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Review Article

A Bibliometric Analysis of Edge Computing for Internet of Things

Yiou Wang,[1,2] Fuquan Zhang,[3] Junfeng Wang,[2] Laiyang Liu,[2] and Bo Wang[4]

[1] *Beijing Institute of Science and Technology Information, Beijing 100044, China*
[2] *School of Computer Science & Technology, Beijing Institute of Technology, Beijing 100081, China*
[3] *Fujian Provincial Key Laboratory of Information Processing and Intelligent Control, Minjiang University, Fuzhou 350117, China*
[4] *Internet Finance Department, Huaxia Bank, Beijing 100020, China*

Correspondence should be addressed to Fuquan Zhang; 8528750@qq.com

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In recent years, with the emergence of many Internet of Things applications such as smart homes, smart city, and connected vehicles, the amount of network edge data increases rapidly. Now, edge computing for Internet of Things has attracted the research interest of many researchers. Then, a thorough analysis of the current body of knowledge in edge computing for Internet of Things is conducive to a comprehensive understanding of the research status and future trends in this field. In this paper, a bibliometric analysis of edge computing for Internet of Things was performed using the Web of Science (WoS) Core Collection dataset. The relevant literature studies published in this field were quantitatively analyzed based on a bibliometric analysis method combined with VOSviewer software, and the development history, research hotspots, and future directions of this field were studied. The research results show that the number of literature studies published in the field of edge computing for Internet of Things is on the rise over time, especially after 2017, and the growth rate is accelerating. China and USA take the lead position in the number of literature studies published. Zhang is the most productive author, and Satyanarayanan is the most influential author. IEEE Access and IEEE Internet of Things Journal are the main journals in this field. Beijing University of Posts Telecommunications has published most literature studies. Research hotspots of edge computing for Internet of Things mainly include specific problem research such as resource management, architecture research, application research, and fusion research of this field with some other fields such as artificial intelligence and 5G.

1. Introduction

At present, the global Internet of Things (IoT) has entered the third wave of development. In 2018, and the number of IoT connections around the world had reached about 8 billion [1]. Artificial Intelligence (AI) technologies [2], such as deep learning, provide technical supports for intelligent analysis of massive data in the IoT. With the rapid development of IoT and AI, more and more intelligent applications appear in front of people, such as smart home, smart city, industrial IoT, and Internet of vehicles. These applications are usually resource-intensive [3], which bring great challenges to resource-constrained terminal devices. In the traditional cloud computing architecture, data need to be transferred centrally to the cloud for processing. However, such a large amount of data transmitted in the IoT will increase the network load, resulting in transmission congestion and data processing delay. At the same time, the transmission of these massive data in the IoT will also increase the risk of data leakage, which puts the privacy and confidentiality of data at risk. Therefore, the processing of data information relying only on traditional cloud computing cannot be completed effectively. At this time, edge computing arises at the historical moment.

Pang et al., based on cloud computing, put forward the concept of edge computing [4] to improve the overall availability and extensibility of the system by pushing data to the edges of the Internet. Edge computing can effectively solve the problem of big data processing in the IoT [5]. Edge computing is a kind of computing mode [6]. Compared with the data-centralized cloud computing model, edge computing processes data at the network edges. Functional entities with the capabilities of application, storage, and computing between data sources and cloud data centres can serve as network edges. Qian et al. [7] proposed a workflow-aided Internet of Things (WIoT) paradigm with intelligent edge computing (iEC) to automate the execution of IoT applications with dependencies. Their design primarily targeted at reducing the latency from two perspectives, including IoT application perspective and edge computation perspective. Liao et al. [8] provided a promising paradigm to support the implementation of industrial IoT by offloading computational-intensive tasks from resource-limited machine-type devices (MTDs) to powerful edge servers. In addition, Bonomi et al. [9] proposed the concept of fog computing which bridges the gap between the cloud and IoT devices by enabling computing, storage, networking, and data management to the network nodes within the close vicinity of IoT devices. Compared with fog computing, edge computing lays more emphasis on the coordination of resources among edge devices. Edge computing is a technology for processing upstream data of cloud or downstream data of IoT [5]. Edge computing provides a theoretical basis for the implementation of fog computing services [10].

Edge computing for Internet of Things (EC-IoT) is an emerging research field in recent years. Now, it is in a period of rapid development, and its hotspots are constantly emerging. Li et al. [11] proposed a design scheme of intelligent building gateway based on edge computing and priority classification for the problems of various types of equipment, inconsistent communication protocols, large data communication volume, and poor real-time performance in the field of large buildings. Zhang et al. [12] established an industrial edge network model and proposed a new cache replacement algorithm based on combing Persistence Prediction and Size Caching Strategy (PPPS). This algorithm effectively improved the hit ratio and cache utilization efficiency of edge cache and reduced the delay of user request files. Du et al. [13] proposed optimization strategies in NOMA-based vehicle edge computing network, which could effectively reduce the cost of task processing under the premise of guaranteeing the maximum delay. Yi et al. [14] proposed a vehicle-adaptive interest packet routing scheme based on relationship strength and interest degree for both inter-/intracommunities which combined the idea of edge computing. Although some breakthroughs have been made in some application fields, the development of EC-IoT has been hampered by some problems such as fragmentation, insecurity, and increased network load. Therefore, it is urgent to conduct a systematic analysis of the knowledge system of EC-IoT, analyze the key technologies, and discuss the future development trends and hotspots.

In this paper, a bibliometric study of EC-IoT literature was conducted with the aim of revealing some valuable insights to the active scholars and practitioners in the EC-IoT field. In terms of scientific impact, bibliometrics research has been widely used to analyze trends and identify emerging scientific fields [15–19].

The results extracted from the bibliometric study presented in this paper included (1) the top 10 most cited literatures; (2) the most popular journals; (3) the most productive authors; (4) annual literatures and citation trends; (5) main research institutions; (6) the most published countries/regions; and (7) hotspots.

This paper is organized as follows: in Section 2, the data sources, main methods, and research questions in this paper were introduced. In Section 3, core literatures, core journals, core authors, overall growth, main research institutions, notable countries/regions, and hot spots related to EC-IoT from WoS core collections were studied in detail. In Section 4, a brief conclusion was given, and a brief summary of the future development of this field was made.

2. Data and Methods

2.1. Description of Data Source. The literature data of this paper came from the Sci-Expanded database of Web of Science (WoS) Core Collection of the Institute for Scientific Information (ISI). The knowledge development system of EC-IoT was expected to be fully understood, and this field has been around for about 20 years, so the time frame is limited to 2000–2020, which covers almost the entire period of large-scale scientific production in this field. By December 16, 2020, 13,498 references were retrieved in WoS Core Collection datasets under the theme of “edge computing” or “mobile computing.” The retrieved literature studies were then further refined under the theme “IoT” or “Internet of things” or “smart Home” or “Smart City” or “Industrial Automation” or “Connected vehicles.” At this time, a total of 2732 literature studies were retrieved. The complete records and references of these literature studies were exported as the dataset.

2.2. Research Methods. Based on bibliometric analysis, the main literature studies, journals, authors, research institutions, countries/regions, and keywords of EC-IoT were statistically studied. Bibliometric analysis is based on mathematics and statistics to quantitatively analyze scientific literature studies published in a specific field of knowledge [20]. The status quo and development trend of science and technology are described, evaluated, and predicted to a certain extent, and the current research status and frontiers of the discipline are reflected [21]. Through bibliometric analysis, the development history, research hotspots, and future directions of EC-IoT were explored.

In recent years, knowledge mapping tools are used in bibliometrics research to transform the table analysis of written data into visual maps that are more visual and easier to read. Visualization of Similarities Viewer (VOSviewer) is a kind of bibliometric analysis and knowledge visualization software jointly developed by N. J. Van Eck and L. Waltman from the Science and Technology Research Centre of Leiden University in the Netherlands in 2010 [22]. In this paper, the clustering algorithm in VOSviewer was used to carry out co-occurrence analysis of published countries and high-frequency keywords. In addition, cocitation networks of cited literature, journals, and authors were built for visual analysis of the knowledge maps.

2.3. Research Questions. The current situation in the world raises many questions that need to be answered. In this paper, the following questions need to be answered that will help to identify the dynamics of EC-IoT and provide a holistic means for future research in field. These questions are addressed as follows:

RQ1: what are the most influential literatures of EC-IoT?

RQ2: which journals are the most popular in the EC-IoT field?

RQ3: which authors are leading the EC-IoT study?

RQ4: what is the evolution of EC-IoT research field?

RQ5: what are the main research institutions?

RQ6: what is the research status of EC-IoT in countries/regions around the world?

RQ7: what are the EC-IoT hot spots?

3. Bibliometric Analysis of EC-IOT Literatures

The publication status of literatures is usually regarded as an important indicator to measure the development level of a discipline and the level of scientific research achievements and contributions [23]. Trends in EC-IoT research were studied in this paper using statistical literature studies and the frequencies of citations over time.

3.1. Analysis of Core Literature Studies. The main literature studies on EC-IoT were highlighted. The top 10 most cited literatures in the world are listed in Table 1. These literature studies have had the widest influence in EC-IoT.

On top of the list, Shi et al. [5] first proposed the definition of edge computing in 2016. They analyzed the applications of edge computing in smart homes and cities through case studies and pointed out the opportunities and challenges of edge computing. Their paper had the highest total citations, with a value of 1342. And, the value of its average citations per year is also the highest. This shows that their paper has a strong impact. In the second place of the list, Mao et al. [24] provided a comprehensive survey of the state-of-the-art mobile edge computing (MEC) research. They discussed a series of issues, challenges, and future research directions for MEC research, such as MEC system deployment and cache-enabled MEC. Chiang et al. [25] expounded the opportunities and challenges of fog computing in view of the IoT network context. Stankovic et al. [26] presented a vision for how IoT could change the world in the distant future and enumerated eight key research topics. Lin et al. [27] conducted an overview of IoT with respect to system architecture, enabling technologies, security and privacy issues, and presented the integration of fog/edge computing and IoT and applications. Satyanarayanan et al. [28] introduced the emergence of edge computing. Gu et al. [29] proposed a Service-Oriented Context-Aware Middleware (SOCAM) architecture, aiming to solve the context-aware problems of wireless network and mobile computing. Abbs et al. [30] provided the definition of mobile edge computing, its advantages, architecture, application areas, and future directions. Dastjerdi et al. [31] introduced the advantages of fog computing. Shi and Dustdar [32] analyzed the promise of edge computing.

EC-IoT is an emerging field of research. Edge computing was not formally defined until 2016. Therefore, the majority of the most cited literature studies in the world are summary articles, as shown in Table 1. These articles mainly analyzed and discussed the problems such as the concept, application, challenge, and development prospects of EC-IoT.

3.2. Analysis of Core Journals. In the development of EC-IoT, journals play an important role as the main disseminators of the process of studies. The top 7 leading journals with the most published literatures in the EC-IoT field are listed in Table 2.

According to Table 2, IEEE Access and IEEE Internet of Things Journal are the most popular journals in the EC-IoT field, and they have the greatest number of literature studies published. Among them, IEEE Access has published 279 literature studies in this field, ranking first. Meanwhile, the total number of literature studies published by the journals listed in Table 2 reaches 832, accounting for about 30% of all literature studies retrieved. These journals provide significant supports for research and development in the EC-IoT field.

Next, the journal citation totals [33, 34] were studied, that is, the most cited journal and the journal frequently cited by the same source. The minimum number of citations of journals was set 50 in VOSviewer. A visualization of journal cocitation network is shown in Figure 1. In Figure 1, the sizes of dots and words represent the cited times. The larger the dots and words are, the more times they are cited. It can be seen from Figure 1 that IEEE Access and IEEE Internet of Things are cited the most times, indicating that these two journals have very strong influences in the EC-IoT field. Besides, the sensor with the third place in Table 2 has been cited much less often.

3.3. Analysis of Core Authors. The core authors are the most productive authors. They are researchers who have published many literature studies in a certain research field. Studying the core authors is conducive to analyzing and finding authoritative EC-IoT experts. Price's law in bibliometrics can be used to determine the core author in a research field [5]. Place's law pointed out the core authors, which can be expressed as follows:

$$M = 0.749\sqrt{N_{\max}}, \tag{1}$$

where $N_{\max}$ is the maximum number of literature studies published by the same author and M is the minimum number of literature studies published by the core authors. The authors who published more than M literature studies are the coauthors. As shown in Table 3, the maximum

Table 1: The top 10 most cited literatures.

Number	Literature title	Total citation	Average citation per year
1	Edge Computing: Vision and Challenges [5]	1342	268.4
2	A Survey on Mobile Edge Computing: The Communication Perspective [24]	836	209
3	Fog and IoT: An Overview of Research Opportunities [25]	801	160.2
4	Research Directions for the Internet of Things [26]	796	113.71
5	A Survey on Internet of Things: Architecture, Enabling Technologies, Security and Privacy, and Applications [27]	598	149.5
6	The Emergence of Edge Computing [28]	442	110.5
7	A Service-Oriented Middleware for Building Context-Aware Services [29]	438	27.38
8	Mobile Edge Computing: A Survey [30]	417	139
9	Fog Computing: Helping the Internet of Things Realize Its Potential [31]	342	68.4
10	The Promise of Edge Computing [32]	325	65

Table 2: The top 7 leading journals with the most published literatures.

Number	Journal title	Number of literatures published	Impact factor (2019)
1	IEEE Access	279	3.74
2	IEEE Internet of Things Journal	251	9.51
3	Sensors	98	3.27
4	Future Generation Computer Systems: The International Journal of eScience	72	5.38
5	IEEE Transactions on Industrial Informatics	50	9.11
6	IEEE Network	44	7.50
7	IEEE Communications Magazine	38	11.05

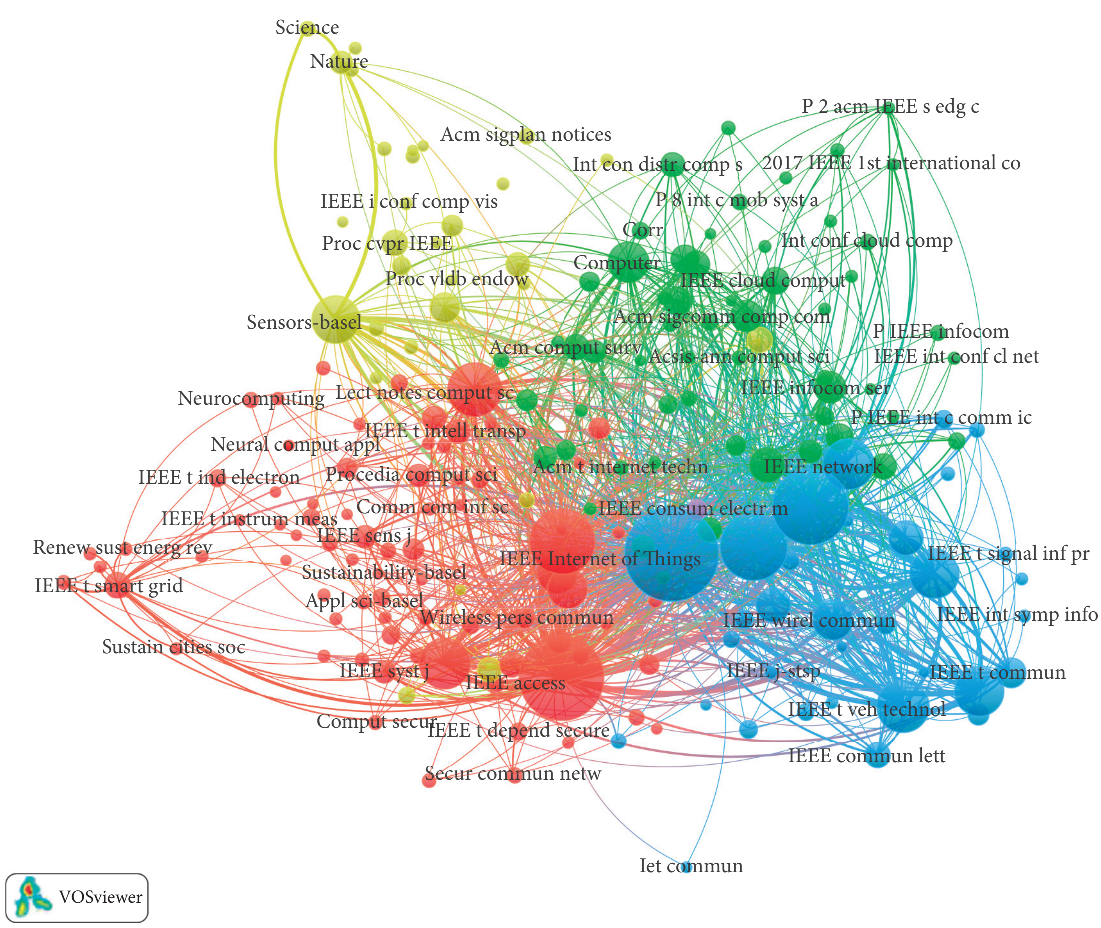

Figure 1: A visualization of journal cocitation network.

Table 3: The top 10 authors with the most published literature studies.

Number	Author name	Number of literature studies published
1	Y. Zhang	27
2	J. Zhang	23
3	Y. Chen	22
4	X. Chen	21
5	J. J. Liu	19
6	J. J. P. C. Rodrigues	18
7	S. Dustdar	17
8	Y. Jararweh	16
9	Y. Liu	16
10	M. Villari	15

number of literature studies published by the same author in the EC-IoT field is 27. Then, $M = 4$. Therefore, the authors who have published more than 4 literature stuides are the coauthors in this field, totaling 466. The number of literature studies published by these 466 core authors accounted for 88.61% of all published literature studies.

According to Table 3, Zhang is the most productive author. However, scientometrics have done a great deal of work on how to meaningfully quantify the publication of academic results. They believe that counting the number of literatures is one way, and that counting the total number of citations is considered the other way that is more meaningful [35].

The minimum number of citations of the authors was set 50 in VOSviewer. Then, of the 36638 authors, 155 meet this threshold. A density visualization of author cocitation network is shown in Figure 2. If the color is lighter and the words are larger, the author's number of citations is higher. As can be seen in Figure 2, M. Satyanarayanan, W. Shi, F. Bonomi, and X. Chen have the highest authors' number of citations. This indicates that their work is recognized by many researchers and has a strong impact in the EC-IoT field.

3.4. Analysis of the Overall Growth Trend. When downloading data from the WoS Core Collection database, the time range was set from 2000 to 2020. However, the first EC-IoT literature retrieved was in 2005 [29]. Therefore, the data we used were from 2005 to 2020. Number of literature studies and total number of citations by year are shown in Figure 3.

As can be seen from Figure 3, number of literature studies and total number of citations generally show an upward trend in the EC-IoT field. In particular, their growth accelerated rapidly after 2017, almost exponentially. This may be because the definition of edge computing had not been proposed before 2016, and the research on EC-IoT was still on the exploration stage. Shi et al. [5] defined edge computing for the first time in 2016, which attracted the attention of many researchers. Therefore, EC-IoT entered a period of rapid development after 2017. The number of EC-IoT literature studies reached a maximum of 947 in 2019 but fell slightly to 783 in 2020. This may be due to the impact of COVID-19 on a global scale. Nevertheless, the total number of citations in EC-IoT has been on the rise. As such, EC-IoT is in the explosion stage, and future research in this field is likely to continue for a long time. With the booming development of edge computing, EC-IoT will be urgently needed to be applied in various fields such as smart home, smart city, industrial automation, and connected vehicles. At the same time, the rapid development of IoT is also driven by the practical problems in various industries.

3.5. Analysis of Main Research Institutions. From 2005 to 2020, Beijing University of Posts Telecommunications has published 115 literature studies, accounting for 4.21% of all literature studies in this field. Beijing University of Posts Telecommunications ranks first in the number of published literature studies of EC-IoT. Xidian University ranks second, with 52 published literature studies. It was followed by University of Electronic Science and Technology of China and King Saud University. The top 10 research institutions with the most published literature studies are shown in Figure 4.

As can be seen from Figure 4, the top 10 research institutions are dominated by universities, and Chinese research institutions are the majority. China's research and development in EC-IoT has reached a certain scale. Besides, King Saud University in Saudi Arabia and the University of Messina in Italy are also among the top 10 research institutions. This indicates that these two research institutions are also concerned about EC-IoT.

3.6. Analysis of Notable Countries/Regions. Considerable efforts have been made to promote the development of EC-IoT to generate knowledge that can be used to solve problems encountered in practical applications of IoT. The top 10 most published countries are shown in Figure 5. It can be seen from Figure 5 that China is the country with the highest productivity, which produced 931 literature studies in total, accounting for 34.08% of the total. It is followed by USA, which produced 576 literature studies, accounting for 21% of the total. Then comes Italy, England, and South Korea. Many literature studies in the EC-IoT field have been published by 10 countries in Figure 5, which provide a good foundation for this work. This gives these countries a leading position in research and a better opportunity and development prospect in the future development process of IoT applications.

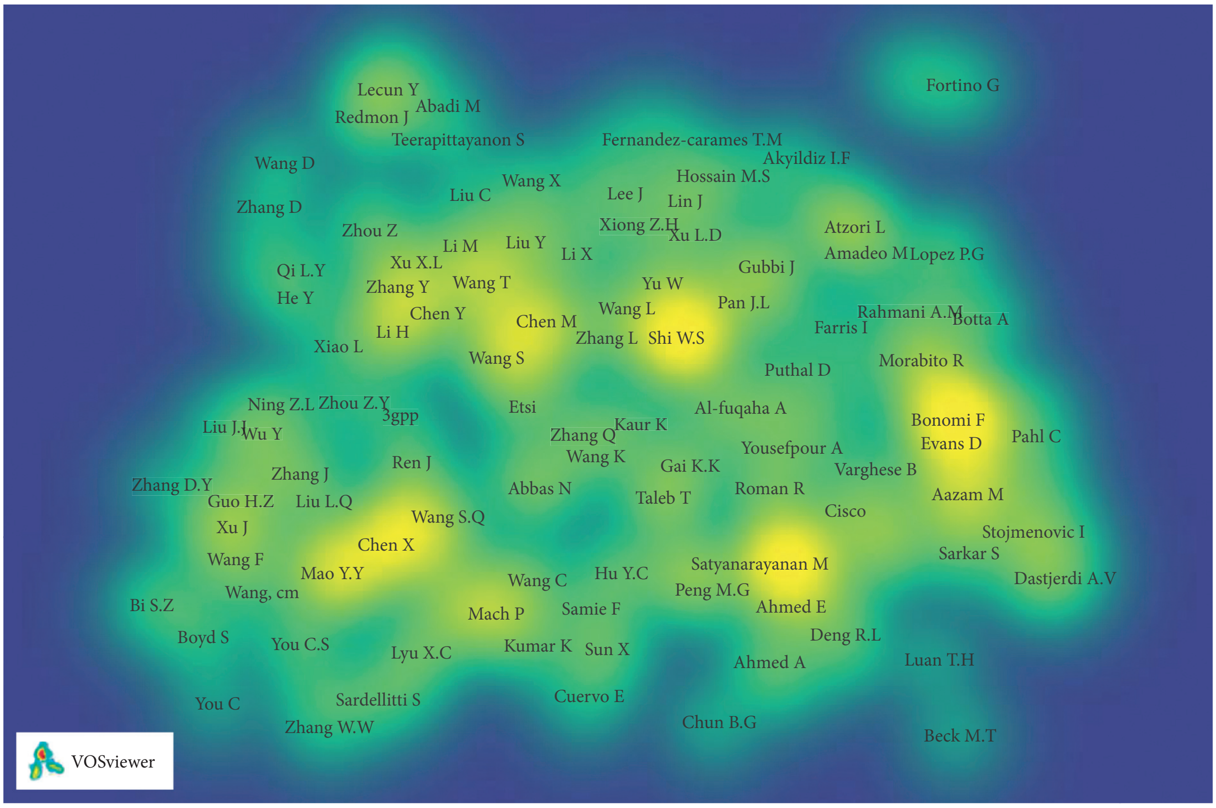

FIGURE 2: A density visualization of author cocitation network.

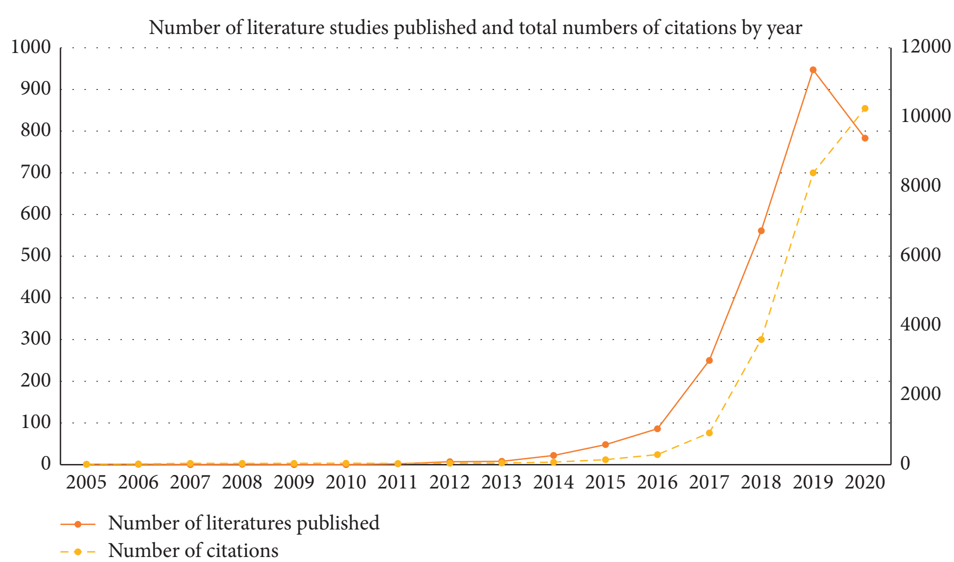

FIGURE 3: Number of literature studies published and total number of citations by year.

Next, the spatial distribution of the literature studies published is discussed. A geographic visualization of the literatures published is conducive to the clear understanding of the geographic output distribution of literature studies, so as to help researchers further understand the overview of scientific research achievements of EC-IoT. A geographic visualization of research co-occurrence network is shown in Figure 6. According to Figure 6, countries all over the world attach great importance to EC-IoT, and there are three research intensive regions in the world, namely, Europe, southeast North America, and Southeast Asia.

3.7. Analysis of Hotspots. Keywords are an important part of the literature, which highly condense the content of the literature. The co-occurrence network analysis of keywords

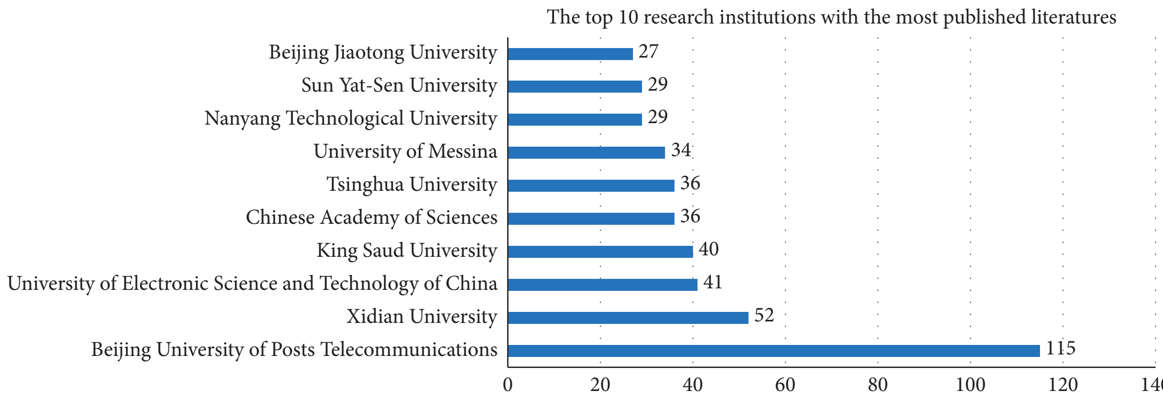

Figure 4: The top 10 research institutions with the most published literature studies.

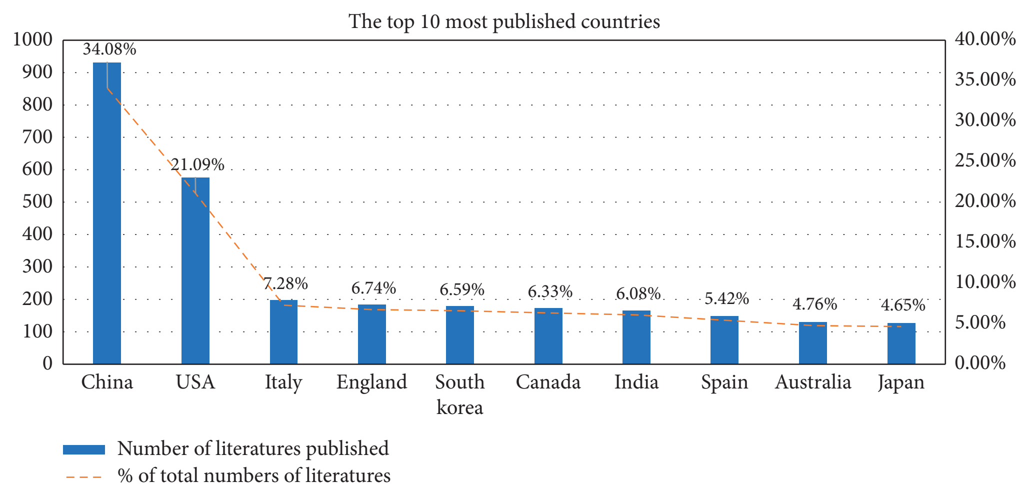

Figure 5: The top 10 most published countries.

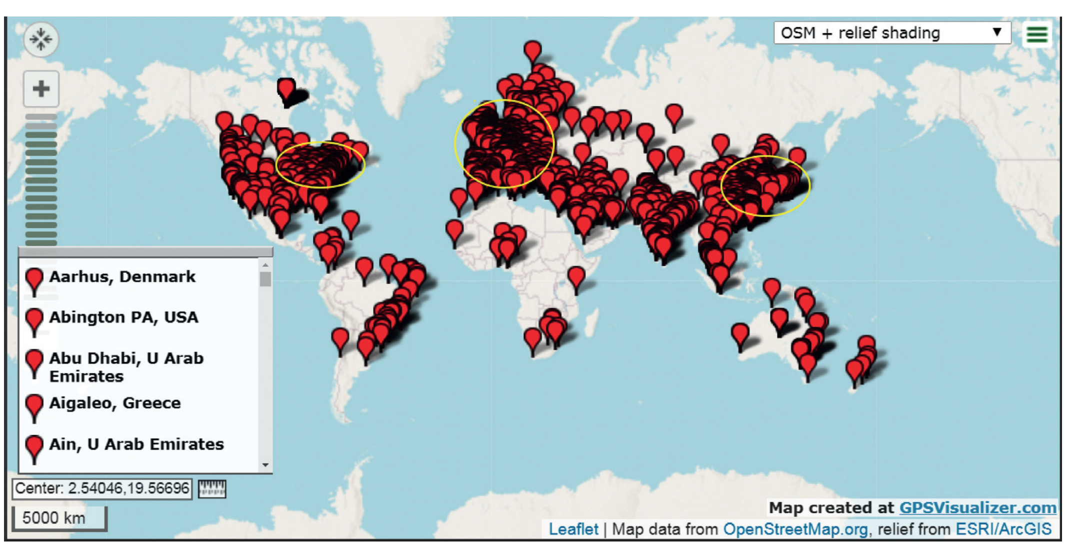

Figure 6: A geographic visualization of the research co-occurrence network.

can effectively reflect the research hotspots in the subject area. The minimum number of occurrences of a keyword was set 40 in VOSviewer. After merging EC-IoT and its synonyms, four clusters of high-frequency keywords were obtained, whose nodes of the same color belong to the same cluster. A visualization of keywords co-occurrence network

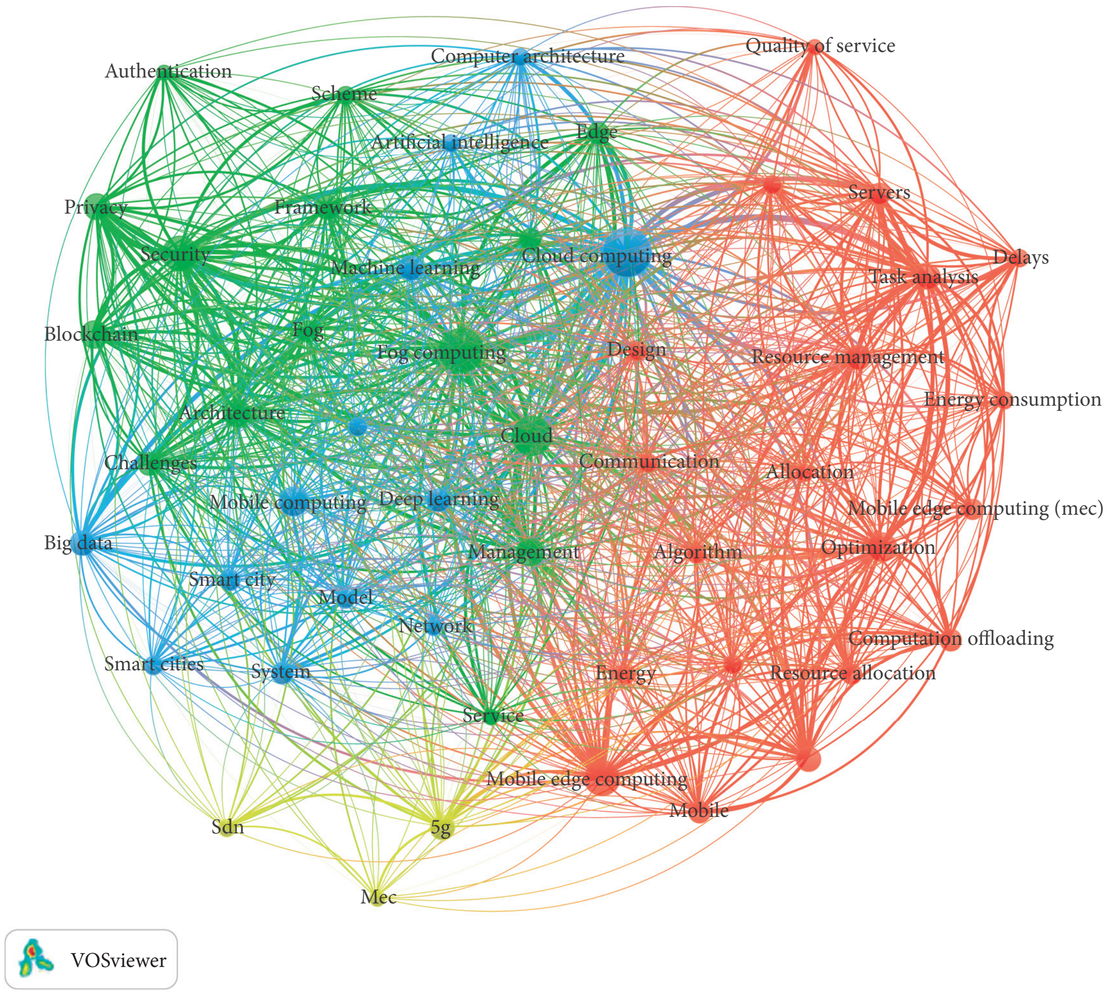

Figure 7: A visualization of keywords co-occurrence network.

is shown in Figure 7. Keywords of "edge computing," "Internet of Things," "Internet," and "IoT" are not shown because literature studies retrieved all related to "edge computing" and "Internet of Things."

Cluster 1: cluster 1 is the study of specific difficult problems of EC-IoT, as shown in the red node region. The specific problems of EC-IoT include resource management, resource allocation, computation offloading, energy consumption, and delay.

Cluster 2: cluster 2 is the study of the overall architecture of EC-IoT, as shown in the green node region. Through the optimization and innovation of the overall architecture, the protection of privacy and security will be further increased.

Cluster 3: cluster 3 is the study of EC-IoT applications, as shown in the blue node region. Mobile computing is combined with big data technology and artificial intelligence algorithms to make EC-IoT better applied in smart homes, smart city, and some other fields.

Cluster 4: cluster 4 is the study of mobile edge computing (MEC) with 5G, as shown in yellow node area. The development of 5G ensures high bandwidth and low latency in the transmission process, which provides the network security for EC-IoT. With the continuous maturity of 5G technology, the study of MEC will also usher in rapid development.

Research hotspots of EC-IoT are understood through the statistics of keywords with frequent co-occurrence. In summary, it includes four aspects: specific difficult problems, overall architecture, applied research and joint research with 5G.

The literature keyword analysis not only provides an effective way for the knowledge structure of the research field but also provides an effective way for the exploration of the development trend in the field. Therefore, it can be speculated that problems of EC-IoT related to resource management, resource allocation, computation offloading, energy consumption, and delay will be further studied in the future. Meanwhile, with the gradual maturity of EC-IoT technology and 5G, EC-IoT will be further promoted and popularized in smart cities, smart transportation, and some other applications.

4. Conclusions

Significant influential aspects of EC-IoT literatures were studied in this paper. It can be summarized as follows: the most influential literature in the world was written by Shi who first proposed the definition of edge computing. IEEE Access and IEEE Internet of Things are the two leading journals that have published most literature studies and are cited most times. According to Price's Law, there are 466 EC-IoT core authors in the world, among which Zhang is the most productive author, and Satyanarayanan is the most cited author. On the whole, the number of EC-IoT literature studies published and literature studies cited are on the rise. In particular, they showed an exponential growth trend after 2017. The future research of EC-IoT will continue for a long time. Beijing University of Posts Telecommunications ranks first in the number of published literature studies of EC-IoT. Countries all over the world attach great importance to EC-IoT, and there are three research intensive regions in the world, namely, Europe, southeast North America, and Southeast Asia. China and USA are the most published countries. In addition, the research hotspots of EC-IoT mainly focus on four aspects, including specific difficult problems, overall architecture, applied research, and joint research with 5G. In the future, with the constant maturity of EC-IoT technology and 5G technology, EC-IoT will be further promoted and popularized in smart cities, smart transportation, and some other applications.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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