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Blockchain and Internet of Things: A bibliometric study ☆

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ABSTRACT

Blockchain is a distributed, decentralized and immutable digital ledger which records transactions across a global network of computers where the information is highly secure. Since its merger with other domains has solved numerous relevant problems, it has potential to resolve the issues of privacy and security in the domain of Internet of Things (IoT). IoT is reshaping the world into smart cities, smart farming, smart grids, smart transport, smart home, and smart healthcare systems. Thus, application of Blockchain in the domain of IoT gives birth to a new domain of Blockchain in IoT (BIoT). This research presents a bibliometric analysis of articles in BIoT domain, covering papers published in top journals and conferences, and finds research trends. It also explores diverse research areas, the most influential publications, top publication venues, top funding agencies and future research direction. This research can be a good learning point for young researchers to find attractive relevant research insights within BIoT.

1. Introduction

Internet of things (IoT) is an active research domain which is playing an essential role in the development of society. The term IoT was introduced by Ashton in 1998. He highlighted the importance of the IoT to change the world as the Internet did in early 1990s. MIT Auto-ID center was pioneer to present vision related to IoT in 2001. Later in 2005, ITU Internet report formally introduced the concept and technology of IoT. IoT is usually defined as the Internet of Things which allows people and things to be connected anytime, anyplace, with anything and anyone, ideally using any network and service. IoT devices are interrelated and are connected through the internet and cover almost every field of life, such as transportation, safety, home automation, and different wearable gadgets. Fig. 1 shows the statistics of globally connected IoT devices. The main components of IoT include sensors, devices, gateways, cloud, etc. IoT is expanding at high speed and the worldwide market for IoT solutions is expected to grow up to $7.1 trillion by 2020 [1]. There are many challenges in IoT such as installation and maintenance of centralized cloud server farms, firmware updates to millions of smart devices regularly from security and maintenance point of view [2]. Moreover, the lack of trust has also become the main research problem in IoT especially after the leaks of Edward Snowden user data, used for a mass surveillance programs and closed source code in IoT which was stored by the internet and telecommunication companies that lead to the lack of trust. There

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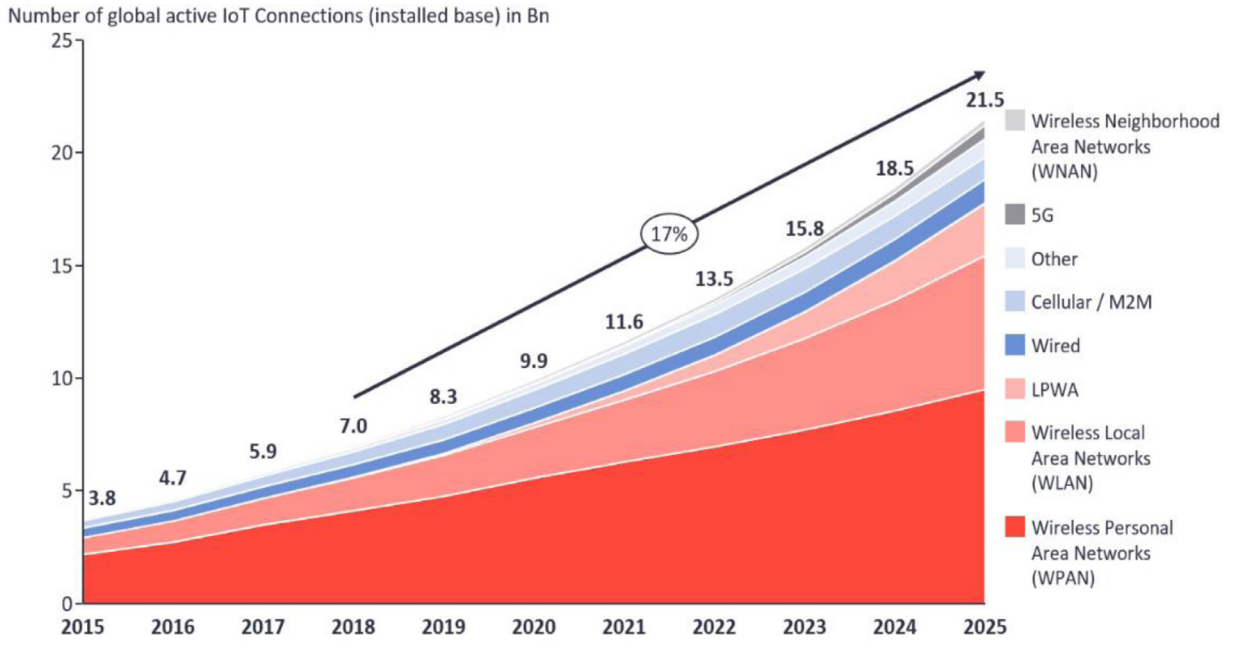

Fig. 1. Global Number of Connected Devices.

are fifty four IoT application domains and seven major characteristics in the IoT based on their study such as intelligence, time considerations, architecture, size considerations complex system, space considerations, and everything-as-a-service. The main challenges in IoT are security and privacy [3].[1]

The research domain of Blockchain began when Satoshi Nakamoto released a white paper in 2008, introducing a purely peer-to-peer version of electronic cash known as Bitcoin. Blockchain technology is defined as a combination of cryptography, game theory and peer-to-peer networking without central co-ordination. There are several consensus algorithms which are applied in Blockchain related research which are divided into two main types: proof-based consensus algorithm and voting-based consensus algorithm. Blockchain technology is categorized into two types: private and public Blockchain. Private Blockchain is controlled by a single company and as a result does not correspond to the independence principle of the Blockchain. The proof-based consensus algorithm is applied in public Blockchain, whereas the voting-based consensus algorithm is applied in private and consortium Blockchain [4]. Blockchain is a combination of diverse technologies which are considered as standard technologies for quite long period of time. These technologies are simply combined in a new and creative way to provide a new platform on which one can start building diverse solutions. Generally, Blockchain looks like a network of node computers where data is no longer stored in a central place, but distributed across a global ledger, using the highest level of cryptography. The main components of Blockchain are Ledger, Peer Network, Membership Services, Smart Contract, Wallet, Events, Systems Management, and Systems Integration. When any transaction is conducted on Blockchain, it is posted across tens of thousands of computers around the globe which are the part of this Blockchain network. These transactions are then recorded as blocks. Further, these blocks are joined using the information of adjacent blocks in a chain. It has three main features, namely Decentralized control, Immutability (written data is tamper-resistant, and the block is ordered) and Independent ability to create & transfer assets. Blockchain was first used for financial transactions in a cryptocurrency Bitcoin, but currently it is emerging in several research domains. At the same time, the Blockchain technology has been applied to many fields, including medicine, economics, Internet of things, software engineering, healthcare, voting, election reforms, supply chain, value chain, Walmart [5].

Blockchain is contributing to the Internet of Things. The decision to determine whether Blockchain is required in IoT is based on several factors [7]. Among those the first factor is related to decentralization, if decentralization is required in IoT or there are privacy and security issues, then Blockchain can play a very important role to address these issues. Secondly if peer to peer (P2P) system is required in IoT, then Blockchain is a good solution. P2P communication is only required for applications such as mist computing and intelligent swarms. The third factor is the requirement of the payment process in IoT. In such cases, Blockchain may be a good choice as Blockchain got famous because of a payment system such as Bitcoin that eliminates the need to trust any third party, such as a bank. It is expected that Blockchain technology will automate the payment process in cryptocurrency [8]. The fourth factor is related to the requirement for keeping a log

[1] Lueth, K.L. *State of the IoT 2018: Number of IoT devices now at 7B – Market accelerating*, https://iot-analytics.com/state-of-the-iot-update-q1-q2-2018-number-of-iot-devices-now-7b/. (accessed April 4, 2019).

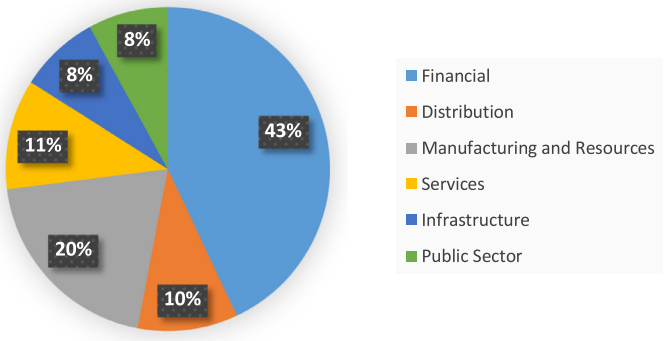

Fig. 2. IDC's Worldwide Semi Annual Blockchain Spending Guide [11].

of sequential transactions, if required Blockchain can be used. Finally, if traceability is required in the IoT systems then Blockchain will be very helpful. Traceability can be required for different reasons, such as for auditing purposes. Blockchain merged with the Internet of things is referred to as BIoT. Although the first application of Blockchain was Bitcoin; however, it was not limited to just Bitcoin; it found its applications in smart contracts. Later, it evolved into applications where coordination was an important factor. Blockchain can be used in many cases and in many fields where IoT is involved, such as management of identities, data storage, in different sensors, for timestamps [9], daily life applications like smart homes [10], wearables, supply chain management and cyber law. It has been proposed by some researchers to control and configure the IoT device remotely for that Blockchain based system can be really helpful. The main challenges in IoT and the main features of Blockchain relate each other and opened ground for researchers to work in this domain. Hence the number of publications in this domain is increasing. The research topics in this domain include edge/fog/cloud computing, industrial IoT [6], methodologies, security and privacy, healthcare, management, etc. Expansion of Blockchain by 2022 according to IDC spending guide is shown in Fig. 2.

Bibliometric analysis is defined as the statistical analysis of books, articles, or other publications to measure the output of individuals/research teams, institutions, and countries, to identify national and international networks, and to map the development of new multi-disciplinary fields of science and technology. As the number of publications in the BIoT domain is increasing, therefore, there is a need to provide an overview of the research published in this domain by systematically collecting, characterizing and analyzing research papers related to the BIoT. For this purpose, the research study uses bibliometric methods to examine the academic research in the domain of BIoT to reveal insights to the active scholars and practitioners in the BIoT domain. The web of science (WoS) core collection database is used in this research study for bibliometric analysis.

The rest of the paper is organized as follow. Section 2 describes the research methodology followed in the research. Section 3 presents a comprehensive bibliometric analysis of BIoT. In Section 4, we provide answers to the research questions before concluding the research work and sharing potential future research directions.

2. Research methodology

The research methodology of this research study consist of formulation of research questions, data set extraction, data preprocessing and data analysis that is explained in detail.

2.1. Formulation of research questions

The main objective of this research study is to conduct a bibliometric analysis of BIoT papers that are indexed by WoS Core Collection. To achieve this objective, the research questions are set out to answer. Research questions are taken from bibliometric studies related to Blockchain [12] and IoT [13]. These research questions and significance of their answers are mentioned in Table 1.

2.2. Data extraction

The first step before data extraction is the selection of an appropriate search engine that fulfills bibliometric analysis requirements. WoS is selected for the said purpose based on its features and scope like leading scientific citation index, rigorous selection process to maintain high-quality and influential research publications, research publications covering prestigious journals, conference proceedings, and books providing analytical features to the researchers. The second step is the selection of appropriate related terms as a query string to start extracting papers. After trying multiple terms like “Blockchain & IoT”, “Blockchain AND Internet of thing”, “Blockchain AND Internet of things”; “Blockchain AND Internet of

Table 1
Research questions and their significance.

Research Questions	Significance
What is the trend of BIoT publications and citations?	It will help researchers to predict the future pattern in BIoT.
Which research areas have more BIoT research based on the number of publications?	It will help researchers to determine the research effort in every area of BIoT, which will help them to identify future research directions.
What are the most influential papers in BIoT according to the number of citations?	It would help to find research studies and methods that may lead to conduct high-quality research work in BIoT.
What are the most popular publication venues for BIoT papers?	It would help BIoT researchers to make the best selection of journals and conferences to publish their research work, which will affect the number of citations of the paper in the future.
What are the top most supportive funding agencies of BIoT papers?	It will help researchers and practitioners to initiate any research collaboration or to apply for a BIoT related position.
What is the future research direction in the BIoT domain?	It would help researchers in selecting a research problem in this domain.

Table 2
Research document types.

Document Types	Counts
Article	134
Review	17
Editorial Material	6
Proceedings Paper	3

Things" is found as the most appropriate term. This research study selected the span of 2008 to April 2019. This search string is applied on WoS to search in topic, title, abstract, authors, keywords, publication name, publication year and funding agencies. Table 2 describes the number and type of documents found in the databases totaling 157 documents. There is not a single Conference paper in this domain so far.

2.3. Data preprocessing

The number of documents retrieved as per defined query is 157. The editorial material is excluded as per existing relevant studies and thus 151 documents are selected for analysis. The short name of country is used for easy of representation and discussion such as Peoples R China to China for ease. Keywords and their synonym are considered interchangeably to avoid redundancy as the Internet of thing, the Internet of things and IoT are three different terms, but convey the same message. Moreover, all multi-words keywords are renamed to a single word by putting a hyphen for ease in the analysis. There was no duplication found in the record.

2.4. Data analysis

After the formulation of research questions, data set extraction, data preprocessing, the analysis is performed in Section 3 that consist of temporal trend of publications, categorization of BIoT, top publishing venues, top countries, organizations and funding agencies working in BIoT, top relevant research areas, citation analysis and keyword analysis.

3. Bibliometric analysis

This section presents the bibliometric analysis of BIoT domain. The analysis is performed in a way, that will answer the research questions formatted in Section 2.1. The result analysis feature and citation report feature available on the WoS is used for the analysis, that is standard for this type of studies.

3.1. Temporal trend of publications

The first analysis is the temporal trend of publications. The number of publications in three research domains of Blockchain, IoT and BIoT are 976, 14,917 and 151 respectively. Table 3 shows time trend comparison of Blockchain, IoT and BIoT. In 2016, the number of IoT, Blockchain, and BIoT publications are 1996, 31 and 3 respectively, where BIoT publications' percentage with respect to IoT and Blockchain is 0.15% and 9.6% respectively. In 2017, number of IoT, Blockchain, and BIoT publications were 3191, 170 and 16 where BIoT publications' percentage with respect to IoT and Blockchain is 0.50% and 9.4% respectively. In 2018, number of IoT, Blockchain, and BIoT publications were 5060, 499 and 83 where BIoT publications' percentage with respect to IoT and Blockchain is 1.64% and 16.63% respectively which is significantly increased. In 2019, the number of IoT, Blockchain, and BIoT publications are 1862, 275 and 49 respectively where BIoT publications percentage with respect to IoT and Blockchain is 2.63% and 17.81% respectively. This shows that the publications BIoT is increasing in both BIoT domains. Fig. 3 shows that the number of BIoT publications is increasing every year which shows the importance of BIoT research domain.

Table 3
Time trend of BIoT publications in IoT and blockchain domain.

Years	% of BIoT Publications in Total IoT Publications	Total IoT Publication	% of BIoT Publications in Total Blockchain Publications	Total Blockchain Publications
2016	0.15%	1996	9.60%	31
2017	0.50%	3191	9.40%	170
2018	1.64%	5060	16.63%	499
2019	2.63%	1862	17.81%	275
2016–2019	1.24%	12,109	15.48%	975

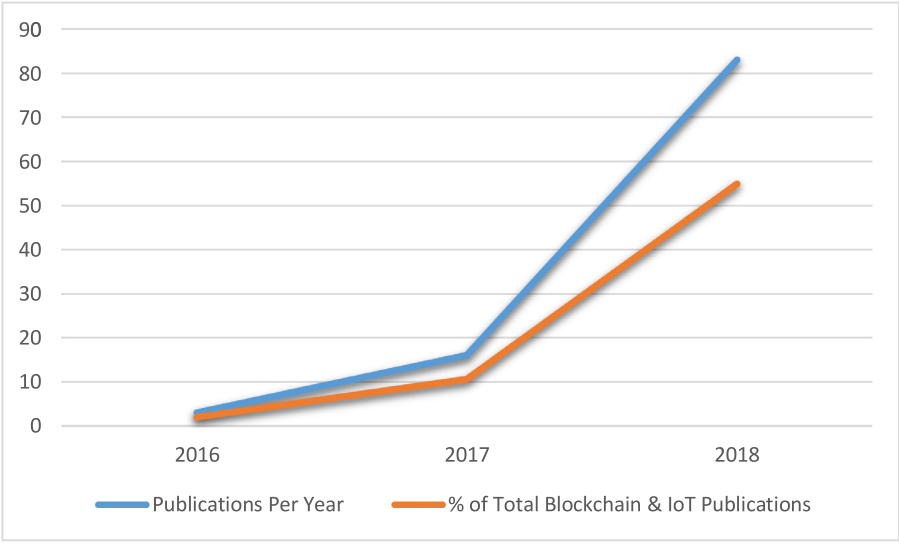

Fig. 3. Yearly Publication Trend.

3.2. BIoT categories

This section analyzes the WoS categories in which BIoT papers are published. Fig. 4 shows that computer science information systems are the top leading category with 63 publications followed by engineering electrical electronic with 53 publications. The other leading categories are chemistry analytical, instruments instrumentations, computer science software engineering, engineering industrial. It's interesting to find fields that seem to be unrelated to BIoT such as Chemistry. BIoT is used in this field for food traceability systems, smart agriculture ecosystem and supply chain management [14–16] These categories also show that BIoT is multi-disciplinary domain.

3.3. Top publishing venues

Table 4 presents the top 10 publication venues for the research papers related to Blockchain, IoT and BIoT domains in ascending order. The table shows that IEEE Access, Sensors and Future Generation Computer Systems and the International Journal of Science are the common journals in all three domains publishing the highest number of papers respectively. This also shows that BIoT domains are tightly linked to having research work.

3.4. Top countries, organizations and funding agencies working in BIoT

In this section, the list of top countries, list of top organizations and list of top funding agencies having the highest number of publications is presented. Fig. 5 shows that China published the highest number of papers i.e., 42 followed by the USA with count of 33 publications and then followed by South Korea, England and Australia with 19, 17 and 10 publications, respectively. Fig. 6 shows the top organizations that published research papers in the BIoT domain. Among these top 10 organizations, 6 are from China with 21 publications and 4 are from other countries. It is strange but interesting to share that there is no organization from the USA in this list. Fig. 7 shows the list of funding agencies with the highest number of funds in the BIoT domain. In this list, the top 6 agencies are from China with 49 research funding.

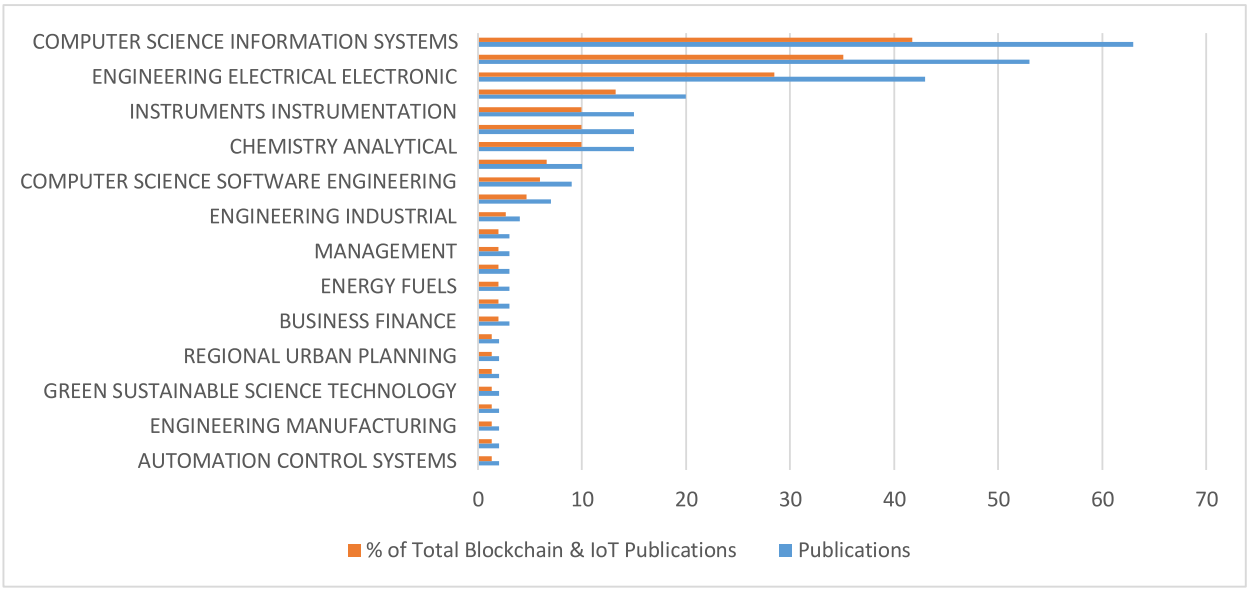

Fig. 4. BIoT Categories.

Table 4
Top publishing venues.

Blockchain		IoT		BIoT	
Source Titles	Count	Source Titles	Count	Source Titles	Count
IEEE Access	110	IEEE Internet Of Things Journal	1000	IEEE Access	21
Sensors	19	IEEE Access	956	Sensors	15
Sustainability	16	Sensors	810	International Journal Of Distributed Sensor Networks	6
Future Generation Computer Systems The International Journal Of eScience	15	Future Generation Computer Systems The International Journal Of eScience	324	Future Generation Computer Systems The International Journal Of eScience	5
Journal Of Medical Systems	13	International Journal Of Distributed Sensor Networks	266	International Journal Of Advanced Computer Science And Applications	5
Ercim News	12	IEEE Communications Magazine	199	IEEE Internet Of Things Journal	4
Strategic Change Briefings In Entrepreneurial Finance	12	Wireless Personal Communications	175	Electronics	3
Computer Law Security Review	10	IEEE Transactions On Industrial Informatics	160	IEEE Cloud Computing	3
Future Internet	10	IEEE Sensors Journal	153	Security And Communication Networks	3
Energies	9	Wireless Communications Mobile Computing	147	Wireless Communications Mobile Computing	3

3.5. Research areas

Fig. 8 shows the top ranked research areas in BIoT with the highest number of publications. Computer science is ranked number one with 88 publications. Telecommunication is at second rank, and engineering is at rank three with 53 and 51 publications respectively. Then, the top research areas include Chemistry, electrochemistry, instruments instrumentation, business economics, energy fuels, operations research management science, public administration and science & technology.

3.6. Citation analysis

This section analyzes the citations in BIoT domain papers. Fig. 9 shows that a number of citations in 2017 are 74, which increases by 700% to 523 in 2018 and following the same pattern in 2019. This shows the rise of interest and research work in this research domain. Table 5 presents the list of the top 10 highest cited papers. The top cited research publication is Blockchains and Smart Contracts for the Internet of Things, which is published in 2016 and has received as many as 268 citations in last two and half years. The second top paper is IoT security: Review, Blockchain solutions, and open challenges, which is published in 2018 and has 47 citations. The interesting fact is that the USA has four papers in this list and China

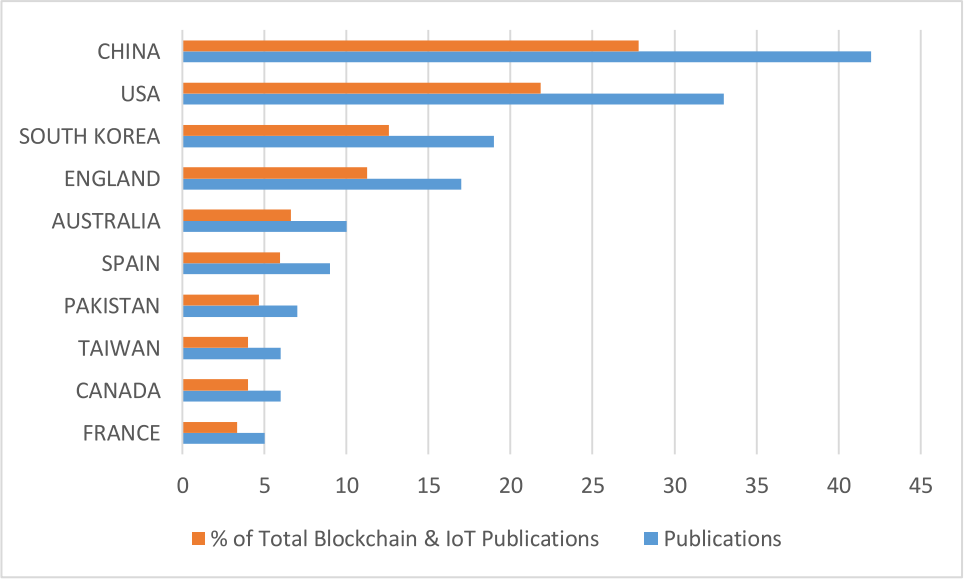

Fig. 5. Countries with Highest Publications in BIoT.

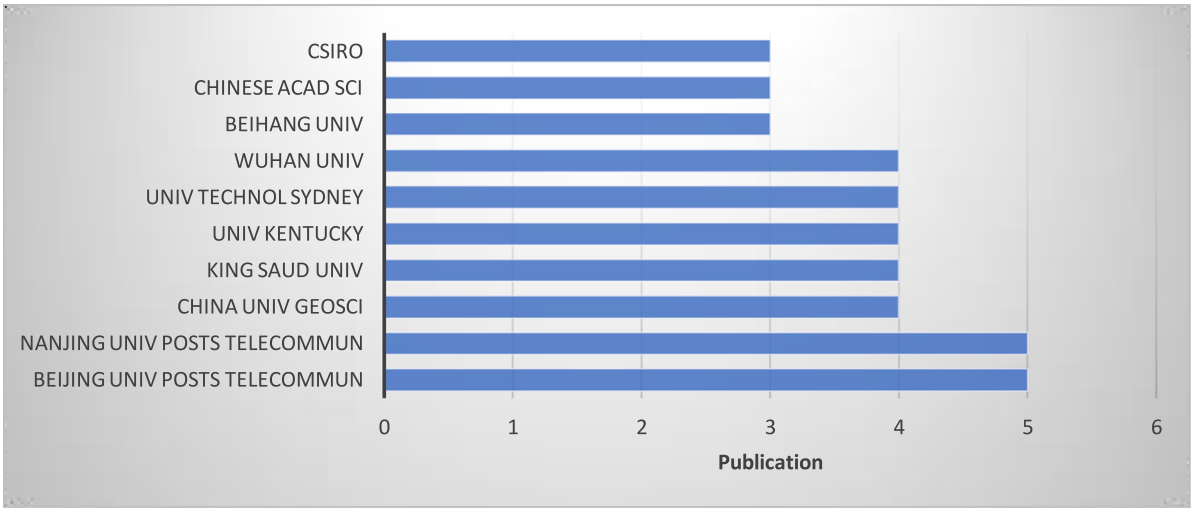

Fig. 6. Organization with Highest Publications.

has two papers in this list, but Section 4.4 presents that China has the highest number of publications and highest number of funded studies in this domain. It was expected that China might have the highest number of cited papers in this domain.

3.7. Keywords analysis

The keywords with the highest frequency that is common in BIoT publications are presented in Table 6 presented in descending order of frequency. Out of the 151 BIoT publication in the relevant literature, the top five associated keywords excluding BIoT are Security, smart contracts, computing, privacy and Smart City where the term frequency of security is 29 and that of privacy is 12. This clearly shows that most of the research conducted in the domain of BIoT is related to security and privacy. This also indicates that Blockchain is contributing to IoT to overcome the main challenges in IoT i.e. security and privacy. Smart contract, a term which is used to define rules and steps, is used for the 18 times as a keyword. Computing, which is a very important area of IoT comes 13 times as a keyword. Besides this, the term computing occurs 17 times in keywords with other words like fog computing, edge computing, etc. Smart City occurs 10 times. Besides this, the term smart occurs 25 times in keywords with other words like smart grid, smart home, etc. In this list, keywords related to Cryptocurrency like bitcoin, Ethereum and cryptocurrency itself occurs 20 times that indicated that research is conducted to use Blockchain technologies for payment processes in IoT.

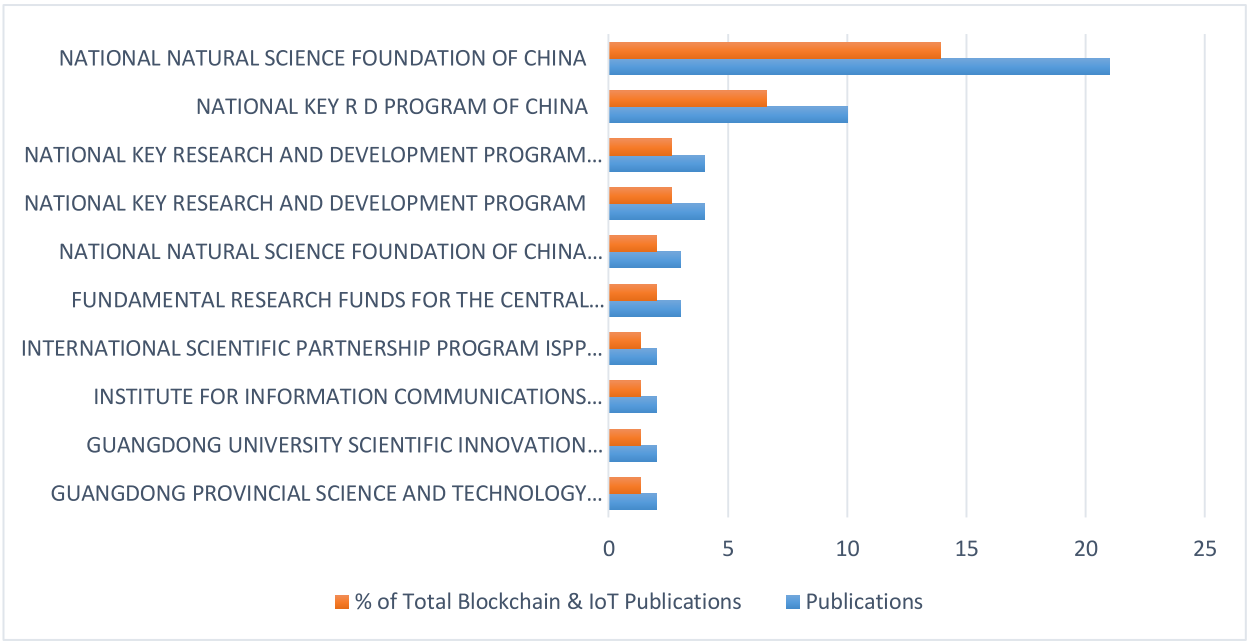

Fig. 7. Top 10 Funding Agencies.

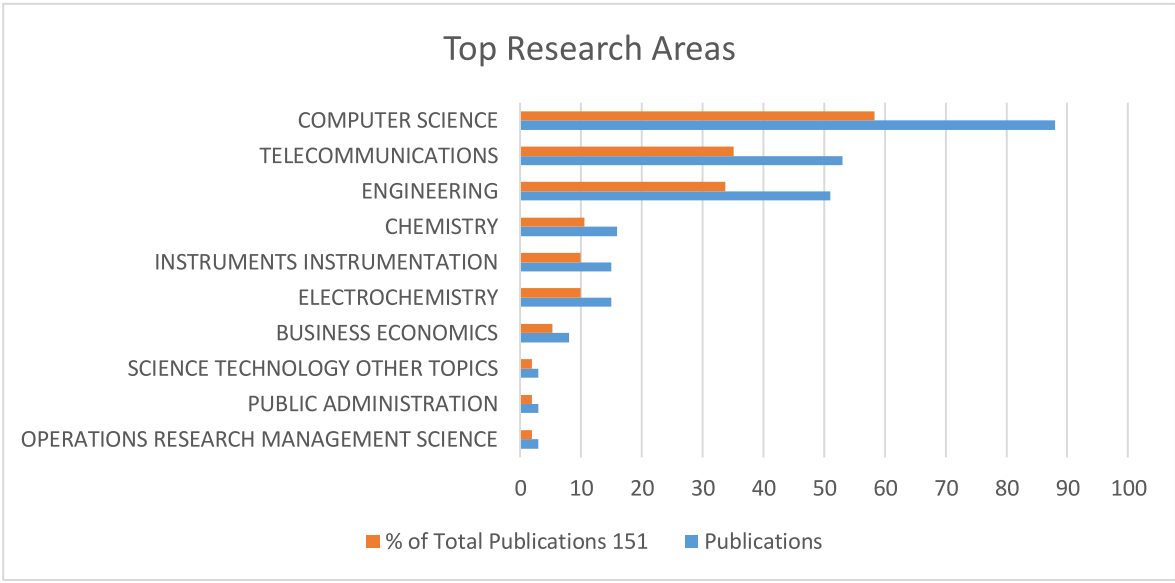

Fig. 8. Top 10 Relevant Research Areas.

4. Discussion about research questions

This section answers the research questions formulated in the research methodology section with discussion.

RQ1: What is the trend of BIoT publications and citations?

The publication and citation trends of Blockchain papers are presented in Figs. 3 and 9 which provide some useful insights. Fig. 3 presents that the yearly number of publications of BIoT papers are growing rapidly in recent years. The publications in 2016 are only three, in 2017 it is 16, in 2018 it is 83 and 49 in just first four months of 2019. This shows that the trend of BIoT papers is increasing. Moreover, the citation of BIoT papers in 2016 is 2, in 2017 is 74, in 2018 is 523 and in the first four months of 2019 is 339. There is a huge change in 2018 and expecting the same trend in 2019. This also shows that

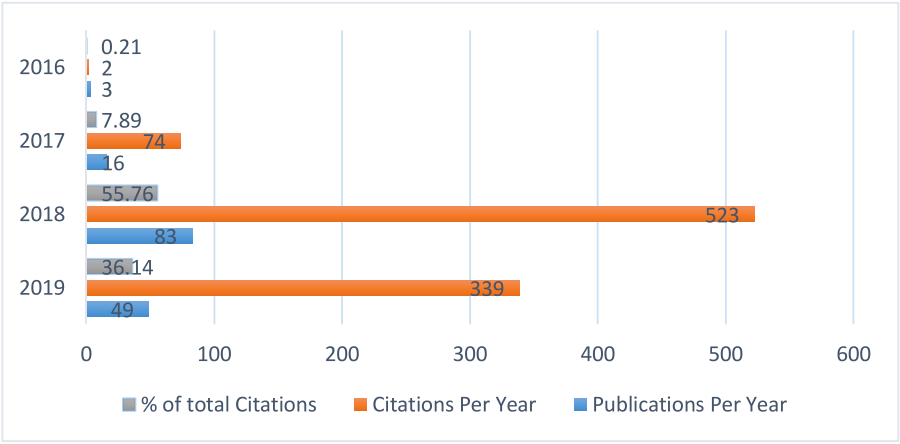

Fig. 9. Citations per Year.

Table 5
Details of top 10 highest cited papers.

Title	Authors	Source Title	Publication Year	Total Citations	Country
Blockchains and Smart Contracts for the Internet of Things [17]	Christidis, Konstantinos; Devetsikiotis, Michael	IEEE Access	2016	248	USA
IoT security: Review, blockchain solutions, and open challenges [2]	Khan, Minhaj Ahmad; Salah, Khaled	Future Generation Computer Systems-The International Journal Of Escience	2018	47	UAE
Industry 4.0: state of the art and future trends [18]	Xu, Li Da; Xu, Eric L.; Li, Ling	International Journal Of Production Research	2018	35	USA
A Software Defined Fog Node Based Distributed Blockchain Cloud Architecture for IoT [19]	Sharma, Pradip Kumar; Chen, Mu-Yen; Park, Jong Hyuk	IEEE Access	2018	31	USA
Blockchain Based Decentralized Management of Demand Response Programs in Smart Energy Grids [20]	Pop, Claudia; Cioara, Tudor; Antal, Marcel; Anghel, Ionut; Salomie, Ioan; Bertoncini, Massimo	Sensors	2018	29	Switzerland
Blockchain-Based Dynamic Key Management for Heterogeneous Intelligent Transportation Systems [21]	Lei, Ao; Cruickshank, Haitham; Cao, Yue; Asuquo, Philip; Ogah, Chibueze P. Anyigor; Sun, Zhili	IEEE Internet Of Things Journal	2017	29	USA
Block-VN: A Distributed Blockchain Based Vehicular Network Architecture in Smart City [22]	Sharma, Pradip Kumar; Moon, Seo Yeon; Park, Jong Hyuk	Journal Of Information Processing Systems	2017	29	South Korea
Blockchain challenges and opportunities: a survey [23]	Zheng, Zibin; Xie, Shaoan; Dai, Hong-Ning; Chen, Xiangping; Wang, Huaimin	International Journal Of Web And Grid Services	2018	24	Switzerland
The IoT electric business model: Using blockchain technology for the internet of things [24]	Zhang, Yu; Wen, Jiangtao	Peer-To-Peer Networking And Applications	2017	24	China
Blockchain-based sharing services: What blockchain technology can contribute to smart cities [25]	Sun, Jianjun; Yan, Jiaqi; Zhang, Kem Z. K.	Financial Innovation	2016	22	China

Table 6
Highest frequency keywords.

Keyword	Frequency	Keyword	Frequency
Security	29	Artificial Intelligence	5
Smart Contracts	18	Distributed Ledger	4
Computing	13	Traceability	4
Privacy	12	Trust	4
Smart City	10	Industrial IoT	4
Access Control	8	Cryptography	4
Bitcoin	8	Fog Computing	4
Ethereum	7	Hyperledger Fabric	4
Supply Chain	6	Sharing Economy	3
Cloud Computing	5	Cyber Security	3
Authentication	5	Machine Learning	3
Distributed Ledger Technology	5	Software Defined Networking	3
Cryptocurrency	5	Smart Home	3
Consensus	5	Big Data	3
Healthcare	5		

BIoT is highly emerging domain and has a good future for researchers. The analysis of highly cited papers in BIoT domain is also mentioned in more detail in Table 5.

RQ2: Which research areas have more BIoT research based on the number of publications?

In this section, all the selected BIoT papers are classified based on different research areas according to WoS. Fig. 8 presents research areas based on the total number of BIoT papers with respect to the ranking of each research area. As can be seen in Fig. 8, Computer Science research area has the most number of BIoT papers, i.e. 88 papers, followed by Telecommunications, Engineering, and Chemistry with 53, 51, and 16 papers, respectively.

RQ3: What are the most influential papers in BIoT according to the number of citations?

Table 5 presents the top ten most cited BIoT papers indexed by WoS. Among these "Blockchains and Smart Contracts for the Internet of Things" written by Konstantinos Ch. and Michael D has the highest number of citations i.e., 248 (till April 2019). This paper was published in the IEEE Access journal in 2016. This paper also has the highest average number of citations per year. Four out of the top ten cited papers were conducted in the USA. Moreover, two research studies were conducted in China and two in Switzerland. Among this list, the IEEE Access has published the two of the highly cited papers based on the average number of citations per year.

RQ4: What are the most popular publication venues for BIoT papers?

Table 4 presents the top 10 venues that have published the highest number of papers in the BIoT domain. Among these, IEEE Access published 21 papers and Sensors published 15 papers, respectively. Moreover, papers of these two venues have the highest number of citations as hence proving that these are the most popular venues in this domain.

RQ5: What are the top most supportive funding agencies of BIoT papers?

Fig. 7 shows the list of funding agencies with the highest number of funds in the BIoT domain. Among all the selected and analyzed research papers, Natural Science Foundation of China has supported the highest number of papers with 21 papers followed by National Key R&D Program of China who supported 10 papers. Moreover, among the top list of funding agencies, six agencies are from China.

RQ6: What is the future research direction in the BIoT domain?

Based on this research and analysis of data, the research suggests important directions in BIoT for future research. A framework is proposed that divides research areas into four important dimensions in BIoT named security, applications, computing, and digital payment process, presented in Fig. 10 along with the identification of sub-areas in each dimension. The security dimension includes issues related to privacy, access control, data protection, and encryption. This is a hot domain for a researcher having interests in security, cryptography, etc. Further Application dimensions identify issues associated with the implementation of certain technology using BIoT. This dimension further identifies applications in smart health, smart grid, smart home, P2P trade. These can further be extended to the smart city. Computing and digital payment process are other important directions in BIoT.

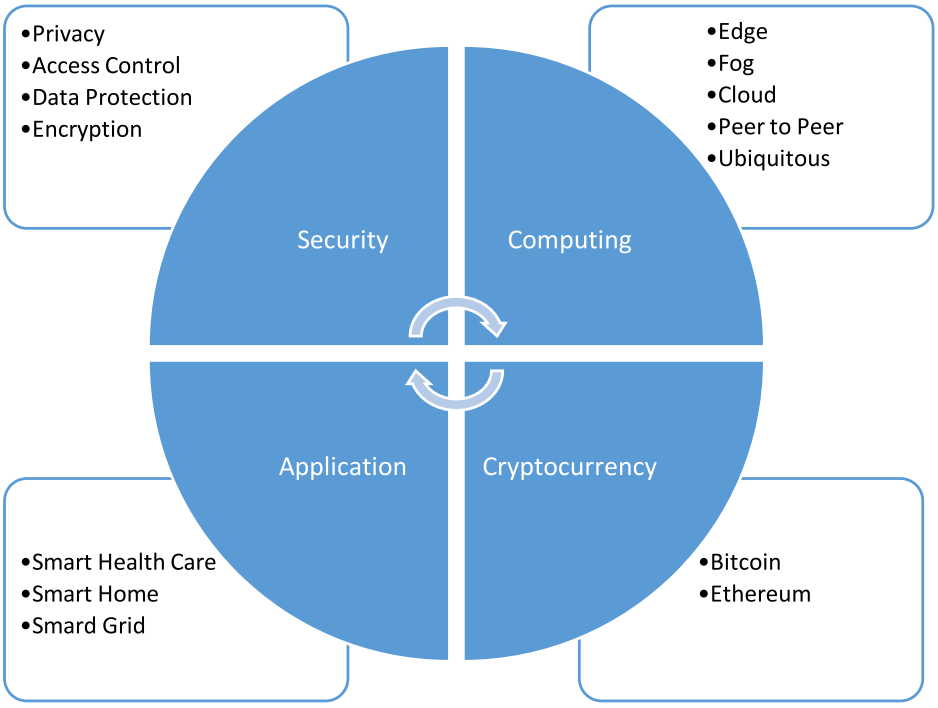

Fig. 10. Future Research Direction in BIoT.

5. Conclusion and future work

This bibliometric study indicates that the interest of researchers is increasing in the domain of BIoT in last few years as the number of citations to relevant research papers published has been growing rapidly since 2017 and is increasing every year. The top research areas related to BIoT include computer science, telecommunications, engineering, and chemistry. The most influential paper is "Blockchains and Smart Contracts for the Internet of Things" written by Konstantinos Ch. and Michael D. was published in 2016 in the journal of IEEE Access. This paper has also received the highest average citations per year. IEEE Access and Sensors are the most popular venues, based on the highest number of publications. BIoT papers published in IEEE Access have the highest impact among researchers as the papers published in it receive the highest number of citations. The analysis indicates that the National Natural Science Foundation of China is providing research funds to a number of projects related to BIoT research. This reflects the significance of Blockchain in IoT. This research explores diverse and relevant potential future research in BIoT which include a detail research study on highly cited papers with respect to the technical aspect and replication of similar research study using different literature database like Scopus to check the similarity of this study.

Declaration of Competing Interest

None.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.compeleceng.2019.106525.

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