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A BIBLIOMETRIC ANALYSIS OF EDGE COMPUTING IN INDUSTRIAL INTERNET OF THINGS (IIoT) CYBER-PHYSICAL SYSTEMS

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Abstract. With the development of the Industrial Internet of Things (IIoT), human-machine interaction system automation has reached a higher level of research, contributing to the integration of intelligent technologies in the industrial sectors. Modern technological innovations, including edge computing and fog computing, significantly accelerate the advancement of manufacturing processes. This paper aims to thoroughly review the scientific literature related to a specific set of terms derived from integrating IIoT and edge computing. The paper presents a bibliometric analysis of edge computing and IIoT merging. It focuses on prevailing trends, prominent authors, key publications, and research productivity over the past 5 years. The paper identifies notable patterns and trends by examining scientific papers and using analytical tools such as bibliometrics, emphasizing the role of advanced technologies like AI and blockchain in enhancing IIoT systems. The data indicate a significant increase in research outcomes, highlighting the need for effective use of edge computing to address data processing challenges and improve system security. This bibliometric analysis reveals current research areas and promising directions for the development of edge computing within the IIoT framework.

Keywords: IIoT, edge computing, cyber-physical systems

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ӨНДІРІСТІК ЗАТТАР ИНТЕРНЕТІ (IIoT) КИБЕРФИЗИКАЛЫҚ ЖҮЙЕЛЕРІНДЕ ШЕТКІ ЕСЕПТЕУЛЕРДІ ҚОЛДАНУҒА БИБЛИОМЕТРИЯЛЫҚ ТАЛДАУ

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Аннотация. Өндірістік заттар интернетінің (IIoT) дамуының арқасында адам мен машинаның өзара әрекеттесу жүйесін автоматтандыруды зерттеу деңгейі жоғарылады, бұл өз кезегінде интеллектуалды технологиялардың өнеркәсіп салаларында интеграциялануына ықпал етті. Қазіргі заманғы технологиялық инновациялар, оның ішінде шеткі есептеулер мен тұманды есептеулер, өндірістік процестердің жылдам дамуын айтарлықтай жеделдетеді. Мақаланың мақсаты - IIoT және шеткі есептеулерді интеграциялау арқылы туындаған нақты терминдерге қатысты ғылыми жарияланымдарды жан-жақты қарап шығу. Мақалада шеткі есептеулер мен IIoT-тің бірігуіне арналған библиометриялық талдау ұсынылды. Соңғы 5 жылдағы танымал авторларды, маңызды жарияланымдарды және зерттеу өнімділігі қарастырылды. Сондай-ақ, ғылыми мақалаларды зерттеу мен bibliometrix құралын қолдану арқылы елеулі үлгілер мен тенденциялар анықталды. Жасанды интеллект заманауи технологиясың IIoT жүйелерін жетілдірудегі рөлі атап көрсетілді. Мәліметтер зерттеу нәтижелерінің айтарлықтай өскенін көрсетті, бұл деректерді өңдеу мәселелерін шешу мен жүйе қауіпсіздігін жақсарту үшін шеткі есептеулерді тиімді пайдаланудың қажеттілігін көрсетеді. Бұл зерттеуде библиометриялық талдау IIoT контексіндегі шеткі есептеулердің дамуындағы қазіргі зерттеу салалары және перспективалы бағыттары көрсетілді.

Түйін сөздер: IIoT, шеткі есептеу, кибер-физикалық жүйелер

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БИБЛИОМЕТРИЧЕСКИЙ АНАЛИЗ ПРИМЕНЕНИЯ ГРАНИЧНЫХ ВЫЧИСЛЕНИЙ В КИБЕРФИЗИЧЕСКИХ СИСТЕМАХ ПРОМЫШЛЕННОГО ИНТЕРНЕТА ВЕЩЕЙ (IIoT)

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Аннотация. С развитием промышленного интернета вещей (IIoT) автоматизация систем взаимодействия человека и машины достигла нового уровня исследований, способствуя интеграции интеллектуальных технологий в промышленность и энергетический сектор. Современные технологические инновации, включая граничные вычисления и туманные вычисления, значительно ускоряют развитие производственных процессов. Цель этой работы — всесторонний обзор научной литературы, связанный с определенным набором терминов, возникающих из интеграции IIoT и граничных вычислений. В работе представлен библиометрический анализ слияния граничных вычислений и IIoT. Основное внимание уделяется преобладающим тенденциям, ведущим авторам, ключевым публикациям и продуктивности исследований за последние 5 лет. Работа выявляет заметные паттерны и тенденции, исследуя научные статьи и используя инструмент bibliometrix, подчеркивая роль передовых технологий, таких как ИИ и блокчейн, в улучшении систем IIoT. Данные показывают значительное увеличение результатов исследований, подчеркивая необходимость эффективного использования граничных вычислений для решения задач обработки данных и улучшения безопасности систем. Этот библиометрический анализ раскрывает актуальные области исследований и перспективные направления развития граничных вычислений в рамках IIoT.

Ключевые слова: IIoT, передовые вычисления, киберфизические системы.

Introduction

The IIoT and edge computing have emerged as fundamental components of contemporary industrial frameworks, significantly augmenting operational efficiency, security, and data governance. Edge computing facilitates the processing of data at the periphery of the network, thereby minimizing latency and enhancing performance, a factor of paramount importance for industrial applications. The advancement of IIoT and edge computing technologies culminates in substantial enhancements in both efficiency and security.

Background studies

In the context of Industry 4.0, the IIoT assumes a pivotal role in facilitating communication among machines while enabling the collection of real-time data. Nonetheless, a significant challenge arises concerning device compatibility within industrial IIoT, primarily attributable to the heterogeneity of technologies and the absence of standardized protocols. Addressing these challenges is imperative for enhancing operational efficiency and minimizing expenditures. Variations in compatibility, coupled with the advent of emerging technologies such as blockchain and 5G, have the potential to augment data interchange and device integration within the IIoT framework (Hazra, et al, 2021). In recent years, IIoT has evolved into a fundamental component of intelligent systems; however, issues surrounding data privacy and security persist as critical concerns due to the substantial quantities of sensitive information being managed. Conventional cloud computing confronts difficulties related to latency and bandwidth, thereby rendering edge computing a viable alternative (Niu, et al, 2023). The IIoT landscape encompasses a multitude of devices and sensors that engage in data exchange within a sophisticated network, necessitating the deployment of contemporary edge computing solutions. Numerous facets of edge computing are scrutinized, encompassing security, latency, resource allocation, and energy efficiency (Bayar, et al, 2023).

Amidst the escalating energy consumption within the industrial sector, the imperative to curtail costs has gained paramount importance. In this context, an energy management architecture predicated on edge computing, which incorporates this technology into energy management protocols, has evidenced a reduction in electricity expenditures (Liu, et al, 2024). Data analytics within IIoT is generally executed within cloud environments; however, the emergence of edge computing has facilitated data processing in proximity to the source, thereby diminishing latency and expediting information retrieval. A comprehensive review of extant edge analytics architectures (Platenius-Mohr, et al, 2021) elucidates critical architectural dimensions and provides support for subsequent academic and industrial initiatives.

The merging of AI and blockchain technology fosters the efficient processing of real-time data and bolsters security measures. Notable applications encompass intelligent transportation systems and unmanned aerial vehicles. The utilization of edge computing in conjunction with blockchain technology in smart manufacturing serves to mitigate challenges related to data processing and security, thereby

ensuring elevated productivity and the preservation of data integrity (Fortoul-Diaz, et al, 2023; Alanhdi, et al, 2024; Shahbasi, et al, 2021).

The integration of IIoT fosters manufacturing efficacy through the aggregation of data and the application of sophisticated analytics via cloud and edge computing; however, it concurrently necessitates the safeguarding of data against vulnerabilities through the adoption of blockchain technologies and AI. When synergized with lightweight intrusion detection frameworks and advanced cryptographic algorithms, such as the Convivial Optimized Sprinter Neural Network (COSNN) and Lightweight Consensus Proof-of-Work (LCPoW), these technologies ensure elevated accuracy and efficiency within IIoT systems (Selvarajan, et al, 2022). To facilitate efficacious data processing and real-time transmission at the network edge, a blockchain-based machine learning framework (BML-ES) has been proposed. This system employs smart contracts in conjunction with the SM2 cryptosystem to enhance both security and model accuracy (Tian, et al, 2021). Analytical evaluations indicate that BML-ES substantially improves the accuracy and security of edge services. Concurrently, safeguarding IoT and IIoT frameworks from escalating vulnerabilities necessitates a multi-tiered architecture, which encompasses physical, network, and application layers, thereby accentuating the importance of cryptographic techniques, intrusion detection systems, and blockchain technologies to bolster security measures (Yajalaxmi, et al, 2021). The merits of edge computing encompass the alleviation of load on cloud servers by facilitating the preprocessing of data at nodes proximal to end-users. This operational paradigm diminishes latency and bandwidth expenditure, thereby enabling expedited decision-making in real time. Furthermore, edge computing enhances mobility, security, and system adaptability, particularly within domains such as smart cities, transportation infrastructures, and healthcare, through its integration with artificial intelligence and blockchain technologies. The examination of progressions and contemporary inquiries regarding edge computing within the Industrial Internet of Things (IIoT) underscores the necessity of incorporating these technologies into security frameworks for IIoT to safeguard against emerging cyber adversities. To substantiate the significance of this subject, the manuscript provides a bibliometric assessment of research about edge computing in enhancing cybersecurity within IIoT. Bibliometric methodologies are progressively being utilized across diverse scientific domains (Aria, et al, 2017).

The objectives of the paper encompass evaluating the efficacy of scientific investigations, ascertaining the present landscape of research concerning the integration of edge computing in IIoT, tracing its academic evolution, identifying the predominant topics within scholarly publications, and delineating the foremost contributors and nations in this discipline.

To fulfil these objectives, the study engages with several pivotal research inquiries:

- Q1: What is the trajectory of scientific publications concerning edge computing in IIoT?

- Q2: Which principal networks of authors, resources, and nations engage in collaboration?

- Q3: Which nations and authors demonstrate the highest productivity?

- Q4: What are the most impactful publications?

Research Contributions:

1. A bibliometric examination of the integration of edge computing within IIoT is proposed.

2. The trajectory of scientific publications regarding edge computing in IIoT over the preceding five years is delineated.

3. Prominent authors and pertinent research themes in the context of edge computing integration for IIoT are emphasized.

4. A comparative examination of the scientific contributions made by authors is presented.

5. The most prolific nations and authors on the subject are identified.

6. Recommendations are proffered based on the findings.

Motivations

In an era of rapid technological advancement, the integration of the Industrial Internet of Things (IIoT) is transforming the industrial sector by enhancing automation and driving the adoption of intelligent technologies across various industries, including manufacturing and energy. With the implementation of advanced technologies like edge and fog computing, the need to address emerging security challenges associated with these innovations arises. Edge computing plays a critical role in optimizing real-time data processing and reducing latency by moving computing tasks closer to the data sources. Organizations can significantly lower latency, improve real-time decision-making, and enhance overall system efficiency by decentralizing data processing and utilizing edge devices. However, this transition also introduces new security vulnerabilities that must be addressed to protect sensitive industrial data and maintain system integrity. As the complexity and scale of IIoT systems expand, ensuring robust cybersecurity measures becomes crucial. Traditional security approaches often fail to address the unique challenges posed by the vast and dynamic nature of IIoT networks.

The structure of the paper: Section 1 begins with the introduction, which includes background studies, research questions, objectives, contributions, and the paper motivation; Section 2 presents the research methodology with bibliometric analysis; Section 3 covers the discussion; and Section 4 provides the conclusion.

Methodology

This section provides a detailed description of the paper methodology, which includes the research selection algorithm, databases containing both quantitative and qualitative data related to the implementation of edge computing in various industrial sectors of IIoT, and the bibliometric analysis of the selected papers.

Bibliometric and Database Analysis

A bibliometric analysis is the application of mathematical and statistical techniques to examine scientific publications within a certain area of expertise (Wang Y., et al, 2021). Scholarly citation analysis is a statistical approach used to assess the influence and monitor the progress and patterns in a specific discipline by analyzing published papers and their citations. This approach involves a quantitative examination of current scientific findings to determine prevailing themes, patterns, and trends, taking into account important aspects such as the sample size, the geographical spread of the studies, and the methodology employed (Bovenizer, et al, 2023). It partially characterizes, assesses, and predicts the present condition and patterns in science and technology, while also reflecting recent research accomplishments and prominent directions in this domain (Song Y., et al, 2021). Through the implementation of this approach and the examination of the above-described elements, one may discern noteworthy patterns that greatly contribute to the field of edge computing in the Industrial Internet of Things (IIoT).

To choose pertinent research for the planned analysis, renowned academic databases like Scopus. In numerous bibliometric analyses, Scopus, a renowned citation database, is frequently employed as a reference repository (Donthu, et al, 2021). Primary emphasis was given to papers published within the past five years to capture the most current trends.

Bibliometric analysis stages

The analyses and visualizations of the results were conducted using the Bibliometrix (Aria, et al, 2017) in the R environment. Data collection typically proceeds in three stages: firstly, data extraction; secondly, data loading and transformation, during which researchers must format the data to ensure compatibility with the bibliometric tools employed; and lastly, data cleaning. The many phases of the bibliometric analysis for this work are depicted in Figure 1.

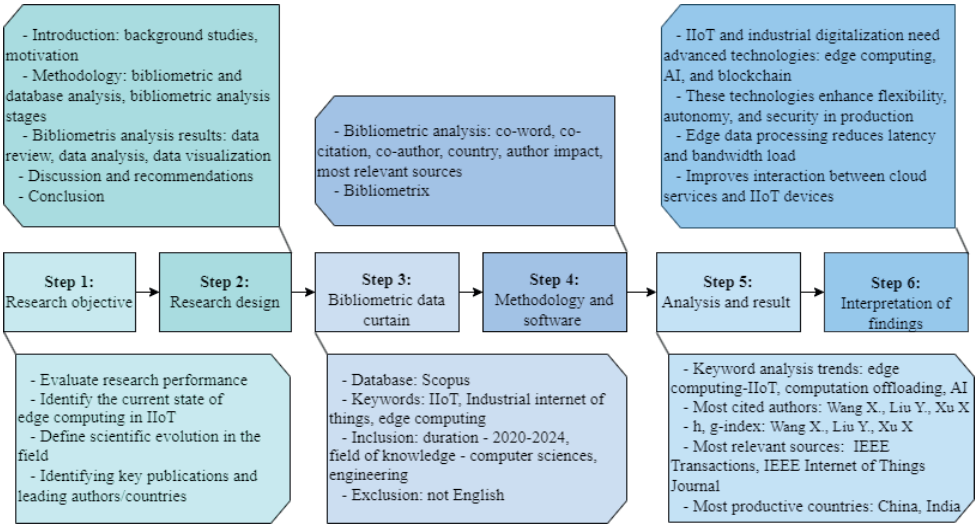

Figure 1. Stages of Bibliometric Analysis

Data collection

The data selection process also consists of three stages. In the first stage, a query was performed in the selected academic database Scopus using the keywords "IIoT" and "Edge computing." The query used to identify publications is as follows: TITLE-ABS-KEY ((((iiot) OR ("Industrial internet of things")) AND ("edge computing"))) AND PUBYEAR > 2019 AND PUBYEAR < 2025. In the second stage, 882 research documents matching the search criteria with the given keywords were found for the period 2020-2024. In the final stage, research articles were selected, as they were evaluated for originality and underwent rigorous peer review, indicating a high level of scientific quality (Paul, et al, 2021). Complete records and bibliographic data of these studies were exported as a dataset.

Data Analysis

This study uses a co-word analysis based on co-occurrence to provide a thorough picture of the most studied themes in the integration of edge computing and IIoT. It also showcases the efficacy of keyword selection for the research. Co-authorship analysis and author rating are additional techniques employed in bibliometric analysis to accurately identify the most pertinent authors in the domain of edge computing and IIoT. The application of Price's Law in bibliometrics enables the identification of prominent writers within a specific research field (Wang, et al, 2021). Citation analysis is a widely used technique in bibliometrics that employs citation counts to quantify the similarity present among papers, authors, and journals. Bibliographic coupling refers to the establishment of a relationship between authors of articles and co-citation, which is the identification of authors who cite the studied documents. Bibliographic coupling is the analysis of citing documents, whereas co-citation is the examination of cited papers. The technique of bibliographic coupling is employed to chart the present state of the research frontier. An essential measure for assessing scientific production, the h-index considers both the quantity of publications and the influence of those articles within the scientific community. To analyze countries and international collaboration networks to identify research trends in this field, significant efforts were directed towards creating knowledge that can be used to address issues encountered in practical IIoT applications.

Data Visualisation

Visualization methods were used to present maps and results of various analyses, such as co-citation analysis to assess collaboration networks between authors and countries based on relevant articles. These networks facilitate the creation of new research and the exchange of ideas. Additionally, a co-occurrence approach was applied to analyze keywords, providing an overview of the topics most studied in the integration of edge computing within IIoT.

Bibliometric Analysis Results

This section presents the results of the bibliometric analysis, from data overview to publication analysis and visualization.

Data Overview

Figure 2 provides a detailed overview of the data collected from scientific

publications covering the period from 2020 to 2024. The dataset includes 417 sources, such as journals and books, totalling 882 publications. The annual growth rate of publications is 7.69%, with an average document age of 1.84 years. On average, each document receives 15.42 citations, reflecting its scientific impact in the field. The content of the articles includes 4,498 keywords and 1,948 author keywords, highlighting the thematic diversity and main research directions. The dataset comprises 2,448 authors, of which 27 wrote documents independently, and 34.69% of the publications involve co-authors from different countries. Publications are categorized as follows: 515 articles, 281 conference papers, 6 books, 33 book chapters, and 25 review articles. Other document types include editorial articles, corrections, and conference reviews. This variety of document types indicates a broad range of formats in which research results in this field are published.

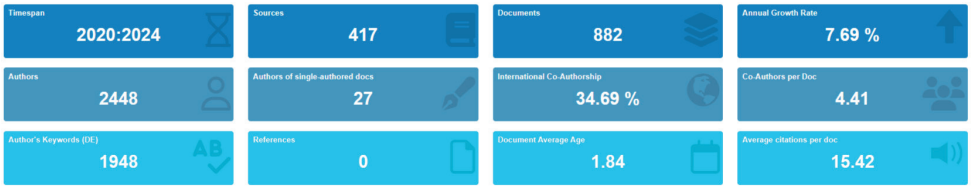

Figure 2. Overview of Data Collected from Scientific Publications

Data Analysis

Co-word analysis is the development of a conceptual framework by the construction of a co-word network. This network is utilized to map and group concepts that are taken from keywords, titles, or abstracts in bibliographic sources. Figure 3 illustrates the emerging pattern of terms associated with the implementation of contemporary technologies, including edge computing and artificial intelligence.

Figure 3. Tree Map of keywords

The 882 papers on edge computing applications in the IIoT display the swift progress in recent years. Between the years 2020 and 2022, research had a steady growth rate, but a significant surge was noted in 2023. These findings demonstrate the substantial influence of edge computing research on the IIoT domain among the scientific community (Figure 4).

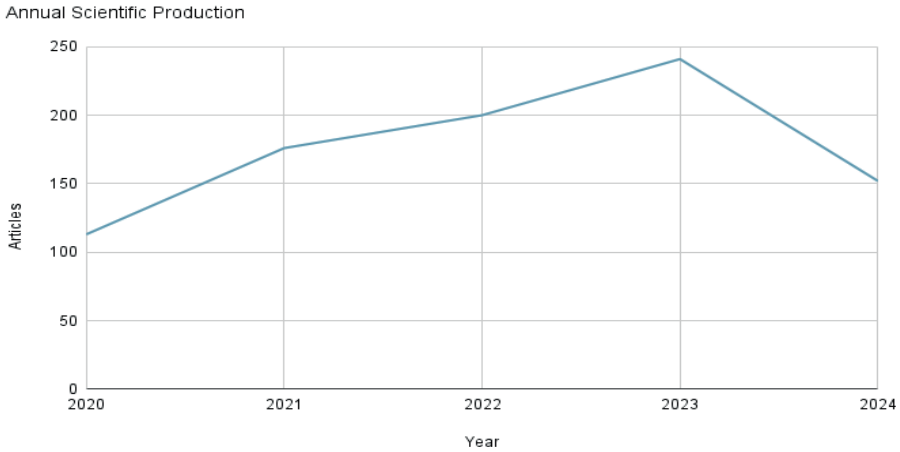

Figure 4. Annual scientific production per 2020-2024 years

Based on Table 3, Wang and Zhang are the authors with the highest number of publications in this field. This indicates that their work is recognized by many researchers and has significant influence in the area of edge computing-IIoT. While counting the number of publications is one method, the total number of citations is considered a more significant measure. Figure 3 shows a visualization of the co-citation network density among authors, revealing that Wang X., Zhang H., and Zhang X. have the highest number of citations and are frequently cited by each other.

Table 3. Most cited authors

Authors	Articles	Articles Fractionalized
Wang X.	23	4,70
Zhang Y.	23	5,17
Liu Y.	21	4,07
Xu X.	17	3,73
Wang J.	16	3,09
Zhang H.	16	3,21
Li J.	14	3,65
Wu J.	14	3,35
Liu X.	13	2,88
Wang Y.	13	2,44

Table 4 presents a comparative analysis of the scientific contributions of ten authors based on various bibliometric indices, which allow for the assessment of their

productivity and impact. Liu Y. ranks first in h-index (11) and total citations (562), indicating his significant scientific contribution. His g-index (21) also confirms the quality of his publications, while his M-index (2.750) points to a sustained impact over several years. Wang X. and Xu X. have h-indexes of 10, demonstrating similar levels of citation, but Wang X. surpasses Xu X. in total citations (644 vs. 512), indicating a more substantial contribution to the scientific community. Zhang Y., with an h-index of 9 and a g-index of 19, shows good publication quality, but his M-index (1.800) reflects slower citation growth, possibly due to the shorter time since his first publication. Thus, the authors are distributed according to their scientific impact indicators related to the research topic. The authors listed in Table 4 have achieved notable results, as evidenced by their h, g, and m-indices. Author Liu Y. exerts a greater influence in his field, as his works are cited more frequently.

Table 4. Authors local impact

Author	h_index	g_index	m_index	TC	NP	PY_start
Liu Y.	11	21	2,75	562	21	2021
Wang X.	10	23	2,5	644	23	2021
Xu X.	10	17	2	512	17	2020
Zhang Y.	9	19	1,8	391	23	2020
Wang H.	8	10	2	476	10	2021
Wu J.	8	13	1,6	182	14	2020
Liu J.	7	10	1,4	249	10	2020
Liu X.	7	13	1,4	322	13	2020
Wang J.	7	14	1,75	224	16	2021
Wang T.	7	10	1,4	527	10	2020

Figure 5 visualizes the scientific collaborations among authors on this topic. Larger nodes represent authors with a higher number of joint publications. Zhang H. forms a dense cluster with many interconnected researchers.

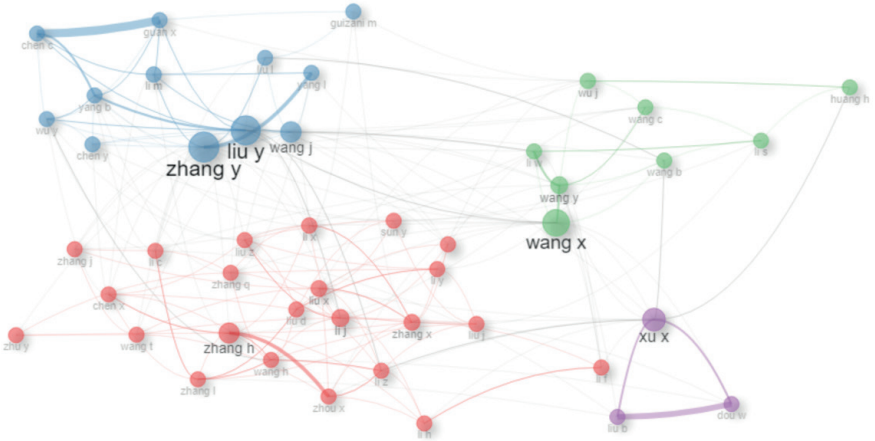

Figure 5. Most mutually cited authors

Figure 6 shows that China is the leading country in terms of productivity, with 931 publications, accounting for 34.5% of the total. India follows with 28.9% of the publications. Other leading countries include Korea, Spain, the USA, Germany, Italy, the UK, and Japan. This indicates that there are significant opportunities and prospects for future development in the integration of edge computing with IIoT.

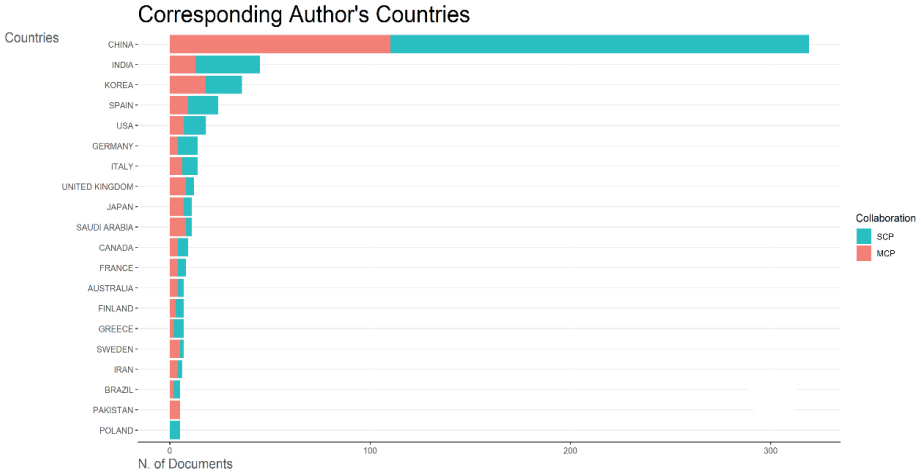

Figure 6. Countries of Corresponding Authors

The analysis of the distribution of the most important scientific sources, considering their frequency of publication, indicates that IEEE Transactions is the predominant source, representing 33.1% of the total publications. These findings demonstrate the extensive utilization of IEEE Transactions for disseminating state-of-the-art research. The IEEE Internet of Things Journal is ranked second, accounting for 30.7% of the total sources (Figure 7). This suggests a notable emphasis on research in IIoT, which aligns with the increasing significance and advancement of IIoT technologies and their implementations in the industrial domain.

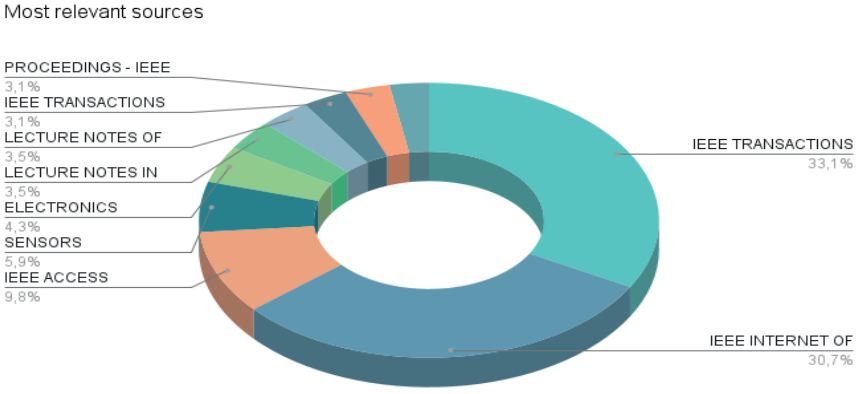

Figure 7. Most relevant courses

Data Visualization

Keywords are a crucial component of literature, and co-occurrence analysis of keywords can effectively reflect the relevant topics in the field of study. By analyzing keywords such as "IIoT", "Industrial Internet of Things" and "edge computing," a network was obtained to illustrate the conceptual structure. The visualization of the keyword co-occurrence is shown in Figure 8.

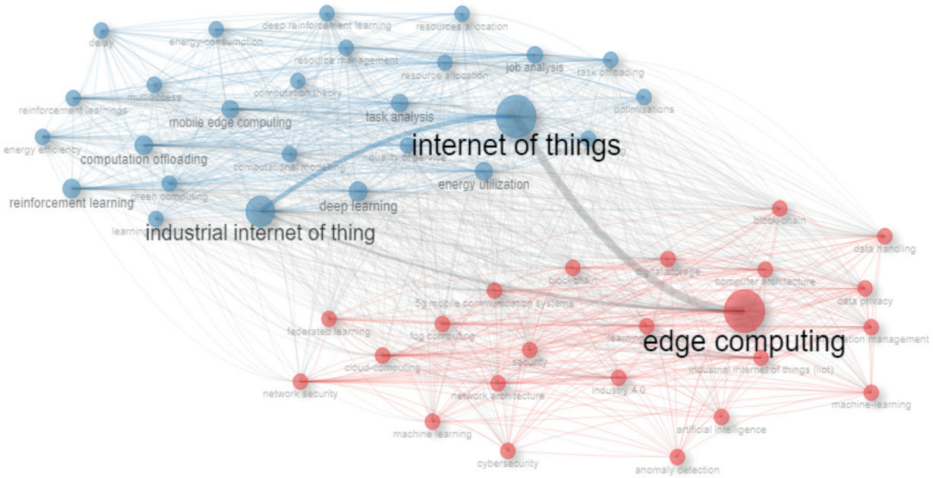

Figure 8. Keywords co-occurrence visualization

Discussion and Recommendations

The bibliometric analysis of keywords reveals patterns in the incorporation of edge computing and IIoT, with a specific emphasis on offloading computations and artificial intelligence. Optimizing resource consumption, lowering latency, and improving efficiency are key objectives of offloading calculations in industrial edge computing (Zhou X., et al, 2022). Analysis of bibliometric data from the last five years indicates a substantial rise in the number of publications on this subject. The primary focus is on incorporating edge computing with technologies such as blockchain, AI, and machine learning into IIoT. This integration greatly boosts the efficiency and security of systems, decreases energy expenses, and improves predictive maintenance. Additionally, it addresses concerns related to data interoperability and protection. Wang X., Liu Y., and Xu X. are the most often referenced authors, attaining high rankings in both the h-index and g-index statistics. The countries of China and India exhibit the highest levels of productivity, while IEEE Transactions and IEEE Internet of Things Journal serve as the primary sources for edge-IIoT developments.

The study focused on a limited set of terms, namely "edge computing" and "IIoT" or "industrial internet of things," and exclusively utilized the Scopus academic

database. Nevertheless, the bibliometric research reveals that the incorporation of edge computing, and AI are necessary for the successful implementation of the concept of IIoT and digitalization in the industry. To overcome the constraints of conventional designs, these technologies enhance the flexibility, autonomy, and security of production processes. The implementation of edge computing results in a reduction of latency and bandwidth load, therefore improving the interaction between cloud services and IIoT devices.

Conclusion

Based on the bibliometric analysis, the primary literary keywords, research, authors, journals, academic institutions, and countries related to edge computing and IIoT have been statistically examined. This method analyzed, evaluated, and forecasted the current state and prospects of research on the integration of edge computing with IIoT. The co-occurrence of published data by countries and the most frequently used keywords was analyzed using the bibliometrix program algorithm. Co-citation networks for journals and authors were constructed, allowing for visual analysis of maps. Analyzing both qualitative and quantitative bibliometric data of publications, such as keywords, literature studies, journals, authors, countries, and their future trends, provides a comprehensive view of the future of IIoT and edge computing. The bibliometric analysis reviewed significant research papers from the past five years and future research directions in edge computing and IIoT Cyber-Physical Systems.

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