Online-Journals.org

iJOE International Journal of Online and Biomedical Engineering

iJOE | eISSN: 2626-8493 | Vol. 20 No. 4 (2024) | OPEN ACCESS

https://doi.org/10.3991/ijoe.v20i04.46559

PAPER

Analyzing Emerging Trends in Wireless Implantable Medical Devices (IMDs): A Bibliometric Study

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ABSTRACT

In the present era of advanced medical technology, there has been a significant increase in the utilization of wireless-based implantable medical devices (IMDs) in various biomedical applications, including health diagnosis, monitoring, recording, treatment, and other clinical concerns. It is essential to closely examine the research trends in wireless IMD topics to understand their growth trajectory. This can be achieved through the utilization of bibliometric reviews. While there are numerous experimental studies and survey papers on the topic, there is a dearth of review papers that utilize a bibliometric approach. Therefore, this study aims to conduct a bibliometric analysis to identify emerging research trends in wireless IMDs for biomedical applications for the first time. An analysis was conducted on 1,650 articles retrieved from the Scopus database from its inception until September 2023. The study used tools such as VOS Viewer to measure performance and science map parameters, and Tableau Cloud to visually enhance the analysis process. This research endeavor allowed us to analyze historical trends, influential papers, top journals, institutions, countries, and authors within this field. The top three influential journals in this field are *IEEE Transactions on Biomedical Circuits and Systems*, *IEEE Transactions on Antenna and Propagation*, and *IEEE access*. The National University of Singapore is the most productive institution in terms of overall publications. The United States, China, and India make significant contributions to overall publications. Finally, we also examined the most significant keywords and current research areas within this field.

KEYWORDS

implantable medical devices (IMDs), bibliometrics, biomedical application, wireless, VOS Viewer, Tableau Cloud

1 INTRODUCTION

The use of information and communication technology in healthcare services has significantly increased in recent years due to its numerous benefits. Smart health has emerged as a pivotal domain in the advancement of sixth-generation (6G) technology [1], [2]. In this context, one indicator is the use of biomedical devices inside

Fuada, S., Särestöniemi, M., Katz, M. (2024). Analyzing Emerging Trends in Wireless Implantable Medical Devices (IMDs): A Bibliometric Study. *International Journal of Online and Biomedical Engineering (iJOE)*, 20(4), pp. 115–143. https://doi.org/10.3991/ijoe.v20i04.46559

Article submitted 2023-11-07. Revision uploaded 2023-12-17. Final acceptance 2023-12-17.

the body, such as implants, which are increasingly utilized in the medical field [3], [4]. The increasing interest in understanding bodily functions and continuous physiological monitoring has made medical implants a crucial aspect of healthcare. By integrating wireless sensor networks into these implants, it becomes feasible to monitor in real time, thereby enhancing the effectiveness and efficiency of biomedical diagnosis and treatment [5–7]. Medical implants can be either deeply inserted into the human body [8] or placed on its surface (under the skin) [9], [10]. Various implant modalities, such as cochlear implants, insulin pumps, retinal implants, brain implants, drug pumps, pacemakers, cardioverter-defibrillators, and neuro-stimulators, are widely used and well-established in clinical practices [11]. These implants have the ability to transmit vital physiological signals and store confidential medical data. Furthermore, the advancement of in-body sensors and smart pills has facilitated the monitoring of physiological parameters, drug distribution, and imaging purposes. The wireless communication systems standard used in healthcare, such as medical implantable communication systems (MICS), rely on existing radio technology [12].

The emergence of 6G wireless communication presents significant opportunities and enables innovative applications across different domains [2]. One notable example of telecommunications technology in the healthcare industry is the concept of wireless body area networks (WBANs). This involves a networked sensor placed inside or outside the patient's body to collect, analyze, and transmit physiological data. Recently, the concept of the Internet of Things (IoT) has been expanded to include cutting-edge healthcare technology, incorporating networks both inside and outside the human body, with the aim of delivering healthcare services [8]. Most contemporary implantable sensors depend on different types of wireless communication to transmit measurements to an external output device, thereby enabling subsequent data processing and analysis [13]. Research focusing on improving wireless implantable medical devices (IMDs) has become highly promising due to advancements in supporting technologies such as microfabrication techniques and biotechnology. These advancements have led to the development of various state-of-the-art implantable medical devices that offer several benefits, including improved diagnosis and treatment [14].

Assessing the research on wireless IMDs is of great significance, as it enables researchers to stay updated on previous advancements in biomedical implant technologies. It also helps identify areas of knowledge that require further exploration (gaps) and potential contributions. This assessment is of the utmost importance for tracking progress in the research field and identifying suitable sources for publication. The review papers cover various perspectives, such as energy harvesting [14–16], in-body antennas [17], wireless power transfer (WPT) techniques [18], wireless communications technologies [13], biosensors [9], and ultra-wideband (UWB) applications for implantable devices [19]. For example, Shuvo et al. [16] conducted a review of energy harvesting technologies for developing implantable medical devices. They evaluated these technologies based on their efficiency, reliability, durability, and capacity to function without a battery. Similarly, Shi et al. [15] classified and summarized the recent types of in vivo energy harvesting devices implanted in living organisms. The devices were examined with regard to their manufacturing techniques, energy output, power management, durability, animal experiments, evaluation criteria, and general applications. They also emphasized future challenges and perspectives. Roy et al. [14] conducted a comprehensive review of energy harvesting, focusing on the challenges associated with current technologies. They discussed the latest advanced solutions used in current research, focusing on energy storage technology, various wireless power transfer techniques that integrate energy sources with external or internal sensors, and power management of implanted medical devices. They also compared the pros and cons of these

proposed solutions. Nelson et al. [13] conducted a brief review of wireless technologies available for use in implantable medical devices, outlining their respective advantages and disadvantages. Nithiyanandham and Sampath [18] reviewed recent methodologies and techniques for efficient WPT in implantable devices. Culjak [19] reviewed the most recent studies and advancements in the application of UWB technology for wireless body sensor communication systems. Aliqab et al. [17] evaluated different antenna design innovations and challenges for use in biomedical implants. This included an overview of design specifications, implementation methods, simulation software, and testing of biomedical antennas within the body. However, the current review papers on wireless IMDs are narrative in nature, lacking a systematic analysis, which hinders the ability to present research hotspots and trends.

Research hotspots and trends can be identified using a bibliometric approach [20]. Bibliometrics, also known as statistical document analysis, involves using specific methods to analyze relevant documents containing strategic intelligence. Its aim is to illustrate and explain the patterns exhibited by the data within these documents [21], [22]. By using bibliometric analysis, we can identify research hotspots and trends in scientific advancements across various fields of study [23]. The use of bibliometric analysis reviews will help practitioners and researchers effectively review articles relevant to their research areas and evaluate the productivity of authors, institutions, and even countries [24]. Researchers can utilize various bibliographic databases to conduct bibliometric analysis, such as Web of Science (WOS), Scopus, Google Scholar, Microsoft Academic, and Dimensions [25]. WOS and Scopus are the most commonly used databases for bibliometric analysis because they provide access to a wide range of documents [20].

This study aims to investigate the research conducted on wireless IMDs from their inception to 2023 using bibliometric analysis for the first time. This paper offers a comprehensive overview of the current state of research on this topic worldwide, emphasizing research trends and their impact, as well as the authors, journals, countries of origin, and institutions involved. Additionally, it identifies research hotspots and suggests potential areas for future investigation through keyword analysis using VOS Viewer. This study primarily examines the publications indexed in Scopus. The following section provides detailed information about the data and methodology used in this study. It also includes an analysis of research trends, influential authors, articles, journals, countries, and research institutions in the field of wireless IMD research. The research also discusses the open areas that require further investigation.

This study offers benefits to various parties, including junior and senior researchers, industry professionals, and funding organizations and agencies. The following points provide a description:

a) For junior researchers, it helps them identify the most relevant literature, authors, journals, and emerging topics in their respective scientific fields. It helps to gain a deeper understanding of the most relevant and methodologically robust subjects identified.
b) For senior researchers, it consolidates current knowledge, provides scientific support for areas requiring further research, and reveals ongoing collaborative networks within this field of study.
c) For industry professionals, this helps them recognize the most relevant advancements, current topics of interest, and potential opportunities in the future.
d) For funding organizations and policymakers, this study is significant as it can assist in making well-informed decisions about allocating funds for research projects by assessing their relevance within the specific discipline.

Upon reviewing the novel, the findings of this study offer a deeper understanding of typical research on wireless IMDs and valuable guidance for future investigations. The remainder of the article is organized as follows: Section II provides a detailed explanation of the methodology and data collection methods used in this study; Section III presents the research findings; Section IV elaborates on future studies; and lastly, Section V provides a concise summary of the paper and suggests potential directions for future research derived from the results of this study.

Our study aligns with the investigation conducted by Jiang et al. [26], as it also utilizes a bibliometric approach to analyze the advancement of future implants using the WOS database. While Jiang's study focuses exclusively on energy harvesting for in-body devices, our study takes a broader perspective on technology for wireless implants. We will conduct a comprehensive review that includes a discussion on energy harvesting at a high level. Similar to the study by [26], in previous research [27], we conducted bibliometric analysis on the subject of energy harvesting for IMDs using a different database, namely Scopus. In this study, our analysis will focus on the discussion of energy-efficient equipment design, in-body antennas, and energy transfer (energy harvesting) in the research area of wireless IMDs. These topics were clustered by VOS Viewer using specific keywords (Section IV).

2 METHODS

Bibliometric analysis is a well-regarded quantitative methodology that enables researchers to identify patterns within specific research areas of study [28]. This approach is highly valuable as it enhances our understanding of the evolving nature of these topics and the advancements being made within them [29]. Through bibliometric analysis, researchers can convert a large volume of literature into visually engaging information, offering valuable insights and predictions about these trends. This visual representation encourages researchers and readers to consider a variety of perspectives and make well-informed decisions based on the explanations provided. The research procedure for this study, as illustrated in Figure 1, comprises four stages: defining search criteria, gathering and selecting data, conducting analysis and review, and drawing conclusions from the primary findings. Each stage will be thoroughly explained in the following subsection.

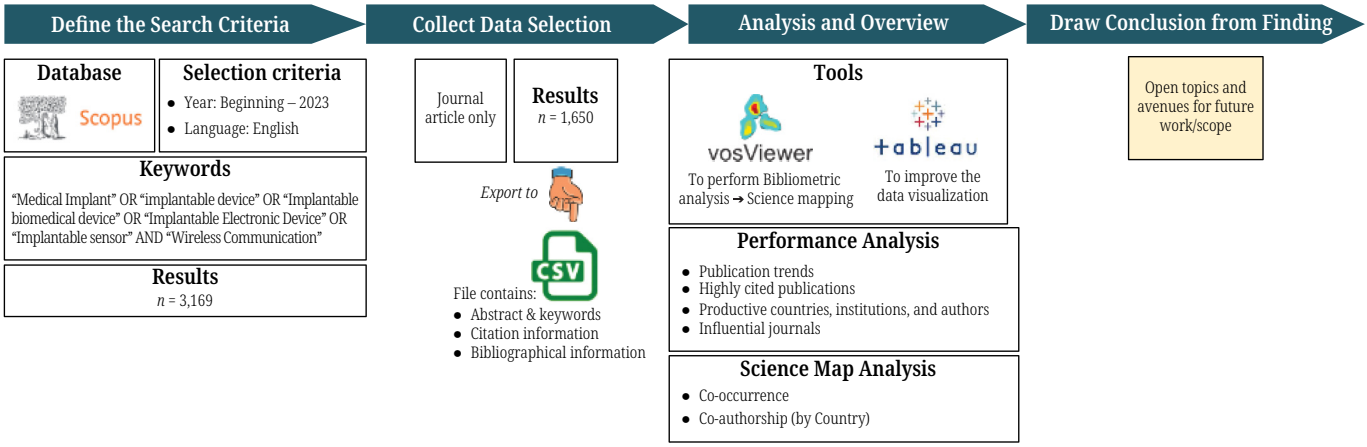


Fig. 1. Research trends and its citations on EH for IMDs research

2.1 Define the search criteria

The first step involves determining the search criteria by gathering relevant literature from various sources, such as WOS, PubMed, Dimension, Google Scholar, and Scopus. However, this study specifically focuses on the global publication data related to wireless IMDs obtained from the Scopus database. The choice of this database is based on its reputation for providing high-quality literature [30–34] and its widespread usage among researchers for bibliometric analysis. The University of Oulu has generously provided us with full access to the Scopus database through the campus intranet network. The search process involves using different keywords and search methods (such as truncation, phrase searching, operators, and order of precedence) until satisfactory results are achieved. The search string used in the Scopus Explorer for the queries is provided below:

> *"Medical Implant" OR "implantable device" OR "Implantable biomedical device" OR "Implantable Electronic Device" OR "Implantable sensor" AND "Wireless Communication."*

Afterward, it is crucial to conduct the search and record the data within a single day to minimize potential bias resulting from daily updates in the database. The publication or indexing of the relevant paper may have occurred on a different day, which could potentially impact the previously obtained data. To ensure the credibility and impartiality of our study, all necessary searches were conducted on a single day, specifically on September 12, 2023. The research period for this study spans from the beginning of the year 2001 until September 2023.

By using these keywords, a total of 3,169 documents were identified and categorized as journal articles (1,668 documents), proceedings (926 documents), reviews (362 documents), book chapters (159 documents), and others (54 documents). In terms of language, the majority of the documents were in English (3,131 documents), with a smaller number in Chinese (20 documents), Turkish (10 documents), and other languages. The data analysis, including visualization, can be conducted the following day.

2.2 Collect data and selection

This study focuses on highly peer-reviewed publications available in the Scopus database, specifically selected from journal papers. Only articles written in English were included in the analysis. The search string used was:

> *"Medical Implant" OR "implantable device" OR "Implantable biomedical device" OR "Implantable Electronic Device" OR "Implantable sensor" AND "Wireless Communication" AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (DOCTYPE, "ar")).*

A total of 1,650 articles that met the search criteria were identified and downloaded in CSV format. The data was downloaded in CSV format, which contained essential metadata, including author names, citation counts, affiliations, keywords, and abstracts. The CSV file was then processed using a visualization tool to facilitate additional analysis. Visualization plays a crucial role in bibliometric analysis, and there are numerous software options available for interpreting the data.

2.3 Analysis and overview

In order to conduct a bibliometric analysis, it is imperative to have appropriate and suitable tools that can generate reliable research results and insightful interpretations from exported datasets [35]. Numerous visual analysis tools and software applications have emerged in recent years, including VOS Viewer, Science of Science, Bibliometrix-R, Pajek, Gephi, RefViz, and HistCit [36]. These tools have the ability to generate visual representations of accumulated bibliographic data. For this study, VOS Viewer (version 1.6.19) is used as the analytical tool and combined with Tableau Public (version 2022.2). The VOS Viewer, developed by Nees Jan van Eck and Ludo Waltman from the Centre for Science and Technology Studies (CWTS) at Leiden University in the Netherlands, is a software visualization tool that was utilized to analyze global research on wireless IMDs. VOS Viewer offers an impressive method for visualizing and organizing bibliometric networks by creating multiple maps of varying complexity to ensure coherence. Additionally, it seamlessly integrates with well-known bibliographic databases, such as Scopus.

The text mining feature of VOS Viewer allows for the visualization of co-occurrence, co-authorship, and co-citation patterns derived from literature. Furthermore, integrating VOS Viewer with Tableau allows for the creation of visually appealing and diverse data visualizations, effectively communicating relevant research findings. The objectives of this study include creating visual representations, such as graphs and maps of countries, to illustrate the growth of research and the number of studies conducted on wireless IMDs from the initial timeframe to 2023. These visually captivating representations will offer valuable insights into the current state of research on this topic, as well as future ideas and challenges within this field. The study is based solely on the analysis of secondary data and does not involve interaction with human participants, so obtaining informed consent was unnecessary.

2.4 Draw conclusion from findings

Researchers can gain valuable insights into advancing a specific field of study by analyzing the quantity and development of publications and their citations. This information facilitates understanding the development of the field and enhances comprehension of other studies, enabling the prediction of potential research subjects. They can also make informed decisions regarding international project proposals or collaboration agreements within the research, community service, and educational domains by being aware of the countries and institutions that make significant contributions. Researchers should be acquainted with the most prominent publications in their field, as these publications form a solid foundation for the research discipline. Furthermore, a profound comprehension of the concepts presented in these influential works can help identify deficiencies in the current literature that require further investigation. Acquiring information about journals that regularly publish research in the field and receive the highest number of citations is crucial for researchers to determine the most suitable journal for disseminating their work. Familiarity with the most influential publications is important. Still, it is equally important to be aware of the authors who have made significant contributions to the discipline and have received the highest number of citations. This understanding facilitates the identification of authors to track in order to stay updated with the latest advancements and make decisions regarding international collaboration.

This study uses a bibliometric approach to investigate seven research questions (*RQs*). These questions encompass the examination of trends in wireless IMDs (*RQ1*), determination of the most prolific contributors (*RQ2*), identification of the most contributed authors (*RQ3*), cited articles (*RQ4*), and prolific journals (*RQ5*). Additionally, the investigation includes visually representing data on a map using Tableau Cloud to determine the countries with the highest research output on this topic and analyzing international collaboration among countries using a co-occurrence approach by VOS Viewer (*RQ6*). Furthermore, the study involves identifying the most important keywords through the analysis of keyword co-occurrence using VOS Viewer (*RQ7*) and investigating open topics within the research area (*RQ8*). The VOS Viewer offers three visualization modes: network, overlay, and density [37]. We will utilize network and density modes to address *RQ7*, while *RQ8* will be tackled using the overlay visualization mode.

3 RESULTS AND ANALYSIS

3.1 Trends research (*RQ1*)

The bibliometric analysis evaluated 1,650 articles and examined their distribution based on publications and citations by year (2001–2023), as shown in Figure 2. Figure 2 shows that the first journal paper on wireless IMDs was published in 2001 and experienced steady growth in publications from 2005, reaching a peak in 2022 with 223 publications. Despite a slight decrease in interest the following year, it is possible that the number of articles will continue to increase, as the publication record for 2023 on this topic is still ongoing. The rise in the number of published articles is closely linked to advancements in medical equipment technology, the widespread availability of Internet access, and the enhancement of health services. The development of smart hospital infrastructure has accelerated this increase in publications. Furthermore, the integration of 4G/5G/6G telecommunication in the healthcare sector has significantly contributed to the substantial increase in scholarly article publications. The evolution of telecommunications has led to the development of a seamless wireless network connection, which brings various benefits to patients, doctors, and nursing staff. These benefits include the capability to remotely monitor chronic illnesses [1], [38]. There is a campaign to integrate the use of 5G technology into international standards for future implantable medical devices, such as pacemakers and cardioverter defibrillators [39], [40]. This study will not further examine the external factors contributing to the slight decline in 2023. These factors, such as global events, new policies or international standards, the role of domestic stakeholders [41], and funding regulations, may have an impact and can be investigated in subsequent research.

A total of 52,398 citations were accumulated, and the trend indicates a consistent interest in the overall citation count despite some fluctuations (Figure 2). Fluctuations in citation numbers indicate inconsistency. According to the trend depicted in Figure 2, there has been a significant decrease in citations from 2019 to 2023. However, this decrease can be attributed to the inclusion of more recent articles in the database since 2019. Typically, a newly published article receives a limited number of citations initially, and it takes approximately ten years to accumulate citations and demonstrate its significance [42–44]. In other words, the significance of an article published in 2019 will become evident around 2029. Our observations suggest that the number of citations for articles published before 2013 peaked and

subsequently declined, possibly due to the outdated information in these articles, which is no longer widely referenced by researchers today [45–47]. As a note, the primary focus of this study is on journal articles. Therefore, acquiring a dataset that encompasses diverse sources, including preliminary research papers (e.g., letters, white papers, etc.) and conference papers, is essential to ensure a more comprehensive analysis in future research. This will allow the inclusion of the initial articles from all scientific sources in Scopus before 2001 in the field under consideration.

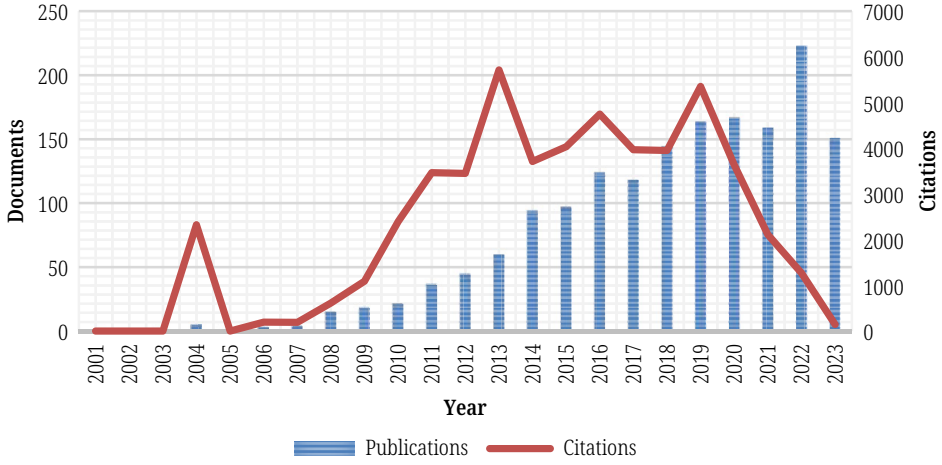


Fig. 2. Publication trends on wireless IMDs research

3.2 Most productive authors (*RQ2*)

Among the 1,650 articles examined, over 160 researchers studied this topic. For analytical purposes, only the top five authors are listed. The authors' ranking, based on the articles they have published and the number of citations they have received for their significant contributions to the field of wireless IMDs, is presented in Table 1. It is essential to acknowledge that some authors collaborated on multiple articles. The top five rankings include ten authors affiliated with different institutions. The authors were ranked according to the total number of citations received by their published articles. As shown in Table 1, Ghovanloo emerged as the most influential contributor in the field, having authored 15 articles (n = 15), closely followed by Balasingham (n = 14) and Guo (n = 13). Rogers (n = 12) also made a significant contribution that received 2,423 citations, accounting for 4.6% of overall citations in relevant publications. This analysis provides valuable insight into academia, suggesting the potential for collaboration with authors who have a significant number of publications and citations for their research. While the top five authors wield significant influence, the remaining researchers in this field, who make up 92.5%, also contribute valuable work. In this ranking, Rogers has the highest H-index. It should be noted that various factors, such as the database utilized in the bibliometric study, can impact the H-index [48]. Generally, Google Scholar yields a higher H-index compared to Scopus and WOS. Furthermore, databases may differ in their coverage of publications, with some databases encompassing more journals or conference proceedings in particular academic fields. Despite criticisms of the H-index by some authors, rankings based on this metric are sometimes dismissed [49]. However, some authors still include analysis based on the H-index value for fair ranking.

Table 1. Contributions of the top 5 authors in user experience research

Rank	Author	TP*	Citation Count	Author's Citations Overall	TD*	Author's H-Index	Scopus Author ID	Current Affiliation	Country
1st	Ghovanloo, M.	15	747	9,023	337	44	6701322320	Silicon Creations Inc.	United States
2nd	Balasingham, I.	14	362	4,304	308	33	6602773063	Oslo University Hospital	Norway
3rd	Guo, Y.X.	13	1,032	12,599	560	61	57198926864	National University of Singapore	Singapore
4th	Rogers, J.A.	12	2,423	129,510	1,155	179	56755517500	Northwestern University	United States
4th	Sawan, M.	12	462	8,424	730	42	7101608933	Westlake University	China
4th	Yoo, H.	12	305	1,614	105	26	25625778900	Hanyang University	South Korea
4th	Khaleghi, A.	12	226	1,193	93	18	57205414769	Norwegian University of Science and Technology	Norway
5th	Liu, C.	11	780	2,098	103	24	54684423500	Soochow University	China
5th	Irazoqui, P.P.	11	688	3,380	117	32	12772995300	Johns Hopkins University	United States
5th	Joseph, W.	11	432	9,209	613	47	22985227300	Universiteit Gent	Belgium

Notes: TP = Total publication related to the topic, TD = Total document recorded by Scopus.

Due to space constraints, this study only focuses on the top five authors. Still, considering the top ten or fifteen authors, they would offer a more comprehensive perspective on influential individuals in this field. Furthermore, collaboration among authors is taken into account in the ranking process, with equal credit given to all authors involved in joint publications.

3.3 Most cited articles (*RQ3*)

Citation analysis identifies influential articles by examining the relationship between cited articles and citations in specific publications. The significance of a publication is determined by the frequency of citations it receives; a higher number indicates greater importance. Additionally, it provides researchers with information about the current state of the art in research [50]. In the context of wireless IMDs, this approach will be beneficial for researchers as they strive to follow up on influential publications that can offer valuable insights into future implant technologies. Despite being influenced by various factors, the citation of an article remains widely used as an indicator for assessing its quality [51], [52].

Table 2 presents the articles that received the highest number of citations from 2001 to 2023. These top 10 articles were considered the most influential due to their numerous citations in their respective fields, collecting a total of 8,953 citations, which accounts for 17% of the overall citations. Among the 1,650 articles analyzed, we identified the ones with the highest number of citations. According to Table 2, the article by Zhang and Ho [53], published in *IEEE Transactions on Wireless Communications*, has the highest number of citations, 2,206 times (4.2% of the overall citations).

When scholars from different countries collaborate on a paper, it is recognized as a result of international cooperation [21], [22], [54], [55]. Among the top ten articles with the highest number of citations, three were co-authored by individuals from more than one country, highlighting the significance of international collaboration

in the literature on this topic. Five of the top ten articles feature authors affiliated with the United States, illustrating the influential role of the United States in this field.

Table 2. Top ten cited publications based on citation analysis

Rank	Title	Citations	Journal Name	Year	Authors	Country
1st	MIMO broadcasting for simultaneous wireless information and power transfer	2,206	IEEE Transactions on Wireless Communications	2013	Zhang, R., Ho, C.K.	Singapore
2nd	Three-dimensional battery architectures	1,149	Chemical Reviews	2004	Long, J.W., et al.	United States
3rd	Wireless sensor networks for healthcare: A survey	1,044	Computer Networks	2010	Alemdar, H., Ersoy, C.	Turkey
4th	A survey on wireless body area networks	887	Wireless Networks	2011	Latré, B., et al.	Belgium
5th	Wireless Charging Technologies: Fundamentals, Standards, and Network Applications	694	IEEE Communications Survey and Tutorials	2016	Lu, X., et al.	Canada, Singapore, South Korea, United States
6th	Bioresorbable silicon electronic sensors for the brain	668	Nature	2016	Kang, S.-K., et al.	United States, South Korea
7th	Implanted antennas inside a human body: Simulations, designs, and characterizations	658	IEEE Transactions on Microwave Theory and Techniques	2004	Kim, J., Rahmat-Samii, Y.	United States
8th	A comprehensive survey of wireless body area networks on PHY, MAC, and network layers solutions	591	Journal of Medical Systems	2012	Ullah, S., et al.	South Korea, United Kingdom, Belgium
9th	A survey on wireless body area networks: Technologies and design challenges	576	IEEE Communications Surveys and Tutorials,	2014	Cavallari, R., et al.	Italy, France
10th	Data security and privacy in wireless body area networks	480	IEEE Wireless Communications	2010	Li, M., et al.	United States

3.4 Most contributed journals (*RQ4*)

This study identifies reputable journals that are valuable resources for researchers and scholars looking to publish their findings on wireless IMDs. Over 160 journals have published studies on wireless IMDs from 2001 to 2023, indicating the widespread interest in this subject among the international academic community. The first publication on wireless IMDs was pioneered by the SPIE publisher in 2001 with a paper entitled "*Embedded electronics for a 64-channel wireless brain implant*" [56].

Table 3 displays the ten most influential journals that have published the highest number of articles. The top ten journals, as listed in Table 3, published 476 articles, which accounted for 28.8% of the total number of publications. It should be emphasized that the ranking of these journals is determined by the number of articles they have published. The most productive journals are the *IEEE Transactions on Biomedical Circuits and Systems*, *IEEE Transactions on Antennas and Propagation*, and *IEEE Access*, which published 114, 79, and 69 articles, respectively. In terms of citation count, the *IEEE Transactions on Biomedical Circuits and Systems* has the highest number with 4,091 citations on wireless IMDs, followed by the *IEEE Antenna and*

Propagation with 3,375 citations, and the *IEEE Transactions on Microwave Theory and Techniques* with 1,900 citations.

The number of citations reflects the value of a published paper, which is why we focused on identifying highly referenced articles. Interestingly, among the top 10 journals, *IEEE Access* experienced rapid growth in this field. It was established in 2015 and has consistently published articles, making it one of the top three in terms of total publications. Additionally, it has garnered 1,595 citations, ranking it fourth in this category. Authors and scholars should consider publishing their recent work in these top ten journals.

Table 3. Top-10 most contributing journals

Rank	Journal Name (Publisher)	Total Publication	Total Citation	Scopus Quartile	H-Index of Journal	SJR in 2022
1st	IEEE Transactions on Biomedical Circuits and Systems (IEEE)	114	4,091	*Q1*	37	1.62
2nd	IEEE Transactions on Antennas and Propagation (IEEE)	79	3,375	*Q1*	29	2.32
3rd	IEEE Access (IEEE)	69	1,595	*Q1*	21	0.93
4th	Sensors (MDPI)	49	729	*Q1*	17	0.76
5th	IEEE Sensors Journal (IEEE)	36	877	*Q1*	13	0.99
6th	IEEE Transactions on Microwave Theory and Techniques (IEEE)	35	1,900	*Q1*	18	1.89
7th	IEEE Transactions on Biomedical Engineering (IEEE)	29	1,051	*Q1*	16	1.17
8th	IEEE Transactions on Power Electronics (IEEE)	23	1,305	*Q1*	15	3.34
9th	Electronics (MDPI)	21	89	*Q2*	5	0.63
10th	IEEE Antennas and Wireless Propagation Letters (IEEE)	21	739	*Q1*	17	2.02

3.5 Most contributed countries (*RQ5*)

The study reveals that the wireless IMDs were conducted in 90 countries, as shown in Figure 3, indicating that the topic attracted attention across five continents. The countries or regions distribution map was created using Tableau Cloud, which contains a database of geographical coordinates for various countries. The map can be created by integrating this dataset with the information on the number of journal articles published in each country obtained from Scopus. Furthermore, data on the number of publications in the field is also available within the map. For example, China has 288 publications, Russia has 17, Indonesia has 3, Australia has 59, and Finland has 23.

Table 4 presents the top 10 countries that contribute the most to this knowledge domain. According to Table 4, the United States has published the highest number of articles (n = 429) on wireless IMDs, with the highest number of citations and H-index, which are 21,544 and 69, respectively. China ranks second (n = 288, with 7,924 citations), followed by India (n = 157, cited 1,906 times), and South Korea (n = 128, cited 7,149 times). The United States emerges as the most promising option for research collaboration. Subsequently, we will analyze the co-authorship patterns to gain insights into the scientific collaboration in the field of wireless IMDs across various countries.

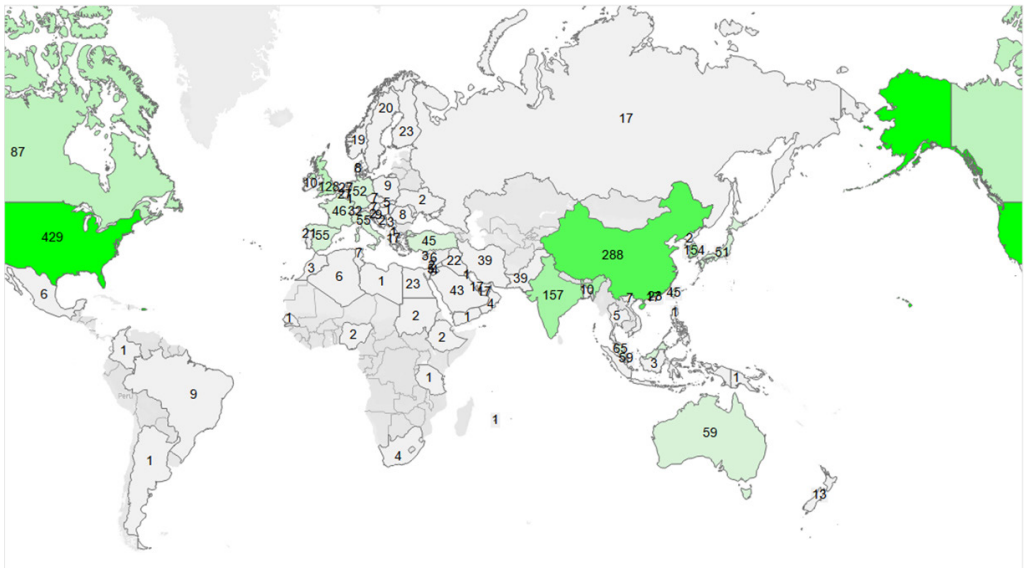


Fig. 3. Country map of wireless IMDs research

Table 4. Top-10 most influential countries

Rank	Country	Total Publication	Total Citation	H-Index of Country	Year of 1st Publication
1st	United States	429	21,544	69	2001
2nd	China	288	7,924	45	2006
3rd	India	157	1,906	24	2012
4th	South Korea	154	7,149	36	2009
5th	United Kingdom	128	4,659	36	2006
6th	Canada	87	3,696	28	2007
7th	Malaysia	65	1,338	14	2006
8th	Australia	59	2,027	24	2008
	Singapore	59	6,240	31	2008
9th	Italy	55	2,369	23	2008
	Spain	55	1,053	18	2008
10th	Germany	52	1,541	18	2008

Scientific collaboration is essential for improving research quality and impact [57]. To examine the level of co-authorship between countries, co-authorship analysis is conducted using VOS Viewer. This approach can reveal international collaborations in wireless IMD research among countries. The co-authorship network among countries is visually presented in Figure 4, where we observe the total link strength (TLS). The TLS is a crucial metric in VOS Viewer that measures the overall strength of connections within a network. The TLS is calculated by aggregating all the connections between nodes, such as keywords, authors, and countries, thereby indicating the degree of connectivity or significance of these elements in the network. This metric is particularly valuable for analyzing networks between nodes, as it helps to

understand the significance of elements in the dataset based on their connections with other nodes. A higher TLS value typically corresponds to stronger connections and greater significance within the network. This analysis established a minimum threshold of 10 documents per country. As a result, 37 out of the 90 countries included in our study met this threshold, forming four clusters represented by different colors. The analysis revealed 322 connections between countries, with a total TLS of 947. The largest cluster, depicted in red (Cluster 1) and comprising 16 countries, is centered on Spain, Italy, and Switzerland. Cluster 2 (green), Cluster 3 (blue), and Cluster 4 (yellow) consist of 10, 6, and 5 countries, respectively.

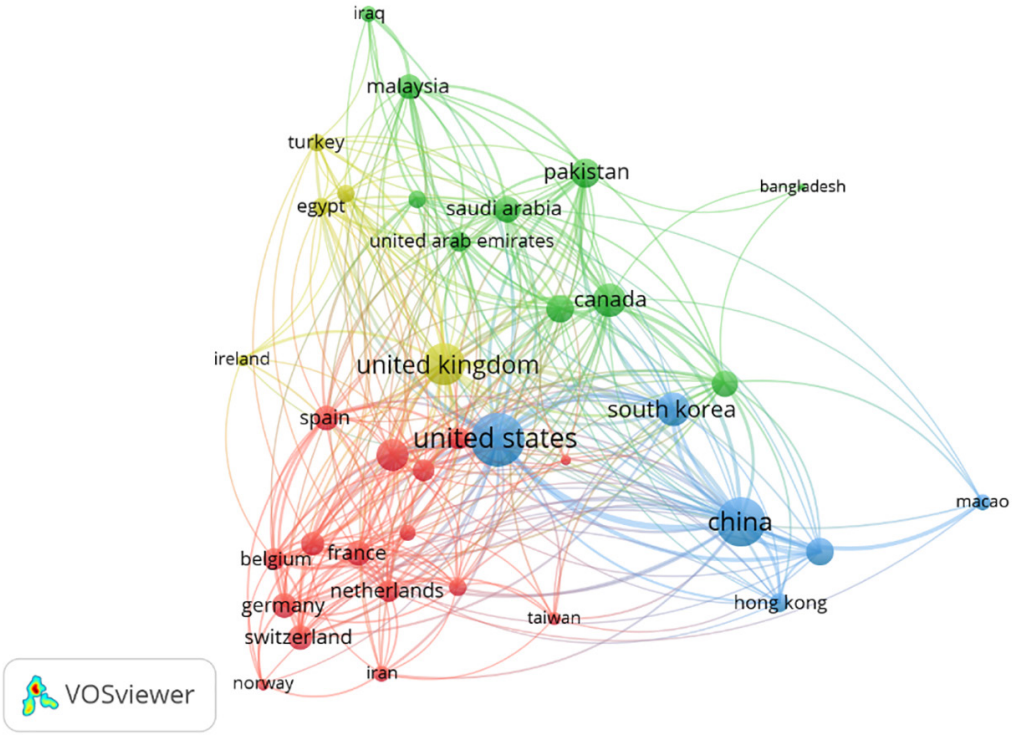


Fig. 4. Screenshot of co-authorship pattern among countries using network visualization mode

Our findings revealed that the United States had the highest TLS score of 245 (32 links). China had a TLS of 197 (32 links), while the United Kingdom had a TLS of 133 (31 links). The term "total link strength" refers to the number of references cited in both publications. In the context of co-authorship analysis, it represents the number of publications that two individuals have co-authored. Associated with co-occurrence, TLS represents the number of articles in which any two terms are found together [28]. The findings suggest that institutions in the United States have a strong foundation for collaboration, as they have made the most significant contributions to collaborative work within the country. This suggests that institutional collaboration goes beyond national borders, as all institutions have partnered with foreign counterparts, emphasizing the global reach of research on wireless IMDs. The reasons why certain countries, such as the United States, China, and the United Kingdom, dominate this research field also require deeper study. It is important to investigate whether specific policies, funding opportunities, or industrial collaborations in these countries encourage this research.

3.6 Most contributed institutions (*RQ6*)

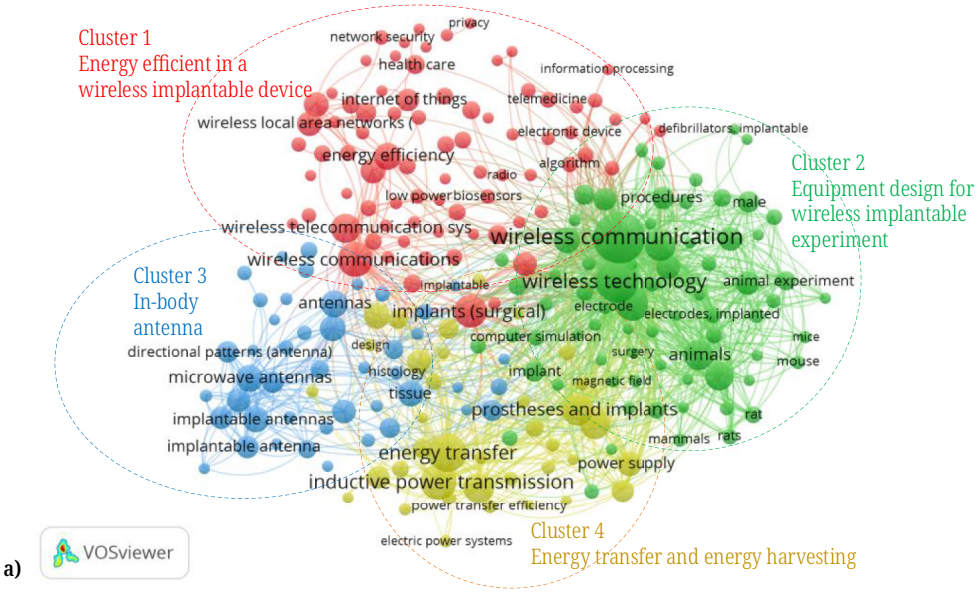
Between 2007 and 2023, 160 institutions published their research findings on wireless IMDs in various journals. However, for our investigation, we will only evaluate the five top institutions that have contributed to this field. Table 5 displays data about these institutions, including their publication count, citation count, country, and the most frequently cited article from each institution, along with its title, authors, and publication year. It is evident that these five institutions have played a crucial role in research on wireless IMDs. Out of all institutions, the top five contributors are from the United States, including Purdue University, the University of California, and the Georgia Institute of Technology. The National University of Singapore had the highest number of publications (n = 39), followed by Purdue University (n = 32) and the University of California (n = 29).

Table 5. Top-5 most influential organization

Rank	Institution	Total Publication	Total Citation	Institution's H-Index	Country
1st	National University of Singapore	39	3,926	25	Singapore
2nd	Purdue University	32	2,596	20	United States
3rd	University of California	29	2,875	17	United States
4th	Georgia Institute of Technology	26	1,379	19	United States
5th	Imperial College London	23	921	15	United Kingdom
	Tsinghua University	23	1,326	13	China

3.7 Most important keywords (*RQ7*)

The author's choice of keywords provides crucial information about the current research status and areas of focus. These keywords have been shown to be significant in analysing future development trends [58]. Our analysis involved examining 13,277 keywords from a total of 1,650 articles. Figure 5 illustrates a snapshot of the co-citation analysis. The co-occurrence of keywords, also known as co-word analysis, is a method used to tally the frequency of keywords within specific publications. Its primary aim is to examine the association among keywords to determine the prevailing and influential topic currently under investigation [59]. Moreover, it can be used to analyse trends and developments in specific research topics over time. Analysing the co-occurrence of keywords investigates the connections between concepts found in the abstracts, keywords, and titles of documents. These keywords can also be extracted from the full text of the papers for analysis. In bibliometric analysis, it is common practice to extract keywords from author-provided keywords. The topic structure can be thoroughly analysed using co-occurrence analysis, which offers insights into future research directions [60], [61]. In summary, co-occurrence analysis is a valuable method for identifying relationships between different research concepts based on their frequency of occurrence. It involves identifying words that frequently appear together in abstracts, titles, or as keywords, and these words are closely linked in a network. This method serves as a valuable tool for visualizing research clusters.



a)

b)

Fig. 5. Screenshot of the bibliometric map illustrating the analysis of keyword co-occurrence on: (a) network visualization mode; (b) density visualization mode

To conduct keyword co-occurrence analysis, we utilized the same database. Among 13,277 keywords, only 241 met the minimum threshold of appearing 22 times. We excluded six keywords: human, humans, survey, adult, swine, and priority journal. Subsequently, the analysis resulted in 4 clusters with 16,331 links

between nodes, with a combined TLS of 70,799 (Figure 5a). Within the scope of this study, the top three most frequently occurring keywords, as visualized in Figure 5b, were "wireless communication" (TLS = 5,719 and occurrences = 444), "wireless technology" (TLS = 4,599 and occurrences = 309), and "equipment design" (TLS = 3,122 and occurrences = 206).

One outcome of the keyword co-occurrence analysis is the generation of a network visualization that reflects the strength of relationships between keywords, determined by their frequency of appearing together. This visualization represents keywords as nodes, connected by lines to indicate co-occurrence. Shorter distances between nodes indicate stronger relationships, while longer distances indicate weaker relationships. The size of the nodes corresponds to the frequency of keywords, while the scale of loops (links) corresponds to the occurrence of specific connections between two keywords. The VOS Viewer features an excellent clustering algorithm that enables color variations in nodes based on a predetermined threshold. This results in clusters of nodes representing distinct areas of knowledge [62]. The study identifies four clusters, which are described as follows:

1. Cluster 1 (red) has the highest population, comprising 79 keywords. Cluster 1 is identified as "energy-efficient in wireless IMDs." The term "energy efficiency" is one of the most frequently used keywords in this cluster, and it plays a significant role in the design of wireless IMDs. Biomedical implants, such as pacemakers and defibrillators, must operate continuously 24 hours a day without interruption [15]. Although batteries provide a constant power source without needing external devices, non-rechargeable batteries have a limited lifespan and need to be replaced or disposed of. For example, the average lifespan of cardiac pacemakers ranges from 7 to 10 years, while deep brain stimulators typically last about 3 to 5 years. Battery replacement accounts for approximately 25% of surgical procedures [13]. Typically, patients require surgery at least twice. The first surgery involves implanting the battery, while the second is necessary for replacing the battery. This explains why battery complications can lead to patients undergoing surgery more than three times [63]. Patients will experience increased psychological, financial, and physical burdens if they undergo frequent surgeries for battery replacement [64]. Therefore, reducing power consumption in these devices is crucial for extending the battery's lifespan. One promising approach to reduce power usage is by optimizing computational requirements using specialized "algorithms" [65–67] or designing special chips that can process medical data efficiently while minimizing energy consumption [68–70]. Furthermore, this cluster also investigates keywords related to "IoT." The publications in this cluster also cover various wireless communication modalities, including "optical communication" [4], [12], [71–73], "ultrasonic" [74–76], and "radio frequency" [77], [78]. In this cluster, there is a group of keywords related to "wireless local area network," "wireless sensor network," WBAN, and sensors, such as "implantable sensor," "sensor networks," "body sensor networks," and "biosensors." There are various wireless technologies and protocols available to support a wide range of medical applications, especially implantable sensors such as ZigBee, Wi-Fi, or Bluetooth [13]. No single sensor or technology is superior in all scenarios; the choice depends on various factors, such as size restrictions, duration of implantation, expenses, safety considerations, and the mobility needs of the patient [13].
2. Cluster 2, depicted in green, comprises 74 keywords. Cluster 2 is labeled as "equipment designed for wireless implantable experiments." The term "equipment" is

the most frequently occurring word in this cluster and defines its characteristics. This keyword is strongly associated with other important keywords such as "wireless technology," "miniaturization," "animals," and "stimulation." It is also linked to human [79–81], along with specific gender references, such as "female" or "male." In this cluster, we can find studies focused on analyzing how researchers validate their proposed systems in simulation or experimental environments (i.e., ex-vivo or in-vivo) [12], [82], [83]. One of the most critical considerations for IMDs is their biological safety, which includes factors such as the safety of the surgical procedure used for implantation, biocompatibility, and the device's long-term durability. The surgical procedure plays a crucial role in in vivo experiments [15]. Animal models such as rats or pigs are used to guide the appropriate surgical approach in order to simulate the human body. The computer simulation can also generate interest in equipment without the need for physical experimentation [84], [85]. In this cluster, the concept of "miniaturization" is also discussed [86–89]. Many researchers are working to reduce the size and weight of IMDs while ensuring sufficient energy capacity for their power sources. The process of miniaturization involves more than just reducing the physical dimensions of IMDs. It also involves addressing the decreased power output, which often necessitates the use of innovative design strategies. Advancements in micromachining techniques, electronic engineering, medicine, and material science have enabled the creation of smaller IMDs with increased durability and functionality.

3. Cluster 3, highlighted in blue, contains 45 keywords. Cluster 3 is designated as an "in-body antenna." The most frequently used keyword is "implantable antenna," which represents a cluster of publications that concentrate on the correlation between "microwave antenna," "microstrip antenna," "specific absorption rate," and "biocompatibility." Implantable nodes consist of various components, such as the battery, microprocessor, sensors, and an antenna. The antenna plays a crucial role in establishing seamless communication and a robust, reliable link between in-body and out-body devices [90]. In this research cluster, scientists aim to design an antenna by carefully considering various factors, such as easy fabrication, high flexibility, and the ability to conform to different shapes. Moreover, SAR (specific absorption rate) and biocompatibility are also topics explored in this cluster. Both of these factors are essential aspects of antenna design to ensure the safety of biological tissues (human subjects). SAR denotes the amount of energy absorbed by human body tissues per unit mass of tissue. This metric is widely recognized as the most appropriate scientific measurement for assessing electromagnetic exposure and aligns with international guidelines [17], [90]. In terms of biocompatibility concerns, it is crucial to consider this metric for implantable antennas, as the electrical conductivity of human body tissues must be taken into account. If the antenna comes into direct contact with the tissues, it could lead to a short circuit [90], [91].

Cluster 4, highlighted in yellow, contains 37 keywords. Cluster 4 is labeled as "energy transfer and energy harvesting." The most common keyword is "energy transfer," which defines this cluster and brings together the publications that focus on the connections between "power supply," "power transfer efficiency," "magnetic resonance," "ultrasonics," "inductive power transmission," "inductive couplings," "energy harvesting," and "implantable medical devices." Some researchers are focusing on optimizing the efficiency of batteries and power supplies (grouped in Cluster 1), while others are attempting to harvest energy from readily available

sources (grouped in Cluster 4). Due to the increasing interest in energy-related issues among researchers, the majority of publications in this cluster are focused on identifying potential energy sources or developing strategies for wirelessly powering IMDs.

One limitation in the development of implantable electronic devices is their power supply. Many of these devices rely on batteries with a limited lifespan and require continuous power to monitor their functions. One of the limitations in the development of implantable electronic devices is the power supply. Most implants use batteries with a finite lifetime, which provides continuous power and tracks their functions. As the lifespan of patients continues to increase, there is a growing need to establish a durable and sustainable wireless powering solution to overcome the limitations of battery capacity [92]. The power requirements of IMDs vary depending on their intended use. This is why the WPT system can be a viable solution to prevent any interruption in the functioning of such devices [18], [93], [94]. Two methods of WPT are commonly used [14]: magnetic resonance and ultrasonics. These two methods are closely associated with the keyword "energy transfer," as depicted in Figure 5a. Inductive power transmission utilizes an inductive coupling mechanism to enable wireless power transfer. This system consists of two elements: the transmitting coil (the primary) and the receiving coil (the secondary). One of the most attractive features of this technology is its capability to transfer power through body tissue, enabling downlink (from outside to inside the human body) or uplink (from inside to outside) transmissions. Researchers in this field aim to find the most efficient way to transfer power.

3.8 Open topics (*RQ8*)

This topic has been researched for over 22 years, and it continues to garner attention due to the rapid growth of ICT adoption in the biomedical sector, advanced sensor technology, and other related technologies. Between 2021 and 2023, the investigation of wireless IMDs has garnered the interest of numerous countries, leading to the publication of 1,650 journal articles. Furthermore, this study has successfully evaluated the research productivity of individuals and institutions, identifying trends and research hotspots in wireless IMD research. The VOS Viewer allows us to identify less explored areas in wireless IMD research. Co-occurrence analysis is still used in this process. We analyze *RQ7* using high-frequency keyword parameters represented by large circles. In contrast, we consider two parameters to investigate *RQ8*: (1) keywords represented by small circles that are distant from the large points, and (2) year of publication. In the VOS Viewer visualization, we can observe that the research topic becomes less explored as the distance from a cluster increases. We used the analysis in Figure 5, but changed the visualization mode to overlay (see Figure 6). By referring to the keyword map in Figure 5, we can observe the evolution of the topic over the past five years (2015–2020) through the shifts in color. The topic is considered relatively new as the color shifts toward yellow.

Figure 6 offers a comprehensive understanding of the recently explored area, revealing trends and research hotspots to facilitate a holistic perspective. The early emerging topics in this research area include "IoT," "rectenna," "microwave antenna," "microstrip antenna," "power transfer," "energy harvesting," "wireless power," "piezoelectricity," "optical communication," or "optical wireless communication," and "medium access control."

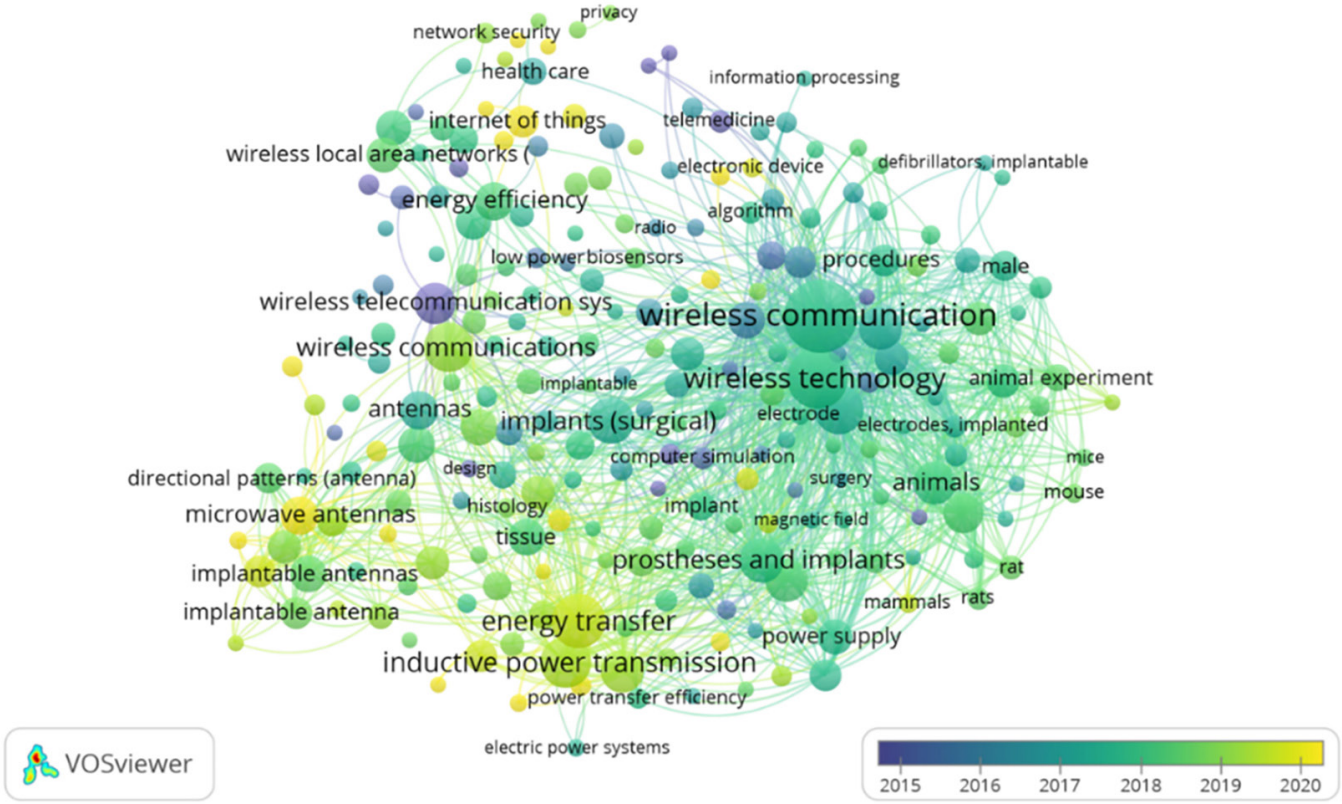


Fig. 6. Screenshot of the bibliometric map illustrating the analysis of keyword co-occurrence using on overlay visualization mode

4 FUTURE STUDIES

In the previous chapter, we presented the process and findings of a bibliometric study aimed at uncovering the evolution of wireless IMDs over time. The significance of this study lies in its novelty and success in measuring performance and science mapping under bibliometric analysis, to the best of our knowledge [28]. However, it is essential to acknowledge the limitations inherent in our study that will be useful for future research. These limitations will be addressed in this section.

4.1 Scientific databases

First, the accuracy and validity of a bibliometric study greatly depend on the quality and source of the dataset used. The selection of a scientific database is crucial because different databases produce varying results. Many researchers commonly use large databases such as Scopus, WOS, Dimension, and Google Scholar [33]. For our study, we selected Scopus to construct our dataset because it is widely acknowledged as a reputable scientific database. It applies transparent and strict exclusion and inclusion criteria, such as country, language, publication type, and year, and employs strict keyword strings, including OR, AND, and NOT operations. Furthermore, it functions as a multidisciplinary global citation database. However, relying on a single database has limitations, as it may exclude high-quality studies that are not indexed by Scopus.

4.2 Type of publications

Second, we limited our analysis to journal articles to ensure high quality in this study. However, it would be beneficial for future research to incorporate articles from other sources, such as book chapters, conference proceedings, letters, etc., to conduct a more comprehensive analysis of research trends. Furthermore, the use of surnames and initials by authors creates difficulties when referencing individuals with common names. Additionally, the formatting of journal citations may vary, including different editions of books with distinct citation styles [62].

4.3 Keywords

Third, in bibliometric analysis, selecting appropriate keywords is of significant importance. The selection of keywords determines the number of papers that can be obtained for the study. Researchers commonly use carefully selected keywords that reflect the topic they are studying. Generally, they rely on widely recognized terminology prevalent in that specific field. Based on our literature screening, we have found that many bibliometric papers may lack comprehensive findings because of the keywords chosen. It is possible that important contributions may not have been adequately captured because different authors may have used different keywords. Therefore, most bibliometric analysis papers commonly include a specific section that discusses the strengths and limitations of the study. Under this established practice, we have also included this aspect in our study. However, despite our anticipation of a few relevant papers being missing based on our chosen keywords (pre-defined keywords), the absence of these papers in the analysis may compromise the generalizability of our findings. To overcome this limitation, we can conduct a follow-up study using datasets obtained from searches performed in these databases, which is consistent with our planned future research efforts. For example, future studies could consider the selection of keywords such as “body-implanted,” “in-body,” “ingestible device,” and “injectable device.”

4.4 Dataset generation

Fourth, creating a dataset is a crucial step in the process of bibliometric research. This study also conducted several initial searches to develop a search strategy that includes literature relevant to the research goals. Ultimately, we decided to limit the search to English-language publications that include the keyword “implant” and its variations in the title, abstract, and author’s keywords. A manual analysis was conducted to determine the relevance of the identified papers. In previous work [95], we explored the use of the two keywords strings “in-body communication” and “in-body wireless communication.” Subsequently, we meticulously analyzed the resulting data using bibliometric protocols. However, we encountered limitations in the number of publications found, specifically 148 papers. Many researchers worldwide are more familiar with the use of terms such as “implant,” “biomedical implant,” and “implantable device” rather than “in-body device.” Interestingly, we found more than 3,000 publications associated with these keywords. This finding is crucial for future researchers when determining suitable titles or keywords.

As a result, the visibility of our paper and its potential for citation opportunities increase when other authors come across it. Bibliometrics provides a viable analytical method for examining search strings within large datasets [27]. The selection of articles for this investigation depends on pre-determined keywords and criteria. Furthermore, a thorough investigation is essential to determining the suitability of the selected articles for this subject. For this reason, future studies should conduct a systematic literature review to enable a more comprehensive examination. This can be achieved by meticulously filtering the articles based on their relevance to wireless IMDs in Scopus before converting them to CSV files.

4.5 Scope of analysis

Fifth, the bibliometric analysis includes two metrics: (1) performance, which involves tracking publication growth trends, identifying the most cited articles, and determining the most contributors based on countries, universities, authors, and journals; and (2) science mapping, which involves analyzing citation, co-occurrence, co-citation, bibliographic coupling, and co-authorship by countries, organizations, and authors. These metrics are used to examine the intellectual framework and knowledge interactions within a specific field [28], [36]. This study measured performance metrics to address the research objectives outlined in *RQ1*, *RQ2*, *RQ3*, *RQ4*, and *RQ5*. Meanwhile, science mapping is conducted using co-occurrence keywords and co-authorship (by country) to address *RQ6* and *RQ7*. Future studies should consider incorporating additional science mapping measurements to provide a comprehensive bibliometric analysis.

4.6 Analysis of thematic research evolution

Furthermore, additional investigation is required to examine the evolution of research in this field over time, specifically to determine if there are distinct periods of increased research activity. BibliometriX is a valuable tool that can facilitate this analysis, enabling a more comprehensive examination of the evolution of primary research areas over the specified research period. For example, it can determine if there was a stronger emphasis on energy-saving techniques in previous years compared to the current focus on the IoT and other related subjects.

4.7 Accuracy

One limitation of the dataset is the potential for inaccuracies in the captured data and the continuous updates to Scopus, which can lead to slight variations in the outcomes of the same search strategy conducted on different dates. We have observed variations in our search results when conducted over different time periods, including differences in the number of papers and the number of citations received by each paper. Although these differences in results are not significant, it is important to acknowledge them. If other researchers apply the same search strategy, it is possible that their findings may differ slightly from those involved in this study, particularly the search results from September 12, 2023. However, we do not believe that this limitation impacts the reproducibility of the study, as it is an inherent attribute of Scopus.

5 CONCLUSION

This study employs bibliometric analysis to examine the literature on wireless IMDs from 2001 to 2023. The study provides valuable insights that can be used by stakeholders, such as researchers, policymakers, and industry professionals, to support their actions or decision-making processes, as outlined in the introduction section. Our findings reveal that the United States leads in scientific contributions, closely followed by China and the United Kingdom. Furthermore, this study also identifies prominent journals that can help disseminate scholars' work on wireless IMDs. The National University of Singapore, Purdue University, and the University of California are the most productive institutions. Ghovanloo, Balasingham, and Guo are the three most prolific authors, while Rogers has the highest H-index. In the last decade, several countries have conducted research on wireless IMDs, leading to various advancements such as energy-efficient techniques, equipment designs, in-body antenna developments, energy transfer, and energy harvesting strategies. In recent times, IoT, rectenna, microwave antenna, microstrip, power transfer, energy harvesting, wireless power, piezoelectricity, optical communication or optical wireless communication, and medium access control have emerged as the primary areas of research on wireless IMDs. This study has the potential to improve the understanding of the global research landscape and provide valuable insights, perspectives, and information for future research on wireless IMDs or related topics. However, certain limitations in this study need to be addressed in future research. These include the potential bias towards English-language publications, the need to refine keywords, and the expansion of the database used for article retrieval. To ensure a comprehensive and high-quality bibliometric analysis, it is essential to consider alternative sources for retrieving articles, such as PubMed, IEEE Xplore, and WOS, to expand the scope and encompass supplementary databases. By integrating and cross-referencing multiple databases, the bibliometric analysis can be significantly enhanced, thereby improving overall comprehensiveness. In rankings, we emphasize publication volume as a measure of the influence of journals, institutions, or countries. A more comprehensive evaluation can be achieved by considering additional metrics, such as the number of citations, h-index, or impact factor. This study introduces new opportunities for investigating further challenges in wireless IMDs that require additional research, such as safety concerns, regulatory issues, and the integration of these devices with existing medical infrastructure. However, despite this paper providing an insight into appropriate research in this context, it emphasizes the importance of conducting systematic literature reviews to enhance the analysis and theoretical foundation of wireless IMDs in future studies.

6 ACKNOWLEDGMENT

The author express gratitude to the University of Oulu´s Infotech (CWC-NS 2406124) for providing financial support to the first author to complete his doctoral studies. This study was partially supported by the Research Council of Finland (former Academy of Finland) Profi6 funding, 6G-Enabling Sustainable Society (6GESS) the University of Oulu, and the Research Council of Finland 6G Flagship Programme (Grant Number: 346208).

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