characteristic of cryptocurrency. In 2015, blockchain and smart contract become a hotspot, the core publications include blockchain: A blueprint for a new economy[2]; decentralizing privacy: Using blockchain to protect personal data[48]; at the same time, some researchers also focus on the volatility and mining of cryptocurrency. In 2016, a growing number of researchers focus on the internet of things. The most popular article is blockchains and smart contracts for the internet of things[45]. In 2017, distributed ledger and blockchain technology become a research focus point. From 2018 onward, research focus on the challenge, and the inefficiency of blockchain appear.

4.9 Funding Agencies of Blockchain-Related Research

Based on all 2451 funding sources we analyzed in this study, the National Natural Science Foundation of China (NSFC) has supported the biggest number of publications with 231 papers, followed by the National Key Research and Development Program of China, which supported the publication of 88 papers. Comparatively, the National Science Foundation of the USA has only supported 46 papers. It is remarkable that the "Ministry of Science and Technology Taiwan" supported 22 papers, which is more than the European Union. Table 16 illustrates the top 20 funding agencies for blockchain research ranked by the number of supported papers. The results indicate that China is one of the major investing countries in Blockchain research with the biggest number of supporting articles.

Table 16 The top 20 funding agencies of blockchain-related research

Rank	Counts	Funding Agencies
1	231	National Natural Science Foundation of China (NSFC)
2	88	National Key Research and Development Program of China
3	46	National Science Foundation (USA)
4	26	Fundamental Research Funds for the Central Universities (China)
5	22	"Ministry of Science and Technology Taiwan"
6	14	European Union
7	10	China Scholarship Council
10	10	JSPS KAKENHI (Japan)
8	9	China Postdoctoral Science Foundation
9	8	Beijing Natural Science Foundation
11	6	Young Elite Scientists Sponsorship Program by Tianjin
12	6	Natural Science Basic Research Plan in Shaanxi Province of China
13	6	Air Force Material Command (USA)
14	5	National Research Foundation of Korea (NRF) — Korea government (MSIP)
15	4	Students Foundation
16	4	Natural Science Foundation of Jiangsu Province
17	4	Guangdong Provincial Natural Science Foundation
18	4	Russian Science Foundation
19	4	Singapore MOE Tier 1
20	4	Science and Technology Planning Project of Guangdong Province

5 Conclusions and Implications

5.1 Conclusions

This research comprehensively investigates blockchain-related publications based on the Web of Science Core Collection and provides a quick overview of blockchain research. In this study, a coherent comprehensive bibliometric evaluation framework is adopted to investigate the hot and promising blockchain domain. We outline the core development landscape of blockchain, including the distribution of publications over time, by authors, journals, categories, institutions, countries (territories), intellectual structure, and research trends in the blockchain academic community. Combining the results of statistical analysis and co-cited articles, authors, and keywords, we formulate the answers to the following research questions:

RQ1 What is the distribution pattern of blockchain publications and citations over recent years?

The published blockchain papers significantly increased since 2013, when the first blockchain paper was published. An increasing number of articles were published since. In 2018, 1,148

articles were published at the peak, and the number of publications is likely to continuously grow. As for the cumulative number of citations, there were only 272 citations in 2013. By 2018 this number has grown to more than 10,000, which implies a widespread influence and attention attracted by blockchain study in recent years.

RQ2 Which are the main international contributing countries (regions) and institutions in blockchain research, as well as collaboration networks among them?

A total of 97 countries (regions) participated in blockchain research during the observation period. USA and China play the leading roles among all countries (regions), with publications of 532 (20.94%) and 489 (19.24%) articles respectively, followed by the UK, Germany, Italy, and Australia. From the aspect of citations, USA-authored papers were cited by 1,810 papers with 3,709 (36.57%) citations, accounting for 36.57% of total citations. Articles from the USA also have a very high average number of citations per paper with a frequency of 6.97. Although the number of articles from China is close to the USA, the average number of citations per paper is lower with a frequency of 2.78. The results indicate that the USA is the most influential country in the field of blockchain.

A total of 2,190 institutions participated in blockchain-related research. Among them, the Chinese Academy of Sciences has the highest number of publications with 43 papers, followed by the University of London, Beijing University of Posts Telecommunications, University of California System, Commonwealth Scientific Industrial Research Organization (CSIRO), Beihang University, University of Texas System, ETH Zurich. In respect of the number of total Times Cited and the average number of Times Cited, Cornell University is cited the most with 499 citations, and the average number of Times Cited is 20.79. followed by the Massachusetts Institute of Technology, University of California System, and ETH Zurich. The number of publications forms institutions in China is large, whereas few papers own high average Times Cited.

In terms of collaboration networks among different institutions, we found that the Chinese Academy of Sciences, Cornell University, Commonwealth Scientific Industrial Research Organization (CSIRO), University of Sydney, and ETH Zurich cooperated widely with other institutions.

RQ3 What are the characteristics of the authorship distribution?

The total number of authors who contribute to the publications of blockchain is 5,862. the average number of authors per paper is 2.4. Among 5,862 authors, 4,808 authors have only one paper, 662 authors have two papers, and 213 authors have three papers. Based on the number of participated papers, the most productive author in the field of blockchain is Choo, Kim-Kwang Raymond from Univ Texas San Antonio, who participated in 14 articles in the field of blockchain, followed by Marchesi M, Bouri E, David R, Miller A, Shetty S and Xu X.

RQ4 What are the core blockchain subjects and journals based on the number of publications?

Blockchain-related researches are more abundant in the field of Computer Science compared with other categories. Other major fields include Engineering, Business & Economics, Telecommunications, and Business & Economics.

RQ5 What are the major journals or conferences for blockchain-related research?

The research of blockchain is published in 1,206 journals (conferences), the major blockchain research journals include Lecture Notes In Computer Science, IEEE Access, Economics Letters, Future Generation Computer Systems, and Finance Research Letters. Meanwhile, the major blockchain research conferences include IEEE International Conference on Hot Information-Centric Networking, International Conference on Parallel and Distributed Systems Proceedings, International Conference on New Technologies Mobility and Security, and Financial Cryptography and Data Security.

RQ6 What are the most influential papers in blockchain research based on the number of citations?

Ranked by the total number of citations during the observation period, the publication: "blockchains and smart contracts for the internet of things" by Christidis and Devetsikiotis[45] is identified as the most cited paper with 266 citations, which also has a highest average number of citation per year, followed by decentralizing privacy: Using blockchain to protect personal data[48] with 169 citations and 33.80 average number of citations per year.

According to the number of times co-cited, the top five influential publications are as follows: Bitcoin: A peer-to-peer electronic cash system[1], A next-generation smart contract and decentralized application platform[42], Majority is not enough: Bitcoin mining is vulnerable[12], Ethereum: A secure decentralised generalised transaction ledger[44], Blockchain: Blueprint for a new economy[2].

RQ7 Who are the most influential authors in blockchain research according to the author co-citation network?

Some authors played a crucial role during the development of blockchain research, Nakamoto S, as the creator of Bitcoin, and the author of the bitcoin white paper, created and deployed bitcoin's original reference, therefore is not surprised at the top of the co-citation count ranking and got 1,202 citations in our dataset. Buterin V, a Russian-Canadian, programmer, and writer, primarily known as a co-founder of Ethereum and as a co-founder of Bitcoin Magazine who follows Nakamoto S and receives 257 citations. Other core authors with high citations include Eyal I, Wood G, Swan M, Christidis K, Bonneau J, Szabo N, Zyskind G, Castro M, and Meiklejohn S.

According to co-cited articles clusters, the research priorities in blockchain-related research keep changing during the observation period. Bitcoin and bitcoin network are the main priorities of researchers, then some researchers changed to focus on cryptocurrency in blockchain research.

RQ8 What are the research trends of blockchain?

The research priorities in blockchain-related research evolve during the observation period. As early as 2013, when the research on blockchain first appears, bitcoin dominated the blockchain research field. Then only one year later, as various altcoins begin to appear, cryptocurrency and digital currency are widely discussed in blockchain-related research. In 2015, blockchain and smart contracts become a hotspot till 2016 when a growing body of researches begin to focus on the internet of things. In 2017, distributed ledger and blockchain technology become the research focal point. From 2018 onward, research focus on the challenge and inefficiency of blockchain.

RQ9 What are the most supportive funding agencies of blockchain research?

The most supportive funding agency of blockchain research is the National Natural Science Foundation of China (NSFC) which has supported the publication of 231 papers. The results indicate that China is one of the major investing countries in Blockchain research with the biggest number of supporting articles.

Given the potential power of blockchain, it is noticeable that governments, enterprises, and researchers all pay increasing attention to this field. The application of blockchain in various industries, the supervision of cryptocurrencies, the newly rising central bank digital currency and Libra, are becoming the central issues of the whole society.

In our research, we conducted a comprehensive exploration of blockchain-related research via a bibliometrics analysis, our results provide guidance and implications for academic research and practices. First, the findings present a holistic view of research in the blockchain domain which benefits researchers and practitioners wanting to quickly obtain a visualized overview of blockchain research. Second, according to our findings of the evolution and trends in blockchain research, researchers could better understand the development and status of blockchain, which is helpful in choosing valuable research topics, the distributed ledger, the discussions on the inefficiency and challenges of blockchain technology, the supervision of cryptocurrencies, the central bank digital currency are emerging research topics, which deserve more attention from the academic community.

5.2 Limitations and Future Work

As with any research, the design employed incorporates limitations that open avenues for future research. First, this study is based on 2,451 articles retrieved from the Web of Science of Core Collection, although the Web of Science of Core Collection is truly a powerful database for bibliometric analysis, we can't ignore the limitation brought by a unique data source. Future research can deal with this limitation by merging the publications from other sources, for instance, Scopus, CNKI, as well as patent database and investment data of blockchain, and it could help to validate the conclusion. Second, we mainly adopt the frequency indicator to outline the state-of-the art of blockchain research, although the frequency is most commonly used in the bibliometric analysis, and we also used H-index, citation to improve our analysis, some other valuable indicators are ignored, such as sigma and between centrality, therefore, it's beneficial to combine those indicators in future research. Besides, it should be noted that, in co-citation analysis, a paper should be published for a certain period before it is cited by enough authors[26], the newest published papers may not include in co-citation analysis, it's also an intrinsic drawback of bibliometric methods.

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