The Internet of Things (IoT) in Healthcare: Taking Stock and Moving Forward

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Review article

The Internet of Things (IoT) in healthcare: Taking stock and moving forward

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ABSTRACT

Recent improvements in the Internet of Things (IoT) have allowed healthcare to evolve rapidly. This article summarizes previous studies on IoT applications in healthcare. A comprehensive review and a bibliometric analysis were performed to objectively summarize the growth of IoT research in healthcare. To begin, 2,990 journal articles were carefully selected for further investigation. These publications were analyzed based on various bibliometric metrics, including publication year, journals, authors, institutions, and countries. Keyword co-occurrence and co-citation networks were generated to unravel significant research hotspots. The findings show that IoT research has received considerable interest from the healthcare community. Based on the results of the keyword co-occurrence network, IoT healthcare applications, blockchain applications, Artificial Intelligence (AI) techniques, 5G telecommunications, as well as data analytics and computing technologies emerged as important topics. The co-citation network analysis reveals other important themes, including authentication schemes, fog computing, cloud-IoT integration, and cognitive smart healthcare. Overall, the review offers scholars an improved understanding of the current status of IoT research in healthcare and identifies knowledge gaps for future research. This review also informs healthcare professionals about the latest developments and applications of IoT in the healthcare sector.

1. Introduction

The proliferation of high-tech hardware and software platforms, the expansion of communication channels, and the development of cutting-edge data analysis tools have all contributed to the rapid rise of the Internet of Things (IoT), which is defined as a network of interconnected devices that monitor environmental variables [1,2]. One of the main ideas behind IoT is to enable objects that generate and/or collect data to interconnect via technologies such as radio frequency identification (RFID), actuators, sensors, and mobile phones [3]. Conceptually, IoT can be roughly broken down into three distinct layers: (1) the perception/physical layer, (2) the network

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Table 1
Examples of review studies on IoT research in healthcare.

No.	Study	Aims	Sample size (no. of papers)	Time span	Approach
1	Baker et al. (2017) [1]	To evaluate the strengths, shortcomings, and overall appropriateness of a wearable IoT healthcare system To outline the challenges faced by healthcare IoT, such as privacy, security, low-power operation, and wearability	-	–	Traditional literature review
2	Dimitrov (2016) [29]	To review medical IoT and big data in healthcare	-	–	Traditional literature review
3	Yin et al. (2016) [22]	To synthesize IoT applications in healthcare and study the intelligentization trend and avenues for future research	–	–	Traditional literature review
4	Aceto et al. (2020) [30]	To examine how the deployment of Industry 4.0 technologies and their integration into healthcare is altering the delivery of conventional services and products To offer a description of the principal paradigms and technologies pertaining to Healthcare 4.0 To discuss the essential application scenarios, benefits, cross-disciplinary issues, and lessons learned from Healthcare 4.0	–	-	Traditional literature review
5	Qadri et al. (2020) [31]	To explore the ways in which the Internet of Nano Things and Tactile Internet are reshaping healthcare IoT systems To discuss the future path for enhancing the Quality of Service using these novel technologies	–	–	Traditional literature review
6	Qi et al. (2017) [32]	To provide a comprehensive assessment of IoT-enabled personalized healthcare systems To examine the present knowledge of IoT-enabled personalized healthcare systems, as well as important enabling technologies, significant IoT applications, and effective case studies in healthcare	–	–	Traditional literature review
7	Sun et al. (2018) [33]	To examine the security and privacy requirements for data flow in IoT To provide a detailed study of the current solutions to security and privacy concerns	–	–	Traditional literature review
8	Habibzadeh et al. (2020) [2]	To examine healthcare IoT from a clinical perspective	–	–	Traditional literature review
9	Dhanvijay and Patil (2019) [34]	To present a Wireless Body Area Network (WBAN)-based IoT healthcare system and analyze the current status of the network architecture topology and applications in IoT-based healthcare solutions To explore security and privacy elements, including authentication, power, energy, Quality of Service, resource management, and real-time wireless health monitoring	–	–	Traditional literature review
10	Da Costa et al. (2018) [35]	To introduce the notion of the Internet of Health Things (IoHT) and concentrate on the different methods that can be used to collect and aggregate vital sign data in hospitals To provide various routes for merging patient data in hospital wards in order to increase efficiency and allow for the optimization of resources and the minimization of patient health decline	–	–	Traditional literature review
11	Pratap Singh et al. (2020) [28]	To investigate the possibilities of combating the COVID-19 pandemic by adopting medical IoT while treating orthopedic patients	–	–	Traditional literature review
12	Al-Turjman et al. (2020) [36]	To describe the current situation of IoT in healthcare considering research and development initiatives and applications To present the technical and design issues of IoT and develop a generic IoT framework consisting of three primary elements, namely data collection, communication gateways, and server clouds To discuss the potential and prospects of IoT in practice, with a focus on relevant open research questions	–	–	Traditional literature review
13	Swayamsiddha and Mohanty (2020) [37]	To explore the new application of cognitive radio (CR) based IoT in the medical domain	–	–	Traditional literature review
14	Selvaraj and Sundaravaradhan (2020) [38]	To examine IoT-based healthcare systems and the architecture used in IoT, particularly cloud-integrated systems	–	–	Traditional literature review
15	Stavropoulos et al. (2020) [27]	To give an overview of IoT wearable devices and sensors in elderly care	–	–	Traditional literature review
16	Marques et al. (2019) [39]	To examine the present status of IoT architectures for enhanced living environments and healthcare systems, focusing on	–	–	Traditional literature review

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Table 1 (*continued*)

No.	Study	Aims	Sample size (no. of papers)	Time span	Approach
		technology, applications, problems, possibilities, operating systems, and open-source platforms			
17	Rahman et al. (2019) [40]	To examine IoT-based smart health monitoring devices with the intention of highlighting common design and implementation trends	–	–	Traditional literature review
18	Qureshi and Krishnan (2018) [41]	To analyze the hardware components necessary to develop wearable devices that are employed in medical IoT	–	–	Traditional literature review
19	Ratta et al. (2021) [42]	To explore the role of cutting-edge technologies such as IoT and blockchain in improving healthcare delivery To explore the applicability of IoT and blockchain in three key areas: tracking the origin of pharmaceuticals, monitoring patients remotely, and organizing medical records To discuss the barriers to IoT and blockchain adoption in healthcare systems	–	–	Traditional literature review
20	Mohd Aman et al. (2021) [25]	To present IoT architecture, applications, technologies, and security advances that have been achieved with regard to IoT in countering the COVID-19 pandemic To provide important insights into particular IoT architectural models, new IoT applications, IoT security measurements, and technological directions to fight COVID-19	–	–	Traditional literature review
21	Kang et al. (2018) [43]	To provide a summary of the most up-to-date patient health monitoring platforms based on IoT-enabled smart devices that can collect patient data in real-time and transmit it to healthcare providers, such as hospitals, doctors, and clinics, or to patients themselves for self-management	–	–	Traditional literature review
22	Scarpato et al. (2017) [44]	To summarize the state-of-art of IoT in a medical environment To investigate wearable and energy-saving properties and the role of IoT architectures in increasing privacy and security during data-transmission	–	–	Traditional literature review
23	Awad et al. (2022) [26]	To provide a detailed discussion of mobile edge computing (MEC)-based IoT healthcare systems	–	–	Traditional literature review
24	Kakhi et al. (2022) [45]	To explore the contribution of Artificial Intelligence (AI) to current IoT developments in healthcare To look at the hardware needed for healthcare IoT and the potential solution for this technology using AI To investigate and classify wearable medical devices	–	–	Traditional literature review
25	Ahmadi et al. (2019) [46]	To identify the main IoT applications in healthcare, aspects of IoT architecture, main technologies in IoT, features of cloud-based architecture, interoperability and security problems in the IoT architecture, and barriers to IoT adoption in healthcare	60	2000–2016	Systematic literature review
26	Mieronkoski et al. (2017) [47]	To familiarize the nursing audience with IoT by discussing current developments in IoT-based technologies that support fundamental nursing tasks in healthcare facilities	62	2006–2016	Systematic literature review
27	Nazir et al. (2019) [48]	To analyze how mobile computing enables IoT applications in healthcare, enables security and privacy in IoT devices, and impacts IoT in health systems	116	2011–2019	Systematic literature review
28	Haghi Kashani et al. (2021) [49]	To classify current research on healthcare IoT taxonomically To provide a thorough taxonomy for healthcare IoT and classify the literature according to sensor-based, resource-based, communication-based, application-based, and security-based approaches To present the advantages and limitations of the chosen approaches, along with a full comparison of evaluation techniques, tools, and metrics	146	2015–2020	Systematic literature review
29	Lederman et al. (2021) [50]	To examine the published research on IoT in healthcare, classify the literature according to prevailing trends, and highlight relevant uses cases of IoT To broaden the scope of existing classifications and better explain IoT's role in medicine To reflect on IoT models, critical success factors, and obstacles to IoT deployment in healthcare	105	2005–2021	Systematic literature review
30	Saheb and Izadi (2019) [51]	To map the current research landscape around the IoT Big Data Analytics paradigm (IoTBDA) in the healthcare sector To determine the effects of IoTBDA on healthcare service providers' ability to design, test, and implement IoT-based innovation	46	–	Systematic literature review
	Our study		2990		

(*continued on next page*)

Table 1 (*continued*)

No.	Study	Aims	Sample size (no. of papers)	Time span	Approach
		To trace IoT research in healthcare since its emergence To identify which countries or world regions contribute most to the development of IoT research in healthcare To identify the most impactful scholars and publications in IoT research in healthcare To reveal the thematic trends of IoT research in healthcare To highlight the main research hotspots and discussions in the literature		2011–2022 (up to July)	Bibliometric analysis

layer, and (3) the application layer. The first layer is in charge of gathering data about the surrounding environment, which is then used by other layers to run algorithms and deliver a particular service [4,5]. As the central part of IoT [6], the network layer is responsible for transferring and processing the data collected by the perception layer [7]. The last layer is the application layer, which contains the collection of services and functions provided to the end users. Located at the very top of the IoT stack, it is this layer where users interact with devices carrying out requests and performing transactions [8]. Data querying, report generation, visualization, and analysis, as well as authentication and interaction with IoT platforms, are all accomplished at the application layer [9], which is made up of two sublayers. The first is the application support platform sublayer, which supports information sharing, coordination, collaboration, and interoperability. The second is the application sublayer, which refers to industry-specific applications, such as smart transportation, smart logistics, smart energy management, and smart healthcare [10,11].

Rapid expansion in recent years has been observed in the worldwide market for IoT [12,13]. Markets and Markets, for instance, projects that the industrial market of IoT will reach 110.6 billion USD in 2025, representing a compound annual growth rate of 7.4% between 2020 and 2025 [14]. It is also predicted that by 2030, nearly 50 billion IoT products and devices will be in use worldwide, creating a huge network of linked gadgets ranging from smartphones to household appliances. This tendency, together with the ever-falling prices of electronics and networking, has helped spur the growth of IoT applications in the healthcare sector.

The emergence of IoT provides huge opportunities in the healthcare field [15,16]. When it comes to tele-monitoring patients, IoT is expected to be crucial in both healthcare facilities and, more significantly, patients' own homes [17,18]. The deployment of IoT in remote health monitoring also has enormous potential for improving healthcare service quality and lowering costs via early detection and prevention of illnesses and other potentially dangerous conditions [19,20]. Chronic illness management, care for the elderly, and fitness activities are just some of the medical uses that may be spawned by IoT implementations. Oftentimes, the majority of patients undergoing medical treatment must remain in the hospital for the whole term of their care, driving up the expense of their hospitalization. As a result, the use of technology with the capacity to remotely monitor sick people offers a potential solution. By gathering and transmitting real-time health data of patients to clinicians, IoT will not only cut health service costs but also allow for the early detection and treatment of health issues [19]. Medical sensors and imaging and diagnostic equipment are smart devices that make up a fundamental aspect of IoT. Moreover, medical services built on IoT are anticipated to improve efficiency, extend patient lives, and reward its users in a number of ways. From the standpoint of healthcare professionals, IoT can minimize equipment downtime via remote provision. Moreover, it has the ability to accurately determine the best times to restock supplies for different equipment to ensure its continued and trouble-free functioning. In addition, IoT allows for the optimal allocation of scarce resources so that more patients benefit from quality services. Another advantage of IoT is the facilitation of cost-effective interactions via secure, real-time, and seamless communication between healthcare institutions, clinics, and patients. Healthcare networks powered by IoT technologies are anticipated to assist with early diagnosis, treatment of chronic illnesses, medical emergencies, and instant monitoring. Also, they support the creation of health records and the provision of on-demand healthcare to authorized parties using health databases, gateways, and medical servers.

An increasing number of academics, organizations, and research institutions are investing in the research and development of IoT-enabled technologies with healthcare applications in mind [21] in an effort to make the most out of IoT's potential in health systems. Consequently, there are a plethora of services, prototypes, and applications available in the healthcare sector. Novel applications and services, network platforms and architectures, security and privacy, and interoperability are just a few areas where IoT-enabled healthcare research is rapidly growing. Many nations and organizations worldwide have already developed regulations and standards for implementing IoT in the healthcare sector [22]. While IoT research has received extensive coverage in healthcare, there has been a paucity of works devoted to dissecting the intellectual structure of related research in this field. This study fills a significant gap in the literature. Not only is this the first effort to employ bibliometric techniques, but it also evaluates the structure of IoT knowledge domain by analyzing information pertaining to co-citation and keyword co-occurrence networks. Ferreira et al. [23] argue that as study fields mature and become increasingly complex, researchers should regularly strive to extract new insights from the accumulated literature, uncover fresh contributions, reveal research trends and traditions, and highlight directions for future inquiries. In this respect, we add depth to IoT knowledge base from the healthcare perspective by investigating the network dynamics and structure of IoT-related studies and identifying the most influential scholars shaping this field. In this way, we concur with Wang et al. [24] who state that frequent reviews are necessary to keep academics abreast of the latest advancements in rapidly evolving technologies. Through a comprehensive review of IoT research in healthcare, we aspire to document and foster the conceptual development of this dynamic field of study. To be specific, our research answers to the following questions:

- How has IoT research in healthcare evolved since its beginning?
- What are the main institutions and countries contributing to IoT research in healthcare?
- Which authors and studies are most influential in IoT research in healthcare?
- What are the main thematic areas in the IoT and healthcare literature?

2. Review studies on IoT in healthcare

Several academic papers have previously discussed the potential of IoT in healthcare. Traditional literature reviews and systematic literature reviews were used by researchers to summarize IoT research in healthcare, as shown in Table 1. Several aspects of IoT adoption in healthcare have been examined, ranging from exploring the privacy and security issues in IoT-enabling healthcare systems [1,25,26] and exploring IoT for elderly care [27], to examining the potential of the technology for combatting the current COVID-19 pandemic [25,28]. For example, Baker et al. [1] review IoT research in healthcare and provide a novel framework for IoT-based healthcare systems, which can be deployed for general systems as well as narrowly focused monitoring applications. They also review non-invasive, wearable sensors with a focus on those that measure vital signs, blood pressure, and blood oxygen level. Two types of communication protocols, long-range and short-range, were compared to evaluate their suitability for medical purposes. Dimitrov [29] examines IoT and big data applications in healthcare and finds that health education, fitness, symptom monitoring, care coordination, and collaborative disease management are just a few of the areas where IoT wearables are making a positive impact. Yin et al. [22] provide a comprehensive overview of IoT-based healthcare systems and offer a summary of the underlying technologies and smart healthcare devices in IoT. Specific implementation techniques and approaches to ontology-based resource management, big data management, and knowledge management are also addressed. Aceto et al. [30] examine in detail the contribution of Industry 4.0 technologies, including IoT, cloud and fog computing, and big data analytics, to the healthcare sector. Through this literature review, the authors deduce how the healthcare field as a whole is progressing towards e-health, and how this transition will be further accelerated in the era of healthcare 4.0, where emerging technologies enhance not only traditional systems and processes (e.g., medical intake, cloud healthcare systems, advanced control of pathological and physiological signals), but also inspire new approaches,

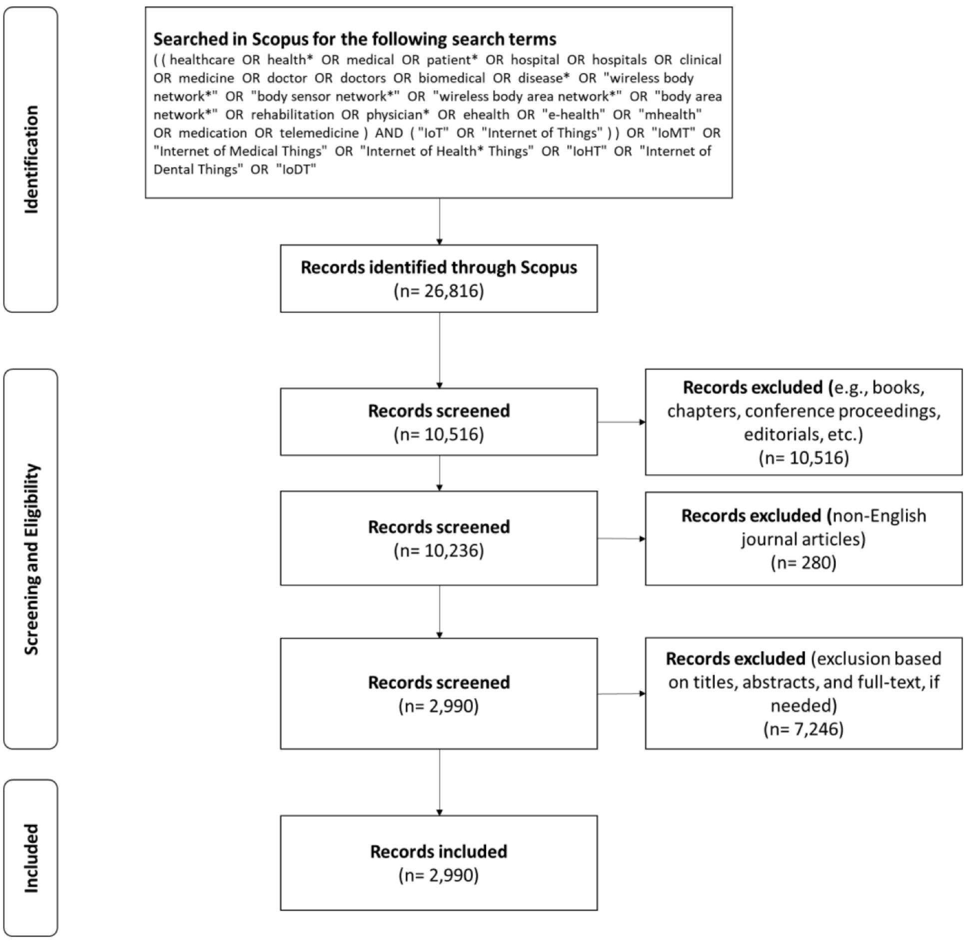

Fig. 1. Review process (adapted from Moher et al. [58]).

applications, and processes, such as personalized healthcare, home-based rehabilitation, and enhanced living environments. Finally, Qadri et al. [31] discuss some of the cutting-edge technologies that support IoT systems in healthcare. They find that several architectures are deployed in healthcare IoT and identify machine learning, edge computing, and blockchains as driving forces.

While the majority of studies on IoT applications in healthcare rely on conventional (i.e., narrative) literature reviews, a few studies use a systematic approach to analyze the IoT literature. For example, Ahmadi et al. [46] review 60 studies to examine several facets of healthcare IoT architecture, the barriers to IoT adoption, and the ways different parts of IoT architecture interoperate. Mieronkoski et al. [47] summarize 62 studies to examine how IoT can support basic nursing practices. Although the potential of the technology has not been fully realized yet, the authors conclude that IoT can automate hospital environment and patient monitoring, facilitate data collection and management, and improve care quality and patient safety in fundamental nursing practices. Nazir et al. [48] analyze 162 studies to better understand the role of mobile computing in IoT-based healthcare systems. They argue that mobile computing increases IoT devices' privacy and security and paves the way for innovative healthcare applications, including oxygen saturation monitoring, glucose level sensing, and body temperature monitoring. Haghi Kashani et al. [49] review 146 studies and propose a comprehensive taxonomy of healthcare IoT. Based on their review results, the major pending issues involve trust and privacy, power management, resource management, and fog computing. Further, social networks, tactical internet, big data analytics, blockchain, and the internet of nano things are identified as critical future trends, while scalability, interoperability, and mobility issues are all challenges deserving future investigation. So far, researchers have applied traditional and systematic literature reviews of IoT applications in healthcare, while alternative review techniques, such as bibliometrics, have been mostly ignored, which motivated us to conduct this bibliometric study. In doing so, we aspire to gain a better understanding of this research strand and inform future researchers, decision-makers, and practitioners. The findings of this review will add to the current literature by identifying the main thematic categories and future research directions in the IoT healthcare literature (see the last row in Table 1).

3. Methodology

The Scopus database was first searched using the query shown in Fig. 1. Scopus was selected due to its comprehensive coverage as compared to other scientific databases (e.g., IEEE Xplore, Web of Science, ProQuest) [52] and its unique functions that enable scholars to easily retrieve and collect references from a set of publications [53]. Scopus also has a reputation for its inclusiveness, reliability, and trustworthiness in indexing academic journals from prestigious publishers, including Elsevier, Taylor and Francis, Emerald Insight, IEEE, the ACM, and Springer [54]. We looked in the title, abstract, and keywords fields for the following search terms: ((healthcare OR health* OR medical OR patient* OR hospital OR hospitals OR clinical OR medicine OR doctor OR doctors OR biomedical OR disease* OR "wireless body network*" OR "body sensor network*" OR "wireless body area network*" OR "body area network*" OR rehabilitation OR physician* OR ehealth OR "e-health" OR "mhealth" OR medication OR telemedicine) AND ("IoT" OR "Internet of Things")) OR "IoMT" OR "Internet of Medical Things" OR "Internet of Health* Things" OR "IoHT" OR "Internet of Dental Things" OR "IoDT". This process yielded a total of 26,816 documents on 31 July 2022. No subject areas were selected to ensure the maximum coverage of all potentially relevant publications. In order to guarantee the scholarly quality as well as the comparability of the retrieved material [55], only journal articles and reviews in English were selected [56]. In other words, books, chapters, conference proceedings, notes, editorials, and reports were excluded. This resulted in the elimination of 16,300 documents, bringing the total number of retained publications to 10,516. Only English-language journals were considered, resulting in the inclusion of 10,236 articles for further analysis. Due to the large dataset, three authors from the research team were involved in the manual screening of the remaining publications by reading the title, abstract, and the full-text if needed. The reviewers collected the data and compared their findings thereafter. Any discrepancies or sources of bias were discussed and resolved by consensus [57]. During this process, articles without any apparent relationship to IoT applications in the healthcare were excluded. We specifically omitted a huge number of publications on IoT applications for improving soil, plant, and animal health. The selection process ultimately led to the exclusion of 7,246 documents and the identification of 2990 articles which were relevant to the scope of the current review. The articles' citations and references were stored in CSV format. Fig. 1 depicts the search and selection process.

3.1. Review process

The primary purpose of a literature review is to identify, specify, map, and analyze the current body of relevant literature in an objective, systematic, and readily replicable manner [59]. A comprehensive and in-depth analysis that takes into account obvious and contextual linkages [60] is the outcome of a well-structured literature review encompassing a wide variety of publications and research methodologies. There are three primary reasons why we chose to employ bibliometrics in this investigation. First, a bibliometric analysis is more trustworthy and scalable than other approaches for text analysis, including content analysis. Second, bibliometric methods aid in conducting detailed analyses of the relationships between specific works, keywords, citations, and co-citations to provide rich and valuable information [61,62]. One last reason is that bibliometric methods provide academics with a means to visually represent meaningful clusters of study subjects in an informative and intuitive way.

3.2. Quantitative analysis

To begin, we mapped the selected papers according to their annual distribution and assessed the development of IoT research in the healthcare field. Next, we followed the procedure of Fahimnia et al. [63] to assess the influence and quality of papers by looking at a variety of quantitative metrics, including the number of articles per author, the number of citations per article, and the publication location of the article. We used BibExcel, a computer program that allows us to easily enter and manipulate data. The biggest advantage of using BibExcel is its interoperability with a wide variety of academic databases (e.g., Web of Science, Scopus) and visualization software (e.g., VOSviewer, Gephi, Ucinet) [64].

In academia, scholars receiving many citations are regarded as the most influential in their respective disciplines. Consequently, we arranged the authors of all selected publications by their frequency of appearance. The affiliation information of each author was extracted and entered into BibExcel to determine the major academic organizations and the countries in which they are located. To gain a better knowledge of the themes of IoT research in healthcare, we conducted a keyword analysis to determine the most frequently used terms in the publication dataset. Furthermore, we tracked citations and their patterns in order to assess the research's influence and importance [65]. The frequency with which a single publication is referenced demonstrates its significance within the academic community and reveals its influence and impact [66]. We determined the frequency of local citations by analyzing the number of citations obtained by each paper from other papers in the dataset. Citation counts from the Scopus database were used to determine the number of global citations per paper. Given that Scopus covers a wide range of research areas, a paper's relative popularity in its own field, as opposed to other fields, can be inferred by comparing its local citation count to its global citation count [67].

3.3. Network analysis

Following the descriptive analysis of the chosen papers, we looked for underlying trends and patterns. We used a network analysis approach based on bibliometric data and the graphical program Gephi to visualize the network structure of IoT-related studies in the healthcare field. In the first step, we constructed a keyword co-occurrence network to learn more about IoT-related studies in healthcare. A keyword co-citation network, like a co-citation network, displays the connections between author-supplied keywords and how often they co-occur [68,69]. Lee and Su [70] point out that keyword co-occurrence analysis can be used to identify important research subjects and track the progress of research frontiers in a given field of study. If two keywords frequently occur together in the same publication, they will be more closely connected in a network. By mapping the keyword co-occurrence network, we were able to assess the core themes of the literature and provide a snapshot of the present landscape of IoT research in healthcare. As VOSviewer is quite compatible with the BibExcel program, it was chosen to visualize this network [71,72]. Each keyword's frequency is represented by the node's radius, and the frequency with which each pair of keywords was used is shown by the edges' breadth. The themes addressed in IoT research within the healthcare field can be revealed by visually portraying the mutual interactions between keywords.

Small [73] first proposed using co-citation analysis in 1973 to determine the level of semantic similarity of conceptual overlap between publications that cite the same work. Bibliographic coupling occurs when two publications have at least one shared reference or when there is one co-citation between them. The co-citation frequency measures the number of citations shared by two publications, with a high value indicating a strong relationship between them. In the current review, our co-citation technique relies on the cited references from each publication to determine the topic clusters. A co-citation network was created using the visualization program Gephi and the input data from BibExcel. To generate the clusters of the co-citation map, we performed a number of tasks. We set the co-citation frequency at an optimal threshold before importing the bibliometric data into Gephi. If the threshold is set too high, only a small subset of the publications will be grouped together, while setting it too low will result in an overwhelming number of clusters. The circle pack layout, suggested by previous research [74,75], was therefore employed in our investigation to provide a simple and understandable graph inside the Gephi layout. Each publication is represented as a node in the network, and the connection between any two publications is shown by an edge. We manually adjusted node size, hierarchies, and other settings (e.g., color) to construct the network. This can be regarded as a type of manual clustering and regularization. Fig. 2 shows the research approaches used in this

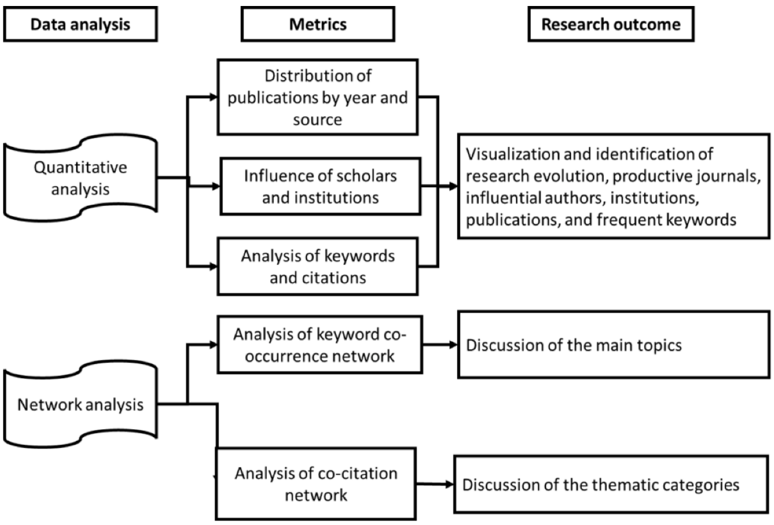

Fig. 2. Research approaches.

review.

4. Findings from quantitative analysis

4.1. Descriptive statistics

As outlined above, there were a total of 2990 relevant publications in the sample pool. In order to address our first research question, we looked back at the history of IoT-related studies in the healthcare sector. The upward trend shown in Fig. 3 has been ongoing since 2011. Between 2018 and 2022, the number of publications on IoT increased steadily. The earliest works were published in 2011 and focused on the role of IoT in supporting smart healthcare and patients' profile management architecture. More specifically, Jara et al. [76] introduce an IoT-based diabetes management system designed to deliver the next generation of mobile assistance services and take into account factors for insulin therapy in an effort to reduce the frequency of hypoglycemia and hyperglycemia episodes, and thus the risks for individual patients. Li et al. [77] suggest pervasive healthcare as application for smart communities, highlighting the role of the technology in facilitating the monitoring of environmental conditions and the bodily state of community members. This is done via the use of wireless body sensors distributed around the human body to facilitate an accurate and prompt emergency reaction. These two studies were groundbreaking because they sparked more studies on IoT applications in healthcare.

Table 2 presents the top 10 journals with the most publications on healthcare and IoT. In total, these journals published 944 articles which form 31.57% of the publications in the domain. IEEE Access, IEEE Internet of Things Journal, and Sensors are the most productive outlets, with more than 100 publications, respectively. The top journals in the list are mostly information technology-related journals, with two exceptions (i.e., Journal of Healthcare Engineering, Journal of Medical Systems) that are specialized in healthcare research.

4.2. Statistics of most productive authors, academic institutions, and countries

Table 3 lists the most prolific scholars in the IoT in healthcare literature. Kumar, N. and Rodrigues, JJPC are the most prolific, having published 31 and 25 articles, respectively. The vast majority of the authors write on IoT technologies and applications. For instance, Kumar, N. is a productive author on IoT and its integration with other technologies such as blockchain, Artificial Intelligence, and fog computing in the healthcare domain.

The most prolific institutions are listed in Table 4. King Saud University (located in Saudi Arabia) and Vellore Institute of Technology (India) are the most productive institutions, with 116 and 98 publications, respectively. The dominant presence of Saudi institutions is evident, with three institutions listed among the top four. Also, India and China have more than one entry in the top list. In conjunction with the institution analysis, Table 5 shows the most productive countries, with India (793) and China (634) being the most prolific. Interestingly, most countries in the table are developing countries and most institutions are located in developing countries, which indicates that IoT applications in healthcare are being supported in third-world countries. Additionally, approximately two thirds of Saudi Arabia's publications belong to the three top institutions listed in Table 4. Furthermore, the dominance of Asian countries is evident in Table 5.

4.3. Keywords frequency and citations

The 20 most frequent keywords are listed in Table 6. According to the table, IoT, IoHT (Internet of Healthcare Things), and healthcare are the most frequently occurring keywords, which is mainly caused by their explicit inclusion in the search query. To receive medical services before the advent of IoHT, patients relied on methods such as making phone calls or in-person visits to

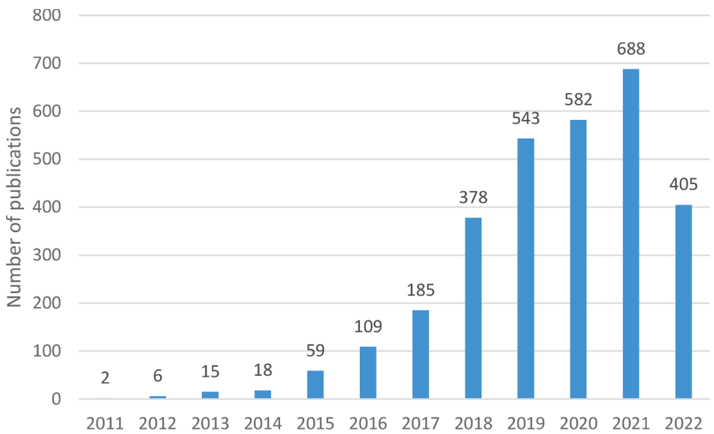

Fig. 3. Year-wise distribution of publications (date of search: 31 July 2022).

Table 2
Most productive journals.

Journal	Number of publications	%
IEEE Access	264	28%
IEEE Internet of Things Journal	195	21%
Sensors	140	15%
Future Generation Computer Systems	89	9%
Wireless Communications and Mobile Computing	46	5%
Electronics	46	5%
IEEE Transactions on Industrial Informatics	45	5%
Wireless Personal Communications	41	4%
Journal of Healthcare Engineering	41	4%
Journal of Medical Systems	37	4%
	944	100%

Table 3
Most productive authors.

Author	Number of publications	%
Kumar, N.	31	15%
Rodrigues, JJPC.	25	12%
Guizani, M.	23	11%
Gupta, D.	20	10%
Ray, P.P.	19	9%
Sood, S.K.	19	9%
Choo, K.K.R.	17	8%
Hossain, M.S.	17	8%
Muhammad, G.	17	8%
Das, A.K.	15	7%
	203	100%

Table 4
Most productive institutions.

Institution	Number of publications	Location
King Saud University	116	Saudi Arabia
Vellore Institute of Technology	98	India
Taif University	46	Saudi Arabia
King Abdulaziz University	45	Saudi Arabia
University of Electronic Science and Technology of China	41	China
Chinese Academy of Sciences	40	China
Instituto de Telecomunicações	39	Portugal
Sejong University	39	South Korea
Qatar University	38	Qatar
Thapar Institute of Engineering & Technology	37	India

Table 5
Most productive countries.

Country	Number of publications	%
India	793	25%
China	634	20%
Saudi Arabia	334	10%
United States	332	10%
South Korea	243	8%
Pakistan	235	7%
United Kingdom	229	7%
Australia	166	5%
Italy	116	4%
Malaysia	116	4%
	3198	100%

healthcare providers or sending emails. The lack of smart devices and associated infrastructure implied that traditional systems could not allow for real-time monitoring or tracking of patients' health. In this regard, the introduction of IoT has significantly improved the healthcare sector. The technology not only lessens the burden on the health system as a whole but also enables patients to be monitored

Table 6
Top 20 frequent keywords in the IoT and healthcare literature.

Keyword	Number of occurrences
IoT	1612
IoHT	442
Healthcare	407
Security	237
Cloud Computing	222
Blockchain	172
WBSN	146
ML	146
Fog Computing	144
DL	135
e-Health	131
Sensor	122
Privacy	119
COVID-19	117
Edge Computing	107
WSN	97
AI	96
Smart Healthcare	96
Big Data	94
Authentication	90

and treated in real time. This crucial shift is visible in a number of ways, including real-time monitoring, online consulting, and telemedicine. The fourth most frequently used keyword is "Security", which represents a critical issue for protecting the personal and health-related information of patients. As a result, during the design of IoT applications in healthcare, greater attention to data security and privacy should be paid to mitigate ethical and legal problems arising from the exposure to patients' personal and medical information.

The keywords "Cloud Computing", "Blockchain", "WBSN" (Wireless Body Sensor Networks), "ML" (Machine learning), "Fog Computing", "Edge Computing", "AI" (Artificial Intelligence), and "Big Data" also occur frequently in the reviewed literature. The integration of cloud computing technologies and IoT into healthcare has enabled health professionals to deliver quicker, more efficient, and higher-quality treatment, resulting in a more satisfying patient experience. Consequently, this leads to enhanced medical treatment for patients and a more pleasant experience for healthcare staff resulting from less paperwork [78]. Cloud computing can also be integrated with IoT to develop a healthcare system that ensures transparent and ubiquitous access to common infrastructure and shared medical data, as well as the provision of on-demand services and better performance of operations to meet increasing demand [79]. Moreover, IoT can be combined with blockchain technology to facilitate drug traceability, remote patient monitoring, and medical record management [42]. Healthcare systems based on wireless sensor networks (WSN) have been developed to monitor important physiological functions. Using WSN, healthcare providers can keep a steady eye on patients' vitals in real time. Sensors can be placed on or near the patient's body or in the surrounding environment. Physiological parameters or signals, such as glucose levels, pulse rate, breathing patterns, and other biomarkers, are often monitored by WBSN systems. Doctors and caregivers can monitor these metrics remotely without interfering with patients' daily routines, thereby reducing the likelihood of human errors and leading to deeper insights into the causes of illnesses. During the COVID-19 pandemic, healthcare monitoring has flourished with the support of IoT and its ability to alert users of potential health problems in a timely manner [80].

The most cited papers at the intersection of IoT and healthcare are listed in Table 7. These papers represent seminal works that contributed significantly to IoT research in healthcare and accelerated the diffusion of knowledge pertaining to IoT applications. Not surprisingly, reviews are dominant in the top list. The reviews address not only IoT applications in healthcare [81], AI applications in

Table 7
Top 10 most cited articles.

Citation	Title	Citations
Islam et al. (2015) [81]	The Internet of Things for health care: A comprehensive survey	1628
Peeri et al. (2020) [86]	The SARS, MERS and novel coronavirus (COVID-19) epidemics, the newest and biggest global health threats: what lessons have we learned?	746
Khan et al. (2016) [87]	Monitoring of Vital Signs with Flexible and Wearable Medical Devices	738
Casino et al. (2019) [84]	A systematic literature review of blockchain-based applications: Current status, classification and open issues	693
Catarinucci et al. (2015) [88]	An IoT-Aware Architecture for Smart Healthcare Systems	687
Swan (2012) [89]	Sensor mania! the internet of things, wearable computing, objective metrics, and the quantified self 2.0	657
Yang et al. (2017) [85]	A Survey on Security and Privacy Issues in Internet-of-Things	642
Rahmani et al. (2018) [90]	Exploiting smart e-Health gateways at the edge of healthcare Internet-of-Things: A fog computing approach	607
Gravina et al. (2017) [83]	Multi-sensor fusion in body sensor networks: State-of-the-art and research challenges	533
Vaishya et al. (2020) [82]	Artificial Intelligence (AI) applications for COVID-19 pandemic	510

healthcare [82], and wireless body sensor networks [83] but also include more general subjects such as blockchain technology applications [84] and IoT challenges, including security and privacy [85]. Additionally, the COVID-19 pandemic has attracted significant attention from scholars [86].

5. Network analyses

5.1. Keyword co-occurrence analysis

Keyword co-occurrence analysis was performed as an alternative clustering method for identifying unique paradigms within a given subject area to extract the textual content of published works [91]. By looking at how often two or more keywords appear together, we can get insights into a wide range of topics that further our understanding of how IoT can impact the healthcare sector. This relational bibliometric method detects common author keywords across publications and groups them together. By studying these intersections, researchers can gain an increased understanding of the knowledge gaps and the prevailing paradigms in this research strand [92]. In order to construct the network, we first extracted and refined the authors' keywords from the relevant articles. Then, VOSviewer was used to process the data. Density-based spatial clustering with the full counting approach was applied to construct the network [93]. To establish a manageable number of clusters for statistical examination, we required a minimum of 5 simultaneous occurrences of each term [94].

The data revealed a clustering structure in the network consisting of five clusters (see Fig. 4). The top 10 frequent keywords in each cluster are listed in Table 8. The size of each node in the diagram corresponds to the relative frequency of the term it represents. A keyword is represented as a node in the network, and the size of the node indicates how often that keyword appears together with other keywords. The distance between two nodes is determined by density, and a greater density indicates a closer proximity between two keywords.

As can be seen in Fig. 4, the red cluster (lower left side) is the largest by far. The researchers in this cluster investigate how IoT technologies such as WSN, sensors, and RFID are revolutionizing healthcare. WSN and RFID are both vital technologies in advancing IoT practices, and each has its benefits and drawbacks [95]. The IoT revolution is reshaping modern healthcare (e-health) in ways that hold great potential in terms of improving health outcomes, healthcare costs, and social outcomes [81]. Indicators of health and social status show that life expectancy is rising. As a result, patients are now more likely to spend a larger portion of their lives dealing with the effects of chronic illness and other co-morbidities. Now more than ever, novel approaches to healthcare delivery are being tested due to developments in information and communication technologies. When it comes to facilitating patient participation, illness

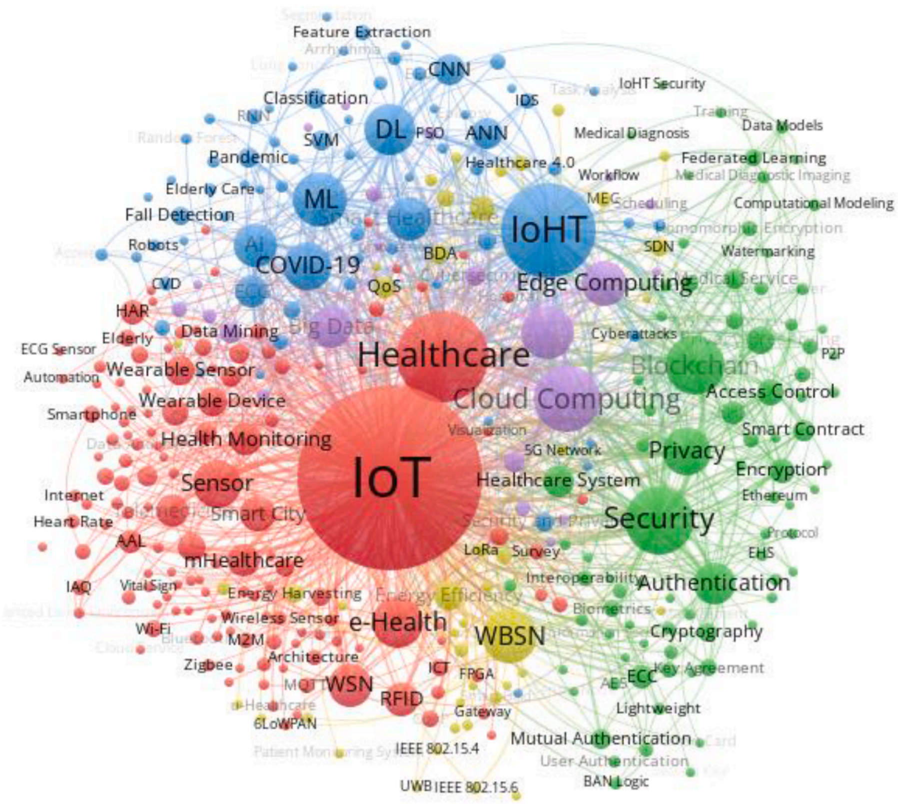

Fig. 4. Keyword co-occurrence network.

Table 8
Top 10 frequent keywords in each cluster.

1 IoHT	2 Blockchain applications in IoHT	3 AI techniques in IoHT.	4 5G telecommunication networks in IoHT.	5 Data analytics and computing technologies in IoHT.
IoT*	Security	IoHT	WBSN	Cloud Computing
Healthcare	Blockchain	ML	Energy Efficiency	Fog Computing
e-Health	Privacy	DL	5G	Edge Computing
Sensor	Authentication	COVID-19	QoS	Big Data
WSN	Healthcare System	AI	BDA	Data Mining
Smart City	Privacy-Preserving	Smart Healthcare	Energy Harvesting	CPS
RFID	Access Control	ECG	SDN	Cybersecurity
Health Monitoring	Encryption	ANN	Reliability	Data Analytics
mHealthcare	ECC	CNN	Healthcare 4.0	Clustering
Telemedicine	EHR	Classification	Wireless Communication	Sustainability

*IoT: Internet of Things/ WSN: Wireless Sensor Networks/ RFID: Radio Frequency Identification/ ECC: Elliptic Curve Cryptography/ EHR: Electronic Health Records/ IoHT: Internet of Healthcare Things/ ML: Machine Learning/ DL: Deep Learning/ AI: Artificial Intelligence/ ECG: Electrocardiographic/ ANN: Artificial Neural Networks/ CNN: Convolutional Neural Networks/ WBSN: Wireless Body Sensor Networks/ QoS: Quality of Service/ BDA: Big Data Analytics/ SDN: Software Defined Network/ CPS: Cyber Physical Systems.

self-management, and remote doctor follow-up, telemedicine and health sensors are crucial instruments [96]. The emergence of mHealthcare services has been made possible by recent developments in IoT and sensors. Multiple instruments facilitate the monitoring of patients as they are treated at a hospital. Additionally, once the patient is released from the hospital, they may be remotely monitored either via the use of wearable sensors or through the use of a smartphone outfitted with sensors to monitor various user-health data [97]. In this way, IoT, WSN, RFID, and other cutting-edge technologies enable e-health, telemedicine, and mHealthcare, which in turn partially leads to the idea of a "Smart City", in which ICT is integrated into an already-existing city's traditional infrastructure for the sake of better coordination and management [98].

The second cluster (green; right side) revolves around blockchain technology's applications in IoHT, specifically how it could promote security and privacy in IoT-based healthcare. Blockchain technology's applications go beyond just cryptocurrencies, and it has vast value-creation potentials in multiple domains, including healthcare [99]. Blockchain has the potential to address the issues of current healthcare systems that rely on centralized databases with bottlenecks in performance and single failure points [100–102]. According to [103], the use of asymmetric encryption, such as digitally signed transactions, hashing, and public key infrastructure, in blockchain supports the traceability of drugs, simplifies patient monitoring, and facilitates the storage and distribution of symmetrical patient information with the proper alliance of healthcare providers and hospitals in a safe and centralized manner. The third cluster (blue, upper part) focuses on the applications of AI techniques in IoT-based healthcare. Related frequent keywords in this cluster include "ML" (machine learning), "DL" (deep learning), "AI" (Artificial Intelligence), "ANN" (artificial neural networks), "CNN" (convolutional neural networks), and "Classification". ML and DL algorithms can be used to process huge volumes of IoT-healthcare data and develop accurate prediction models for the early detection of diseases [104,105]. Moreover, researchers have employed ANNs to recognize and categorize several sorts of human physical tasks and illness diagnosis systems [32], while CNNs have been suggested for medical image diagnosis [106] and detecting and classifying pathologies [107].

The fourth cluster (yellow, lower middle) focuses on the role of 5G telecommunication networks in supporting IoHT and fulfilling the requirements of WBSN in terms of bandwidth, latency, reliability, density, and energy efficiency. The full duplex transmission capability of 5G's device-to-device, multiple input/multiple output (MIMO), and millimeter wave (mmWave) communication technologies make it ideal for a wide range of healthcare applications, including remote surgical operations and connected ambulances. Coverage of smart healthcare facilities from the countryside to the city, from roadsides to train stations, and from rail to air (drones and air ambulance) is made possible by full duplex transmission [108]. Finally, the fifth cluster (purple; middle) focuses on the potential of data analytics and computing technologies in IoHT. According to Jagadeeswari et al. [109], big data analytics can be leveraged to cure epidemic diseases, predict diseases, prevent avoidable death, and enhance the quality of healthcare services. The high frequency of the keywords "Cloud Computing", "Fog Computing", and "Edge Computing" reveals the importance of cloud paradigms to sustain IoT implementations in healthcare. More specifically, the use of cloud computing can significantly aid in the control of healthcare integration expenses and the efficient use of available resources. Cloud computing can also satisfy IoT requirements in terms of storage, computation, and networking resources, thereby streamlining healthcare operations and improving patient experience. Furthermore, the emergence of fog computing provides an opportunity to satisfy healthcare IoT systems that demand low latency and a real-time response [110]. The integration of edge computing in healthcare systems has the potential to overcome processing and computational issues and facilitate low-latency data services by increasing the speed of computation and communication among IoT devices [111].

5.2. Co-citation network

Following suggestions from previous research [112], we settled on a threshold of five for both the number of citations and the number of co-citations. All disconnected nodes were removed from the network. This approach led to the formation of a co-citation network of 629 articles, leading to the removal of 2361 articles from the initial pool of 2990. The nodes of the network can be organized into different clusters, with nodes in the same cluster having a higher edge density than those in different ones [112]. Each cluster thus contains a set of closely related articles pertaining to IoT and healthcare, with only a relatively weak connection to articles belonging to other clusters (see Fig. 5). Clustering articles allows for the study of the network's structure, elucidating themes, connections, and patterns of collaboration.

The co-citation network was built with Gephi's built-in modularity tool, which is based on the Louvain algorithm. Through a series of iterations, this algorithm can find the optimal number of clusters that optimizes the modularity index [113]. The modularity index of a cluster is a number between −1 and 1, which represents the ratio of the number of connections inside the cluster to the number of connections to other clusters [114]. Applying this method yielded a set of seven distinct clusters. The modularity of the network is 0.811, reflecting significant connections between the seven clusters. As closely related articles have common characteristics and qualities, a cluster with a high co-citation relationship is indicative of a shared interest in a certain research field [115]. A deeper look at the articles inside a cluster exposes its major research interest. Due to the high number of articles in each cluster, we chose to analyze the contents of the top ten articles, which helped us to classify and map out research hotspots. The leading articles from each cluster are listed in Table 9 according to their impact, and the seven topics will be outlined in detail in the following sections.

5.2.1. Cluster 1: IoT for healthcare 4.0 systems

According to the classification of research topics presented in Table 9, IoT research in the healthcare sector emphasizes the role of the technology in supporting healthcare 4.0 systems. Healthcare 4.0 is characterized by the adoption of three major technological paradigms: IoT, cloud computing, and big data. These technologies change eHealth and its whole environment, much as Industry 4.0 is doing for the manufacturing sector. Several reviews have been conducted to analyze the potential of IoT for healthcare 4.0 systems. For example, Arora et al. [116] provide a thorough overview of emerging technologies as enablers for healthcare 4.0 systems, with a particular emphasis on IoT-based healthcare applications such as cloud computing, fog computing, big data analytics, and machine learning. The authors also cover topics such as network architecture, topology, platform, applications, and services for Wide Body Area Network (WBAN)-based IoT healthcare systems. They also discuss the vulnerabilities of healthcare IoT networks, the taxonomy of attacks, and the ways in which blockchain technology can be used to mitigate these issues. Similarly, Islam et al. [81] provide a comprehensive analysis of recent developments in IoT-based healthcare technology, including network architectures, platforms, and industry trends. Aspects of IoT privacy and security, attack taxonomies, and threat models are also examined. Zadtootaghaj et al. [153] aim to understand the benefits of IoT in healthcare and find that health effectiveness, empowerment, safety, privacy, and peace of mind are the critical criteria in IoT applications for patients. Firouzi et al. [174] discuss essential aspects of new IoT technologies for smart healthcare systems, body area sensors, pervasive healthcare systems and big data analytics. Interesting research concerns and difficulties are brought to light, including interoperability, scalability, security, and device-network-human interfaces. The combination of IoT and cloud paradigms to ensure high quality of service in healthcare is discussed in three studies. For instance, Asif-Ur-Rahman et al. [20] present a heterogeneous five-layer IoT system in healthcare based on mist, fog, and the cloud that can process and route data in both (near) real-time and offline or batch mode. Their simulation findings show that the developed network can achieve high quality of service through its multiple components, with decreased end-to-end latency and packet loss rate, which is crucial for creating next-generation electronic health systems. Farahani et al. [132] present a comprehensive architecture of IoT eHealth environment and discuss numerous potential applications of IoT in healthcare. To enable the management of complicated data in terms of speed, variety, and latency, the patient-centric IoT requires a multi-layer architecture consisting of a device, fog computing, and the cloud. Porambage

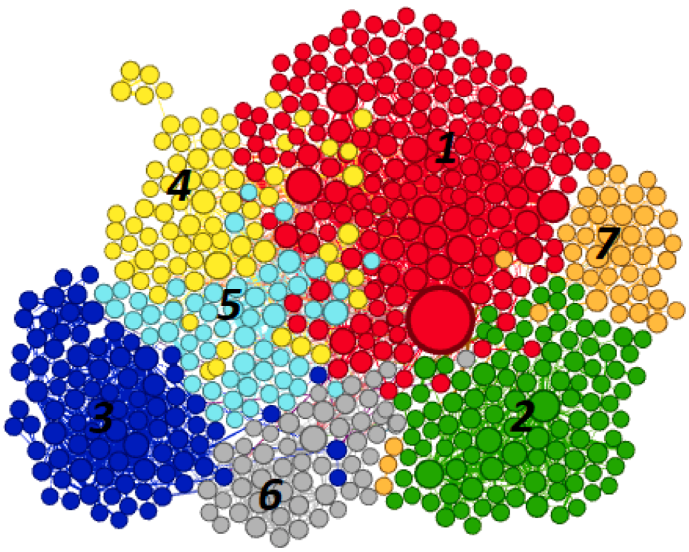

Fig. 5. Co-citation network.

Table 9
Most relevant articles in each cluster.

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
Arora et al. (2022) [116]	Adere (2022) [117]	Wazid et al. (2019) [118]	De Moura Costa et al. (2020) [119]	Bhatia and Sood (2017) [120]	Amin and Hossain (2021) [121]	Yang et al. (2018) [122]
Asif-Ur-Rahman et al. (2019) [20]	Khezr et al. (2019) [123]	Wu et al. (2018) [124]	Mutlag et al. (2019) [110]	Verma and Sood (2018) [125]	Amin et al. (2019) [126]	Li et al. (2019) [127]
Islam et al. (2015) [81]	Mohammad Hossein et al. (2021) [100]	Park et al. (2020) [128]	Minh Dang et al. (2019) [78]	Bhatia and Sood (2019) [129]	Sharma et al. (2021) [130]	Guo et al. (2021) [131]
Farahani et al. (2018) [132]	Siyal et al. (2019) [133]	Deebak et al. (2019) [134]	Feng et al. (2020) [135]	Asghari et al. (2019) [136]	Kamruzzaman et al. (2022) [137]	Zheng et al. (2018) [138]
Desingh and Baskaran (2022) [139]	Khatoon (2020) [140]	Fotouhi et al. (2020) [141]	Shukla et al. (2019) [142]	Lakshmanaprabu et al. (2019) [143]	Muhammad and Alhussein (2021) [144]	Liu et al. (2018) [145]
Sarrab and Alshohoumi (2020) [146]	Zhu et al. (2019) [147]	Alzahrani et al. (2020) [148]	Kishor et al. (2021) [149]	Verma et al. (2018) [150]	Greco et al. (2020) [151]	Qin et al. (2017) [152]
Zadtootaghaj et al. (2019) [153]	Farouk et al. (2020) [154]	Banerjee et al. (2019) [155]	Yang et al. (2014) [156]	Ahanger (2022) [157]	Masud et al. (2021) [158]	Chen et al. (2020) [159]
Khan et al. (2021) [160]	Zubaydi et al. (2019) [161]	Saeed et al. (2018) [162]	Tuli et al. (2020) [163]	Arulanthu and Perumal (2020) [164]	Rahman and Hossain (2021) [165]	Guo et al. (2020) [166]
Porambage et al. (2018) [167]	Moin et al. (2019) [168]	Banerjee et al. (2019)[169]	Nguyen Gia et al. (2019) [170]	Vijayakumar et al. (2019) [171]	Jaiswal et al. (2021) [172]	Deng et al. (2017) [173]
Firouzi et al. (2018) [174]	Ali Syed et al. (2019) [175]	Alsahlani and Popa (2021) [176]	Yin et al. (2016) [22]	Kumar et al. (2018) [177]	Alshammari et al. (2022) [178]	Imtyaz Ahmed and Kannan (2021) [179]

et al. [167] review the use of multi-access edge computing (MEC) technology in the development of IoT applications in healthcare. The integration of these technologies is expected to bring cloud computing capabilities to the edge of the radio access network, thereby offering high-bandwidth, real-time, and low-latency access to network resources. Finally, two articles address the barriers to IoT adoption in healthcare. Desingh and Baskaran [139] determine and examine the factors preventing the healthcare sector from fully embracing IoT. According to their findings, the lack of adequate IT infrastructure and compliance with legal and regulatory norms are the two most significant factors hampering the widespread use of IoT in the healthcare supply chain. Finally, Sarrab and Alshohoumi [146] explore IoT data privacy concerns in healthcare and offer a comprehensive scenario of the flow of IoT data.

5.2.2. Cluster 2: blockchain technology

The second cluster mainly focuses on the integration of blockchain technology in healthcare. The medical sector has already recognized blockchain as a versatile tool with far-reaching possibilities. Health organizations embarking on the technology can ensure efficient healthcare interoperability and support patient-centered health research and the early detection and prevention of counterfeit drugs. In situations where privacy and security provide extra difficulties for the healthcare system, blockchain can help to improve the precision of medical diagnoses. As blockchain, IoT, and healthcare continue to converge, review studies in this cluster emerge. For example, Adere [117] examines current developments and advantages that blockchain implementation can bring and finds that it is mostly used for data management tasks in IoT-based healthcareand especially to increase data security. Khezr et al. [123] review a wide range of blockchain applications in healthcare, highlighting both current and potential study areas. The combination of blockchain and IoT has the potential to empower patients, optimize sharing processes of health data, strengthen information, and enhance patients' control over health data. Siyal et al. [133] summarize the existing trends and introduce blockchain as a tool to promote authentic, personalized, and secure healthcare services. Farouk et al. [154] explore how the fusion of blockchain and IoT can enhance information security management, improve processing efficiency, and contribute to better diagnosis privacy, accuracy, and security. Zubaydi et al. [161] review the latest trends in blockchain applications for healthcare and argue that the technology can support IoT devices to obtain health information by reducing energy consumption and responding to sensing devices' needs. Besides reviews, two studies develop blockchain-based healthcare systems to ensure healthcare data security and privacy. Mohammad Hossein et al. [100] address the trade-off between access control and transparency by proposing a healthcare architecture based on blockchain that allows data owners to specify their preferred access controls pertaining to confidential healthcare data. The detailed experimental investigation of the proposed system confirms the efficiency of blockchain in terms of processing time and its resistance against different types of security attacks. Finally, Khatoon [140] presents a variety of healthcare workflows that can benefit from blockchain's improved capacity for managing data. The Ethereum blockchain platform has been used to develop and execute a number of medical workflows, some of which entail very sophisticated healthcare operations, including clinical trials and surgical procedures.

5.2.3. Cluster 3: authentication schemes

Insecure digital credentials are a major contributor to users' mistrust in online data transmission. Given that IoT devices can be placed in open, unattended settings, secure authentication is critical for IoT systems to prevent attacks. In this regard, the third cluster refers to the research perspective focused on authentication schemes. For example, Wazid et al. [118] outline network and threat models of authentication techniques for cloud-driven IoT-enabled big data environments. The security needs, problems, and obstacles unique to this setting are also discussed. Wu et al. [124] attempt to overcome the security flaws in wireless medical sensor networks (WMSNs) by proposing a lightweight and robust authentication mechanism which not only satisfies the standard security requirements but also prevents attackers from tracking users. Similarly, Park et al. [128] introduce a provably lightweight and secure mutual authentication and key agreement (MAKA) scheme for medical IoT to guarantee secure communication and preserve user privacy. Fotouhi et al. [141] present a novel lightweight hash-chain-based and forward-safe authentication mechanism to secure wireless body area networks in IoT-based healthcare systems, thus allowing trusted users such as clinical personnel and doctors to access patient sensor data. Saeed et al. [162] propose a lightweight online/offline certificateless signature and a heterogeneous remote anonymous authentication protocol to allow users of remote wireless body area networks to confidentially acquire medical services based on IoT applications. The suggested authentication scheme reduces consumption overhead (i.e., the amount of power and resources needed by IoT devices to perform their intended function) and smaller power consumption on wireless body area networks as compared to current, comparable schemes. Given the sensitive nature of medical information, anonymity-based user authentication protocols are needed to address privacy protection issues in the healthcare sector. In this context, Deebak et al. [134] develop a secure and anonymous biometric-based user authentication scheme for use in healthcare settings to protect sensitive data transmissions. Through the use of this scheme, malicious actors are not able to stealthily access or cancel a smart handheld card by posing as a genuine user. Banerjee et al. [155] present a novel lightweight anonymous and user-authenticated session key agreements scheme in IoT based on three-factor authentication: a user's smart card, password, and biometric information. Finally, cloud-IoT-based technological advances have reshaped the monitoring of remote patients and the operations of healthcare facilities. To authenticate cloud-IoT systems, Alzahrani et al. [148] develop a robust authentication scheme for remote patient health monitoring to address the vulnerabilities to attacks using stolen smart cards, compromised session keys, and user impersonation. Alsahlani and Popa [176] introduce a new practical, lightweight authentication and authorization protocol for real-time data access in an IoT cloud-based healthcare environment to mitigate the security risks associated with acquiring and exchanging sensitive health information through a public, unsecured channel. Overall, authentication represents a foundational security measure in IoT research that can prevent several attacks, including sensor and user impersonation as well as man-in-the-middle, reply, and traceability attacks.

5.2.4. Cluster 4: fog computing

The fourth cluster includes articles that mainly focus on the adoption of fog computing in IoT-based healthcare systems. As an expansion of cloud computing, fog computing has been applied in several domains [180], and fog nodes are mainly used to facilitate peer-to-peer payment in content delivery networks. Devices in the fog can perform computations, store data, and connect to other devices. Nodes in the fog can also handle raw data from sensors, share information with other fog devices in the same layer or at higher levels, or carry out data processing activities receiving input from other layers. In a fog computing environment, the processing intelligence is situated in the local area network. Generally, an integrated cloud-fog-based architecture emerges as the result of designing an IoT architecture on both cloud computing and fog computing. These IoT-based architectures have been recently suggested in various domains, including healthcare. According to de Moura Costa et al. [119], fog computing can boost the efficacy and quality of medical treatments, which in turn may enhance patients' health and optimize use of public funds. As such, fog computing can help to gather, analyze, and maintain information locally, enabling real-time analysis as the technology can bring storage and processing capability closer to the end devices. Due to the large volume of data produced by health sensors, the quality of real-time analysis can be enhanced, allowing for better information and improved decisions to be made in real time based on network capacity and local policies. In their study, Mutlag et al. [110] conduct a systematic review of fog computing technologies used in IoT-based healthcare systems and conclude that fog computing is ideal for healthcare applications because they necessitate low-latency, real-time, and high response time. To showcase a superior fog infrastructure, the authors agree that resource sharing results in lower latency, more scalability, increased security, distributed processing, increased privacy, and improved fault tolerance. Moreover, Feng et al. [135] present a fog-based IoT healthcare architecture to reduce the load on the fog edges' power supply. Their experimental findings demonstrate the effectiveness of the suggested framework in minimizing both network latency and power consumption, thereby supporting the services available in fog devices for healthcare big data analytics. Shukla et al. [142] propose a fog computing-based analytical model to reduce the significant lag time experienced by healthcare IoTs, cloud servers, and end-users. With the involvement of fog nodes and servers, as well as the master fog controller, users and patients can connect with fog nodes in a single hop count. Kishor et al. [149] attempt to minimize latency in healthcare systems via the integration of fog computing, IoT, and machine learning. Based on their simulation findings, the proposed model is able to increase the quality of healthcare services and reduce the computation delay to respond to the high need for healthcare multimedia analytics. Fog computing has also gained popularity in applications that can outperform physicians in diagnosing cardiac problems. For example, Tuli et al. [163] present HealthFog, an innovative framework for leveraging deep learning in edge computing devices and use it in a practical setting to automatically analyze cases of heart disease. Using IoT, HealthFog provides healthcare as a fog service, effectively managing the data of cardiac patients. Likewise, Nguyen Gia et al. [170] suggest a fog-based system to simplify remote health monitoring and fall detection. Real-time monitoring of e-health signals (e.g., body temperature, glucose) and environmental factors (e.g., humidity, room temperature, air quality) is made possible via the system. Overall, the effective processing of medical data from a variety of IoT devices represents a key use case of fog computing. This paradigm can process healthcare data at fog nodes or edge devices with high computing capacity, reducing latency and lag times thanks to their proximity to an IoT equipment.

5.2.5. Cluster 5: cloud-IoT integration for disease prediction and diagnosis

In the fifth cluster, the theme revolves around the integration of cloud computing and IoT for disease prediction and diagnosis. Combining these technologies helps to provide a robust infrastructure for remote patient monitoring, allowing medical professionals continuous access to vital data. In this context, IoT relies on the almost limitless resources and capabilities of the cloud, including data processing, energy, and storage. In contrast, IoT can be useful to the cloud since it broadens the cloud's ability to handle physical objects and increase its capacity to distribute and adapt many new services. The integration of IoT and cloud can be expanded to support disease prediction and diagnosis. For example, Bhatia and Sood [120] combine these technologies to develop a comprehensive health vulnerability model for evaluating real-time monitoring during exercise. During workouts, IoT is used to collect data regarding a variety of variables. The captured data values are sent safely to the associated cloud service, where they can be analyzed in detail. Similarly, Verma and Sood [125] present a cloud-based IoT healthcare monitoring illness diagnosing framework that can foresee the presence and severity of a given disease. The suggested system reveals the importance of scale, patterns, and frequencies in diagnosing a patient's possible disease type. Asghari et al. [136] propose a medical monitoring scheme for a cloud-based IoT system whereby patients' medical states are determined by mining their physiological data gathered from IoT sensors and other medical records to predict diseases. The patients' medical records are analyzed using a disease diagnostic model with the goal of providing an optimized medical prescription. Their experimental findings demonstrate the efficacy of the suggested approach in accurately diagnosing ailments and providing comprehensive health and medical recommendations. Arulanthu and Perumal [164] develop an online medical decision support system for predicting chronic kidney disease as a means of providing better medical care. Collecting, preprocessing, and classifying medical data are all steps in their approach to predicting chronic kidney diseases. Vijayakumar et al. [171] describe an intelligent system based on cloud and IoT for distinguishing mosquito-borne diseases and diagnosing the user's susceptibility to them. Finally, Kumar et al. [177] propose a novel IoT and cloud mobile healthcare application for monitoring and detecting serious illnesses and demonstrate the superiority of the suggested system as compared to existing disease prediction systems.

5.2.6. Cluster 6: cognitive smart healthcare

The sixth cluster focuses on the role of IoT in supporting the development of cognitive smart healthcare. The use of IoT in healthcare helps to monitor, manage, and store medical information for continuing treatment by combining communication technologies, sensors and devices, networked applications, and people into a single smart system. According to Amin and Hossain [121], smart healthcare frameworks based on IoT are evolving from basic systems applied for data capture, preprocessing, transfer, and analysis into complex and intelligent systems that have the ability to perform remote data analytics and intensive processing, as well as make evidence-based decisions. Due to the complexity of these models, AI techniques can be adopted to maximize computational capabilities while minimizing resource overhead. For instance, machine learning and deep learning models on local edge nodes, which are physically adjacent to the devices that are collecting data, can be used for purposes such as illness diagnosis, fall detection and prevention, and therapy. As a result, real-time execution is made possible with shorter data transmission times and fewer resources needed. To develop a cognitive healthcare framework, Amin et al. [126] integrate IoT, cloud technologies, smart sensors, and deep learning with the goal of facilitating communication and intelligent decision-making. The smart and cognitive architecture is also expected to continuously monitor the state of patients and promptly deliver high-quality medical treatment at low costs. In the COVID-19 context, Sharma et al. [130] introduce a system for remote monitoring of local cohorts by providing updated information about patients infected by COVID-19. To identify the virus in its earliest stages, the suggested model relies on an IoT-based remote access and alarm-enabled bio-wearable sensor system that can process sensory 1D biomedical signals, including temperature and accelerometer data. Rahman and Hossain [165] build an edge IoT medical system that uses deep learning to identify a wide variety of COVID-19-related health symptoms and uses that information to provide reports and warnings for use in medical decision support. In the same vein, Alshammari et al. [178] assess the efficacy of cutting-edge technologies such as IoT, deep learning, and 5G telecommunications in limiting the spread of COVID-19 and guaranteeing public health. In sum, smart and cognitive healthcare, which is based on new technologies rather than outdated approaches, is rapidly replacing traditional medical systems and helping to detect infections, curb virus transmissions, and encourage the development of new vaccines and innovative medical treatments.

5.2.7. Cluster 7: security and privacy in smart healthcare

The final cluster addresses security and privacy concerns in smart healthcare systems. For example, Yang et al. [122] develop a privacy-aware smart health access control system to overcome the limitations of existing encryption solutions, including the leakage of sensitive health-related information. Li et al. [127] introduce a secure and efficient multi-authority access control system for IoT-based healthcare systems to ensure data security and efficient access to personal health records. In the same vein, Guo et al. [131] propose a method for overcoming several challenges healthcare faces (e.g., eavesdropping, privacy violation, unauthorised access) by using cloud servers and blockchains as part of the IoT medical ecosystem to implement an attribute-based encryption scheme that can function both online and offline. Features such as outsourced decryption, rapid encryption, ciphertext verification, and user verification are all attained by the suggested solution. Zheng et al. [138] present a practical method for exchanging medical records that employ attribute-based encryption to meet privacy concerns and facilitate data sharing. Liu et al. [145] develop a fine-grained electronic health records (EHR) access control system that is safe and effective in allowing an EHR owner to construct ciphertexts without knowledge of EHR data and access regulations. Similarly, Qin et al. [152] propose a new attribute-based encryption system with verified decryption outsourcing and revocable user access to secure information sharing among patients and medical experts. Chen et al. [159] attempt to increase patients' data privacy by suggesting a new scheme based on directed graph and ciphertext-policy hierarchical attribute-based encryption. Finally, Guo et al. [166] offer a ciphertext-policy decryptable attribute-based keyword search technique that operates over a secure channel. The cyphertext can only be decrypted by authorized users who meet the schemes' access requirements. Overall, the studies in the last cluster focus on the development of encryption mechanisms to protect the security and privacy of medical data in IoT-based healthcare environments.

6. Conclusions, implications and future research, limitations

6.1. Discussion of findings

The emergence of IoT presents unprecedented opportunities for the healthcare sector [49,181,182]. IoT devices already have a profound impact on healthcare services by empowering patients with capabilities such as self-monitoring and remote monitoring. Patients can use IoT to adjust their plans and potential safety measures based on their current health state. Patient satisfaction and engagement have increased as a result of IoT applications in healthcare, and communication between physicians and patients has been simplified. A patient's length of hospitalization and overall healthcare spending can be reduced by using remote healthcare monitoring systems. Additionally, IoT can decrease the number of patients needing readmission after finishing their course of therapy. By increasing the number of devices and the quality of interactions between individuals, IoT ensures more personalized monitoring goals. With the support of the technology, users can track and manage a wide range of data, for example, daily calorie intake, activity status, appointment reminders, and blood pressure fluctuations.

Due to the rise of the literature on IoT and healthcare and a paucity of systematic and thorough analyses of this topic, it is imperative to map the present status of existing knowledge. Therefore, this research was driven by the need to chart the development of this area of study and shed light on its underlying intellectual structure by mapping and visualizing the scope and structure of research at the confluence of IoT and healthcare. Using bibliometrics, we studied 2990 documents drawn from the Scopus database over nearly a twelve-year period. By applying multiple bibliometric techniques, we were able to achieve unbiased findings. As Linnenluecke et al. [183](p.2) point out, this is contrary to subjective and biased techniques where "an arbitrary selection of evidence is often not fully representative of the state of the existing knowledge, and the selection of some studies over others ultimately leads to what is known in statistic analysis as a sample selection bias."

To overcome the limitations of traditional methodological approaches, which often overlook the relationships and dynamics between scholars, publications, and journals, we provide a holistic landscape of IoT research in the healthcare context using ideas and tools from systematic network analysis. Chen and Leydesdorff [184] argue that this kind of connection is fundamental to fully understand the conceptual underpinnings and historical development of knowledge in a specific scientific area. To the best of our knowledge, this paper is the first to perform a comprehensive bibliometric analysis of IoT and healthcare by analyzing all scholarly publications on the topic that have been indexed in Scopus since 2011. The sheer number of articles allowed for the identification of the leading scholars, key journals, and main trends and themes within this multidisciplinary research field.

This research yields many significant insights. To begin, there has been a sharp uptick in the number of articles since 2017, and this trend will likely continue in the foreseeable future. Based on the distribution of the publications across academic journals, we showed that the majority of the articles were published in computer science journals such as IEEE Access, IEEE Internet of Things Journal, and Sensors. This highlights the important role which these influential journals play in expanding IoT research and establishing it as a solid tradition in the healthcare sector. When ranked by output, the most prolific researchers were Kumar, N. and Rodrigues, JJPC. Regarding institutional contributions, King Saud University is the most productive academic organization making the most contributions to the scientific community. Interestingly, the majority of prolific universities were located in developing nations. In terms of countries' contributions, we showed that the majority of contributions came from Asian countries, such as China, India, Saudi Arabia, and Pakistan. Meanwhile, the United Kingdom and Italy stand out in Europe. Finally, our analysis of the main content reveals five research clusters based on keyword co-occurrence and seven based on co-citation networks.

6.2. Limitations

This review study has several shortcomings that need to be taken into account. Importantly, the data came from a single source, namely the Scopus database. Therefore, future research may use other datasets to verify the accuracy of our results. Moreover, we were selective and only looked at papers that were originally published in English. Since this may limit the study's overall coverage and applicability, future research should take into account publications in other languages. Third, there is a chance that relevant works were overlooked because of the study's search terms. To remedy this limitation, researchers may seek to broaden their search terms and include other terms associated with IoT and healthcare. Additional review studies based on other bibliometric approaches, such as main path analysis and topic modeling, are recommended.

6.3. Implications and future research directions

In order to help academics better comprehend IoT's role in healthcare, the primary content of IoT research was determined by analyzing the frequency with which certain keywords appeared in the reviewed literature. Using a bibliometric approach, we were able to obtain a thorough understanding of the potential of IoT for the development of personalized, smart, and efficient healthcare systems. In recent years, scholars have increasingly focused on cutting-edge technologies such as cloud computing, blockchain, AI, and wireless body sensor networks. The integration of these technologies with IoT has the potential to offer accurate diagnoses and treatment recommendations, collect a wide range of physiological data about patients, and reduce healthcare expenditures. This review provides a selection of the most prominent publications in the relevant literature for academics to gain a deeper knowledge of

IoT applications in healthcare. Recognizing the pioneering works and their authors can spark new directions and inspire research teams to collaborate on future research projects and improve the quality of their outputs. Furthermore, the keyword co-occurrence network analysis uncovers the core themes and topics explored in IoT research within healthcare. In the same way, it aids in unearthing the key substance of IoT studies.

The primary topics of this study include the enabling role of IoT in supporting e-health, health monitoring, and telemedicine, thereby accelerating the transition toward the smart city. Accordingly, future research is required to understand how IoT aspects are presently integrated with e-health and telemedicine and architecture [185]. Future studies also need to study the possibilities of IoT-based healthcare by theorizing how IoT can make preventive public medical services more widely available and transform existing secondary and tertiary healthcare into a more continuous, proactive, and integrated system. The literature is also strikingly silent on the potential problems that IoT-based healthcare brings, including barriers to wide-scale implementation from the perspective of patients and healthcare professionals, security, and privacy, trust and acceptance, interoperability, data storage, and ownership and control. Policy support, cybersecurity-focused standards, rigorous strategic planning, and clear rules within healthcare providers will all be necessary to facilitate the incorporation of IoT in current healthcare systems.

Moreover, blockchain technology has been identified as a recent solution that can support IoT implementation in healthcare by guaranteeing the transparency and security of patients' records, facilitating drug traceability, and increasing data-sharing efficiency. Future studies evaluating the combination of blockchain and IoT in a testable system are required to provide some real-world security assurances. The development of digital signatures that are immune to the effects of quantum computing is necessary to reduce cyber-attacks and secure IoT-based healthcare systems. Healthcare expenses can be reduced since patients can be reimbursed in tokens. In order for blockchain and IoT to be widely adopted, tokenization must first take place [186]. Similarly, future research needs to clarify how healthcare organizations can revamp their internal procedures, improve blockchain throughput, and design effective consensus protocols that meet the requirements of blockchain and IoT solutions in healthcare. Due to the extensive structure, medical sensor readings can be linked, and the body area network, the collaborative nature, connectivity of IoT, and collaboration are all necessary conditions for the development of data-centric consensus algorithms. The keyword co-occurrence network also reveals the importance of AI techniques, 5G telecommunications, data analytics, and computing technologies in supporting IoT-based healthcare. As a result, future studies should investigate IoT and AI convergence techniques to develop accurate diagnosis models for diseases. Researchers need to explore the potential of 5G for IoT-based healthcare in a variety of contexts and from different perspectives, including scheduling, machine learning, handover, routing, and clustering. Also, future studies should develop IoT solutions that ensure the integrity and veracity of patient information by providing safe and simple connections between smart medical equipment and cloud databases. Finally, the results of our co-citation network uncover important future research areas, including authentication schemes for IoT security in healthcare, the role of fog computing in IoT systems, and the emergence of cognitive smart healthcare.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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