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PAPER

Analyzing the Trends and Global Growth of Energy Harvesting for Implantable Medical Devices (IMDs) Research—A Bibliometric Approach

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ABSTRACT

Implantable medical devices (IMDs) play a crucial role in improving individuals' well-being and ensuring their safety by providing real-time health data monitoring for recovery. The use of energy harvesting (EH) technology has become increasingly popular among researchers because it offers the potential to extend the battery life of IMDs and reduce their weight. This study successfully examined the expansion of EH in the field of IMDs, the distribution of publications across different countries, and the identification of the most influential authors for potential research collaborations. A bibliometric analysis was conducted to evaluate two metrics: performance and science mapping. Data was collected from the Scopus database from the initial publications until October 2023, encompassing 250 articles published in English-language journals. The titles, keywords, and abstracts of these publications were analyzed and interpreted using VOS Viewer (version 1.6.19). Furthermore, network analysis using VOS Viewer enabled the identification of key research clusters. The findings reveal a continuous increase in EH for research on infectious and parasitic diseases over the 15-year period from 2008 to 2023. The United States and the University of Bern are recognized as the leading contributors to this field, based on their country and institutional contributions, respectively. The author with the most published papers and citations hails from China. Additionally, this study identifies several opportunities for collaboration with countries, institutions, authors, and research hotspots in EH for IMDs that benefit the reader.

KEYWORDS

energy harvesting (EH), implantable medical device (IMD), bibliometric, VOS Viewer

1 INTRODUCTION

There have been significant advancements in implantable medical device (IMD) technology in recent decades [1]. This progress has been facilitated by advancements

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in the fields of science and engineering, such as biotechnology, microelectronics, and nanomaterials [2]. The total revenue from IMDs is predicted to exceed 118 billion USD by 2027 [3]. IMDs have played a crucial role in improving patient survival rates. For example, pacemakers, first introduced in 1958, have significantly contributed to saving numerous lives among patients with heart failure [4–6]. In the United States alone, an estimated 250,000 individuals receive pacemaker implants annually, marking a twentyfold increase over the past 15 years [7]. In other countries such as Sweden, France, and Canada, the annual pacemaker implantation rate ranges from 380 to 1,200 per million population, while in Indonesia, Pakistan, and the Philippines, it ranges from 1 to 7 per million. In Germany and the United States, the annual rates of pacemaker and cardiac defibrillator implantation range from 434 to 927 per million in the population. In contrast, in India, Bangladesh, and Peru, the rate falls below 1 per million population [7]. IMDs transmit biosensing signals inside the human body and are used for various clinical purposes, including therapy, diagnosis, and assistive technological objectives. IMDs have undergone significant advancements in healthcare services, enabling the implementation of personalized medicine through proactive drug delivery, precise treatment within the human body, and real-time physiological monitoring in convenient ways [8]. These advancements are in line with the objectives of 5G and future communication technologies (e.g., 5G+, 6G), which involve the concept of the Internet of Medical Things (IoMT) [9].

Most modern IMDs, such as pacemakers, cochlear implants, neuro-stimulators, insulin pumps, bone growth stimulators, artificial hearts, retinal implants, spinal cord stimulators, retinal prosthetics, cardiac defibrillators, and drug pumps, rely on batteries as their power source [10], [11]. However, these devices are limited by their finite battery life [12–14]. For instance, pacemakers generally last for about 7 to 10 years, while deep brain stimulators have a lifespan of approximately 3 to 5 years [15], [16]. Furthermore, batteries significantly contribute to the weight and size of IMDs [10]. The power requirements of IMDs vary depending on their specific functions. Cardiac pacemakers, cochlear implants, bone growth stimulators, and retinal prosthetics, for example, require power levels of approximately 1mW, 40mW, roughly 20μW, and about 40mW, respectively [11], [17]. Installing IMDs poses several significant challenges, including ensuring an adequate power supply and monitoring their functionality [18], [19]. Regular replacement of batteries is necessary for these devices [4], [20], which can lead to complications due to the need for surgical procedures on the patient's body [21], [22], resulting in a significant burden and financial risks for the patient [21], [23]. Despite being inconvenient for patients, the practice of replacing batteries through periodic surgery has been deemed acceptable thus far [19]. Providing clean, sustainable, and renewable energy is essential for powering IMDs, taking into consideration convenience factors [24]. There is a growing need to develop solutions that extend battery life to address the issue of limited battery capacity in IMDs. This can reduce the need for frequent surgical interventions to replace implanted batteries within a 3- to 7-year timeframe [25].

In response to the increasing demand for IMDs and the goal of extending their lifespan, researchers worldwide have shown significant interest and invested substantial efforts in developing resource advancements for them [24], [26]. Two main strategies have been widely demonstrated: enhancing the electrical capacities used in the devices and harvesting energy from the surrounding environment [27]. Integrating EH technology into IMDs allows for addressing concerns regarding battery longevity, resulting in significant improvements [28]. The EH methods have the potential to generate power for IMDs using renewable energy sources such as photovoltaic (PV) cells, vibrations from human movements, and temperature differences in the human body, among others. These sources can be converted into electrical energy, enabling the operation of IMDs. In addition, researchers have explored the use of near-infrared (NIR) light to transmit biomedical data [29–31] and extract energy for IMDs simultaneously using PV cells [28]. Although sunlight (the visible light spectrum) cannot penetrate the human body, NIR, as an alternative light spectrum, has the potential to reach implanted PV cells beneath the human skin. Energy harvesting (EH) techniques could serve as a feasible alternative to implanted batteries for assessing energy availability for implanted biosensors. In addition to the widespread dissemination of experimental research, numerous review papers have been published to offer a comprehensive overview of the latest advancements in this field. There are seminal works that provide comprehensive reviews of recent technology in IMDs, such as antenna design for IMDs [32], wireless power transfer [33–35], EH from the environment [36], biocompatibility and design approaches for developing IMDs [37], extraction of kinetic energy from body movements [38], [39], and wireless technology for IMDs [40], [41]. Due to the rapid advancement of technology in EH for IMDs, which leads to new approaches and shifts in paradigms, it is imperative to conduct the most current review [42], especially in examining trends, global growth, and research hotspots. To achieve this, bibliometrics can be utilized [43].

However, to the best of our knowledge, no publications have conducted bibliometric studies specifically focusing on EH for IMDs. Accordingly, this study conducted a bibliometric analysis to address this gap. The main contribution of this study is to analyze research on EH for IMDs, which will provide guidance for future research in this sensitive field. This research includes a graph illustrating the growth of EH research publications for IMDs, the identification of key contributors (such as journals, authors, institutions, and countries), notable articles in this field, a visualization of the number of publications by country, and the relationship between important keywords in the obtained articles. One of the findings of this study is that it identifies opportunities for research collaboration based on the countries and authors involved in EH research for IMDs. It also suggests ideas for future research in this field. The research question (*RQ*) for this study is presented as follows:

- *RQ1*: What trends and growth patterns can be identified through a bibliometric analysis of the research trajectory in the EH for IMDs, and which individuals or entities (journals and journal articles) have a significant impact in this area?
- *RQ2*: Who are the top contributors in terms of publications and citations, based on their country and university? What are the connections between authors from different countries?
- *RQ3*: What areas of research are currently receiving significant attention within the field of IMDs, and what are the open research opportunities for these areas in future studies?

2 METHODS

Bibliometric analysis is a widely used and rigorous method employed by researchers worldwide to gain an understanding of the current state of a particular scientific field. This analysis involves the examination and interpretation of large datasets using statistical methods, with the possibility of including visual aids to present the data analysis findings. A quick search for the keyword "bibliometric analysis" on October 6, 2023, yielded 404,000 documents, demonstrating the high popularity and interest in the bibliometric method among researchers in various scientific disciplines. The method comprises two main components: performance analysis and science mapping, each serving a distinct purpose in the analysis [44]. Researchers can choose to focus on either one or both aspects, depending on the research goals and scope. Performance analysis aims to evaluate trends, such as the quantity of publications and citations, as well as the influence of scientific activities by authors, institutions, and countries [45]. Science mapping analysis seeks to uncover the evolution of the cognitive structure within scientific fields and identify research hotspots [46]. This study aims to achieve its objectives by analyzing trends and key contributors through performance analysis and identifying research hotspots through science mapping using bibliometric analysis.

In bibliometric analysis, the choice of a database is of great significance as it necessitates careful consideration of several factors, such as user friendliness, information quality and quantity, capacity for bulk data download, institutional grant access, journal coverage, and data volumes. Among the commonly used databases in bibliometric analysis across different disciplines, Scopus by Elsevier and Web of Science (WOS) by Thomson Reuters are the most popular options [47]. For this study, we selected the Scopus database because of its well-established reputation for disseminating reliable research with credible data and analytical resources. Additionally, it offers comprehensive coverage of peer-reviewed publications, similar to WOS, and provides the added advantage of allowing bulk data downloads of up to 2000 documents. In contrast, WOS limits downloads to around 500 documents per session [48]. Moreover, our university provides exclusive institutional access rights to Scopus through the campus intranet, which allows us to conduct our studies without limitations.

The data curation process was conducted in October 2023 using a Scopus database. Our focus was on articles containing specific phrases in their titles, abstracts, and keywords, such as "implantable medical device," "medical implant," "implantable electronic," "implantable device," "in-body device," "implantable biomedical device," "implantable sensor," and "energy harvesting." To collect the data, we utilized Scopus search with Boolean logic functions (AND or OR) to search the titles (TITLE), abstracts (ABS), and keywords (KEY), using the following details: *TITLE-ABS-KEY ("Implantable Medical Device" OR "Medical Implant" OR "Implantable Medical Electronic" OR "In-body device" OR "implantable device" OR "Implantable biomedical device" OR "Implantable Electronic Device" OR "Implantable sensor" AND "energy harvesting")*. Using this query, we found 533 articles. This study employed specific search criteria, including restrictions on language (English), source type (journals), and document type (articles), covering the period from the beginning of the research until October 6, 2023. After applying the criteria, 250 articles met the eligibility requirements for review. These articles were written in English, sourced from journals, and were exclusively in article format. All articles retrieved through this query are downloaded and compiled into a dataset. The downloaded data is in comma-separated value (CSV) format. The CSV file format is commonly used to store tabular data in plain text and is widely acknowledged for its simplicity [49]. Scopus provides data extraction features in CSV files for further analysis, including bibliometric studies, particularly for science mapping visualization. CSV files offer specific advantages for transferring data sourced from Scopus to various analysis or software applications due to their compatibility and user-friendly nature. The data extracted from Scopus includes various information, such as citation details (author, document title, year, EID, source title, volume, issues, pages, citation count, source and document type, publication stage, DOI, and open access), bibliographic information, abstract, and keywords.

This study utilized Microsoft Excel to record and analyze bibliometric data, such as research trends (volume of articles over the years) and the performance of contributors (authors, institutions, and countries) in terms of publications and citations. Excel facilitates the collection of bibliometric data from Scopus by enabling users to record and organize the extracted information. After Scopus generated the dataset using predetermined keywords, we utilized the "Analyze results" function in Scopus. Subsequently, several graphs were displayed: (1) documents per year by source, (2) documents by affiliation, (3) documents by year, (4) documents by country or territory, (5) documents by author, (6) documents by type, (7) documents by subject area, and (8) documents by funding sponsor. However, we limited our analysis to four aspects: article volume over the years, authors, institutions, and countries. The information from these four datasets is then recorded in Excel on the same date, with particular emphasis on the number of publications and citations. To analyze research trends, we utilized Excel's charting and calculation features to visually illustrate and monitor the quantity of articles and their associated citations over time. Additionally, the performance of authors, institutions, or countries was meticulously evaluated using custom formulas that utilized Excel's functions, such as SUM, to quantify publications and citations associated with Scopus.

To conduct science mapping, we utilized VOS Viewer, a software specifically designed for generating and visualizing bibliometric maps. These maps provide insights into the structure and dynamics of scientific research, including analyses of co-authors (by country) and co-occurring keywords. The functionality of VOS Viewer, such as zooming and searching, enables comprehensive map analysis, even with a large number of objects, such as at least 100 items [48]. VOS Viewer allows users to import data in various formats, such as CSV files.

The study presents the following data: (1) a graph illustrating the growth of research publications on EH for IMDs; (2) a list of the top 10 contributors based on their publications and citation counts, including authors, institutions, and countries; (3) a map displaying the number of research publications on EH for IMDs by country (without specific limits); (4) links between authors from different countries (limited by a certain threshold); and (5) links between keywords found in articles (with a specific threshold). This information can be used to assess the advancement of research in this field, identify opportunities for collaborative research among countries and authors, and generate ideas for future research endeavors related to EH for upcoming implantable medical devices.

3 RESULTS AND ANALYSIS

This section is organized into three sub-sections: Introduction to IMDs Research Growth, IMDs Research on Various Countries, Institutions, and its Research Collaboration, and IMDs Research Hotspot. To mitigate any potential bias, the analyses conducted in Sections 3.1 to 3.3 were performed on a single day (October 6, 2023) and aligned with the significant date mentioned by the author in [50]. Section 3.1 utilized Scopus data for analysis, whereas Sections 3.2 and 3.3 employed VOS Viewer. All observations were conducted on the same date.

3.1 Introduction of IMDs research growth

According to the specified criteria, a total of 250 documents on the topic of EH for IMDs were retrieved from the Scopus database between 2008 and 2023. Figure 1 illustrates the global growth of EH for IMD research and the annual citation numbers. The data is accumulated from documents originating from 137 different journals and 41 countries. Notably, in the last five years, the number of publications has been as follows: 14 publications in 2023, 32 in 2022, 28 in 2021, 32 in 2020, and 33 in 2019. While the average number of publications has increased, there is a projected decline in the number of published articles until 2023. However, it is important to acknowledge that this data is provisional, as additional articles can still be added to the Scopus database until its completion in December 2023. Moreover, there has been fluctuation in the number of citations over time, with two decreases occurring from 2016 to 2017 and from 2019 to 2023. The articles are citable within a ten-year span, meaning that typically every article can be effectively cited within a period of ten years [51–53]. For example, an article published in 2021 can demonstrate its impact through citations until 2031, and an article published in 2022 can demonstrate its impact through citations until 2032. In contrast, an article published before 2012 may be considered outdated if it is not recognized as a significant scientific contribution to the specific field [54–56]. In Figure 1, it is evident that the first journal article related to this topic, published under the specified keyword, was in 2008. This article, authored by Kerzenmacher et al. [57], is titled "*An abiotically catalyzed glucose fuel cell for powering medical implants: Reconstructed manufacturing protocol and analysis of performance*" and appeared in the Journal of Power Sources. It is noteworthy that this article, with 105 citations, stands out as the only one published in that year. In their study, they presented a strategy for powering IMDs using a biofuel cell.

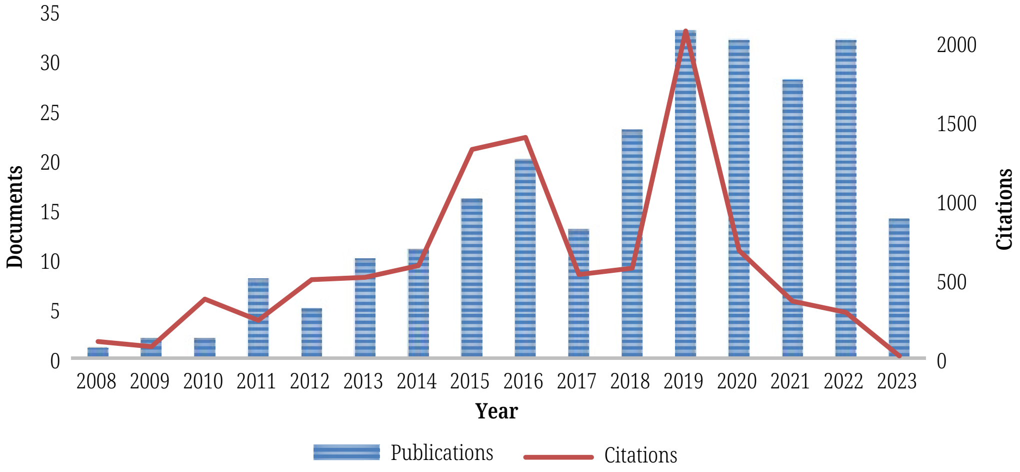

Fig. 1. Research trends and its citations on EH for IMDs research

Researchers from various countries have published their work in numerous peer-reviewed journals since 2008. In simple terms, 250 journal articles were contributed by various parties, including individuals (authors), institutions, countries, and journals that disseminate the articles. In the research growth analysis section, we also report the most contributed authors and journals in EH for IMDs research. On the other hand, the most-cited article is also included. Table 1 presents the top five journals, which collectively contain seven journals, that have published the most articles, highlighting their impressive performance. The rankings show that the *Nano Energy journal* is the leading journal with 16 published articles, followed by *IEEE Access* (n = 12) and *IEEE Transactions on Biomedical Circuits and Systems* (n = 10). These top three journals represented 15.2% of the total publications, with n = 38 out of 250 journal articles.

Furthermore, the number of publications can indicate the research strength of authors and the academic impact of their works, as assessed by the number of citations. Therefore, the number of papers published by researchers in a specific field is considered a key factor in evaluating their influence [58]. As a result, we have also ranked the authors who have made the most contributions (refer to Table 3). The ranking results revealed that Wang, Z.L. (n = 9), Vogel, R., and Zurbuchen, A. (n = 8), Haberlin, A., and Pfenniger, A. Among 41 authors in the field of EH for IMDs research, (n = 7) emerged as the leading contributors, accounting for 15.6% of the overall publications (39/250). The table also reveals that the most cited author is also the most productive, as indicated in Table 2, where Wang, Z.L., is listed. The author emerges as the most productive with nine publications and the most frequently cited, with a total of 320,006 citations. Based on the examination of author rankings, there is an opportunity for collaboration with Wang, Z.L. They possess substantial expertise in EH for IMDs, as evidenced by the significant number of publications and overall citations they have obtained.

Table 3 presents a ranking of the top 10 most frequently cited articles. The number of citations serves as a valuable indicator of academic impact, highlighting the significance of the published work. A higher number of citations indicates the greater importance and influence of the article within the scientific field [59]. For this compelling reason, this study also identifies the articles on EH for IMDs that have received significant citations. The article by Safaei et al. from the United States has the highest number of citations, according to Scopus (n = 481) [60]. The article was published in the Smart Materials and Structures journal in 2019. It conducted a systematic review of EH using piezoelectric materials for various applications, including IMDs. The review focused on papers published between 2008 and 2018. The second and third ranks were achieved by Hinchet et al. (n = 468) and Tang et al. (n = 402), respectively, according to Scopus. These top three articles collectively accounted for 14% of the overall citations (1,351 out of 9,612).

Table 1. Most contributed peer-reviewed journals

Rank	Peer-Reviewed Journal	Publishers	Number of Publications	Number of Citations	Ratio	H-Index of Journals
1st	*Nano Energy*	Elsevier	16	815	50.93	11
2nd	*IEEE Access*	IEEE	12	298	24.83	8
3rd	*IEEE Transactions on Biomedical Circuits and Systems*	IEEE	10	464	49.4	7
4th	*Advanced Functional Materials*	Wiley-Blackwell	6	646	107.67	5
5th	*ACS Applied Materials and Interfaces*	American Chemical Society	5	189	37.8	5
	IEEE Transactions on Biomedical Engineering	IEEE	5	98	19.6	4
	IEEE Transactions on Circuits and Systems II: Express Briefs	IEEE	5	34	6.8	4

Table 2. Most contributed authors

Rank	Authors	Number of Publications	Overall Citations	Affiliations (Countries)	Authors' ID
1st	Wang, Z.L.	9	320,006	Chinese Academy of Sciences (China)	56430045300
2nd	Vogel, R.	8	3,868	Buergerspital Solothurn (Switzerland)	7201707818
	Zurbuchen, A.	8	559	University of Bern (Switzerland)	55311764900
3rd	Haeberlin, A.	7	811	University Hospital Bern (Switzerland)	50661383000
	Pfenniger, A.	7	382	Sonceboz (Switzerland)	25655302100

Table 3. Most cited articles

Rank	Title	Year	Total citations		Authors	Journals
			Scopus	Google Scholar		
1st	A review of energy harvesting using piezoelectric materials: State-of-the-art a decade later (2008–2018)	2019	481	596	Safaei et al	Smart Materials and Structures
2nd	Transcutaneous ultrasound energy harvesting using capacitive triboelectric technology	2019	468	522	Hinchet et al	Science
3rd	Liquid-metal electrode for high-performance triboelectric nanogenerator at an instantaneous energy conversion efficiency of 70.6%	2015	402	446	Tang et al	Advanced Functional Materials
4th	Hybrid nanogenerator for concurrently harvesting biomechanical and biochemical energy	2010	370	465	Hansen et al	ACS Nano
5th	Symbiotic cardiac pacemaker	2019	340	428	Ouyang et al	Nature Communications
6th	Maximum achievable efficiency in near-field coupled power-transfer systems	2012	301	408	Zargham et al	IEEE Transactions on Biomedical Circuits and Systems
7th	In Vivo Self-Powered Wireless Cardiac Monitoring via Implantable Triboelectric Nanogenerator	2016	300	346	Zheng, et al.	ACS Nano
8th	Self-Powered, One-Stop, and Multifunctional Implantable Triboelectric Active Sensor for Real-Time Biomedical Monitoring	2016	253	290	Ma, et al	Nano Letters
9th	Flexible piezoelectric Thin-Film energy harvesters and nano sensors for biomedical applications	2015	230	284	Hwang, et al	Advanced Healthcare
10th	High-performance flexible lead-free nanocomposite piezoelectric nanogenerator for biomechanical energy harvesting and storage	2015	187	211	Siddiqui et al	Nano Energy

3.2 EH for IMDs research on various countries, institutions, and its research collaboration

The study of EH for IMDs has made significant progress due to the substantial interest from numerous researchers in this field, as demonstrated by the research growth (Section 3.1). It has been previously noted that the number of published works is a crucial metric for assessing the progress of a specific research field. In this section, we analyze the performance of a bibliometric study focusing on the countries and institutions that have made the most contributions to EH for IMDs. On the other hand, research collaboration can also be examined through co-author analysis by country using VOS Viewer. Table 4 presents the top 3 contributing institutions, including four institutions. It shows that University Hospital Bern (*n* = 12) was the leading institution, followed by the Chinese Academy of Sciences and the University of Bern (*n* = 11), and the Georgia Institute of Technology (*n* = 10). These top three institutions are the most productive based on the number of publications, accounting for 13.5% of the overall publications (33 out of 250).

Table 4. Most contributed institutions

Rank	Institutions	Country	Total Publications	Total Citations	Ratio	H-Index of the Universities
1st	University Hospital Bern	Switzerland	12	316	26.33	9
2nd	Chinese Academy of Sciences	China	11	1741	158.27	10
	University of Bern	Switzerland		292	26.54	9
3rd	Georgia Institute of Technology	United States	10	1925	192.5	9

Based on the performance analysis of institutions in this field, it is evident that the United States is the leading country in terms of the number of articles (*n* = 79) and total citations (*n* = 4435), as shown in Table 5. China ranks second in the number of publications (*n* = 51), followed by South Korea (*n* = 23). This demonstrates that the United States, China, and South Korea offer the greatest potential for research collaboration, as they possess the necessary resources and a favorable environment (e.g., technology, financial support, proficient research teams, professors, faculty members, and other factors) to support productive publication outcomes.

Table 5. Most contributed countries

Rank	Country	Total Publications	Total Citations	Ratio	H-Index of Countries
1st	United States	79	4435	56.14	32
2nd	China	51	3053	59.86	22
3rd	South Korea	23	1492	64.87	13
4th	Germany	16	359	22.44	7
	India		336	21	10
5th	United Kingdom	15	433	28.87	9

Subsequently, a comprehensive analysis of country collaboration was conducted through a co-authorship analysis using VOS Viewer with the full counting method [61]. When authors from different countries collaborate on a publication, it is recognized as an international collaborative effort [62], [63]. The results of this analysis are depicted in Figure 2. The analysis established a threshold of 5, indicating that only countries with at least five occurrences of articles were included. A total of 38 links were identified among 17 out of 41 countries, resulting in six clusters with a total link strength (TLS) of 79. Noteworthy collaborations were identified between various pairs of countries, such as United States-China with a link strength (LS) of 20, United States-Switzerland (LS = 3), China-United Kingdom (LS = 3), Australia-Iran (LS = 3), United Kingdom-South Korea (LS = 4), and United Kingdom-China (LS = 3). Additionally, further insights were gained regarding the number of co-authors, revealing that the United States (12 links), China (9 TLS), and South Korea (8 links) had the highest number of collaborations, among others.

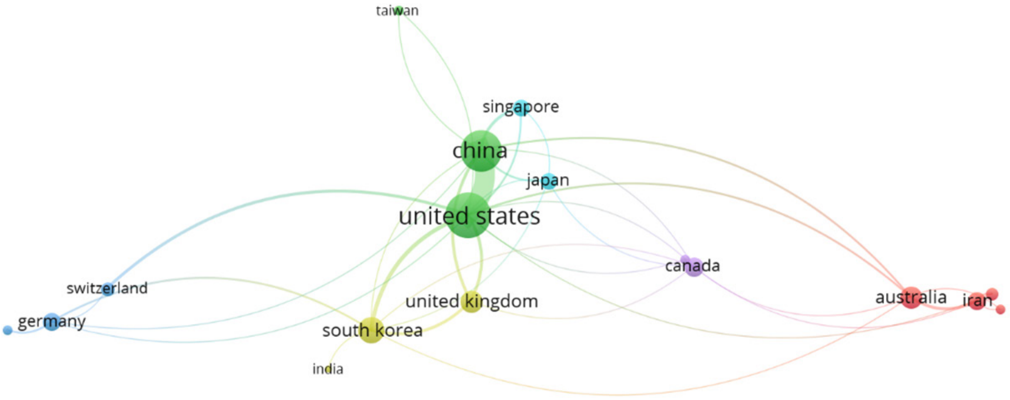

Fig. 2. Co-author (by country) analysis using VOS Viewer

3.3 Research hotspots

To identify the primary research areas and key themes on EH for IMDs, it is essential to thoroughly understand each document and extract the most significant keywords from the dataset. This analysis is essential for identifying emerging trends and research hotspots that could be explored in future research, development, and innovation. Our findings revealed that the dataset contained 2,920 keywords. However, only keywords that occurred at least five times were selected for a co-occurring keyword analysis. Subsequent to this selection process, 193 keywords (6.6% of the total) meet the threshold. VOS Viewer offers three visualization modes [64]. Figures 3a and b depict a network visualization mode where the size of the circles corresponds to the frequency of the keywords. The larger circles around certain keywords indicate a higher frequency of research on those topics, suggesting extensive investigation. Conversely, smaller circles indicate the opposite. The colors of the circles indicate clusters that have been automatically grouped by VOS Viewer's algorithm based on themes. VOS Viewer categorizes the keywords into five clusters by utilizing predetermined criteria.

1. Cluster 1 (red), containing 58 items, e.g., supercapacitor, photovoltaics, magnetic field, energy storage, conversion efficiency, antennas, etc.
2. Cluster 2 (green), comprising 55 items, e.g., biocompatibility, biomechanics, flexible electronics, fluorine compounds, mechanical energies, nanogenerator, nanotechnology, piezoelectricity, thermoelectricity, thin films, triboelectricity, smart materials, etc.

3. Cluster 3 (blue), grouped by 42 items, e.g., cardiac pacemakers, electromagnetism, in vivo study, kinetics, solar cells, computer simulation, etc.
4. Cluster 4 (yellow), comprising 42 items, e.g., bioenergy, biofuel cell, inductive couplings, skin, tissue, signal processing, etc.
5. Cluster 3 (purple), containing 3 items, i.e., power harvesting, ultrasonics, and ultrasound, etc.

The data visualization analysis conducted using VOS Viewer revealed the occurrence of the following keywords with the highest frequency and TLS: energy harvesting (n = 217, TLS = 1864), surgical implants (n = 76, TLS = 700), piezoelectricity (n = 63, TLS = 583), power supply (n = 33, TLS = 569), implantable devices (n = 54, TLS = 518), equipment design (n = 29, TLS = 472), electric power supplies (n = 25, TLS = 447), and human (n = 28, TLS = 445). The keyword "energy harvesting" (EH) has the highest frequency, accounting for 7.4% of occurrences. The colored circles around the keywords represent five distinct clusters, demonstrating how various cutting-edge technologies facilitate EH for IMDs, including ultrasonics, ultrasounds, solar cells, flexible electronics, triboelectricity, kinetic energy, inductive power transmission, nanotechnology, etc.

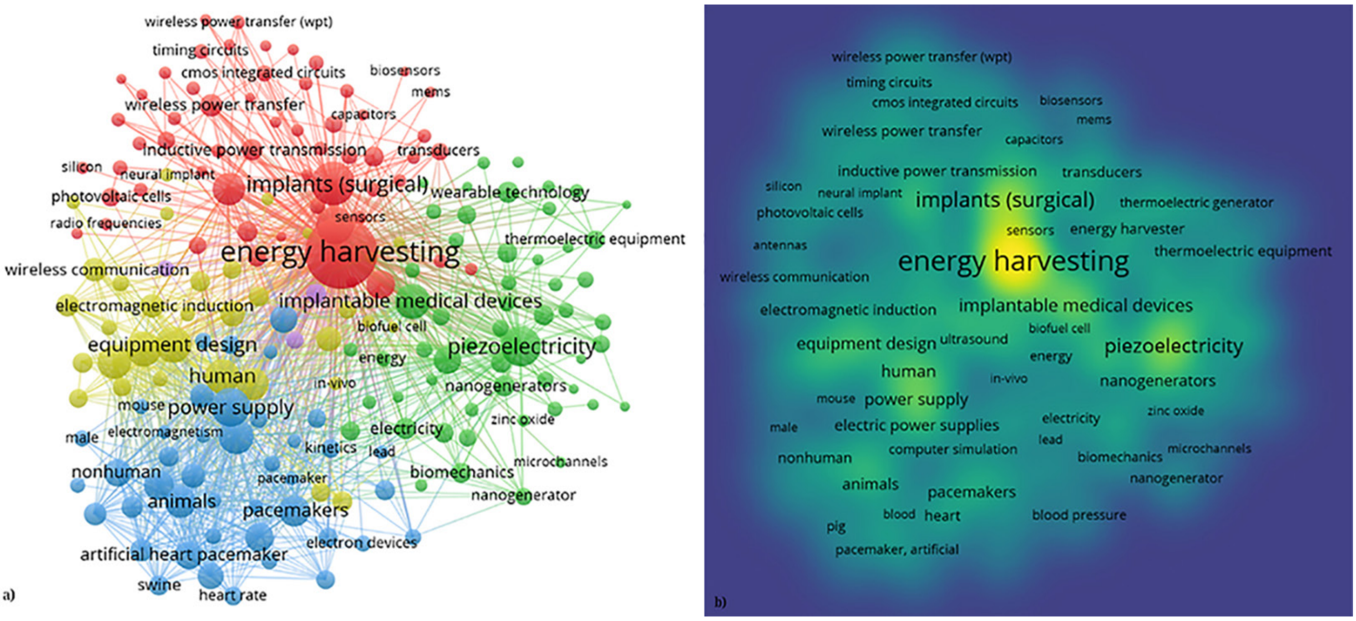

Fig. 3. Co-occurrence keyword analysis using VOS Viewer: (a) the highest TLS on network visualization mode; (b) the most frequently keywords (occurrences) on overlay mode

The VOS Viewer can visualize an expanding array of topics over the years using overlay mode. Figure 4 illustrates three colors—red, orange, and white—representing the publication year of each document. White denotes the start of the publication in the selected year (from 2016), while the transition from orange to red signifies the most recent year of publication. Figure 4 shows that prior to 2020, numerous researchers concentrated on artificial heart pacemakers, mechanical energy, flexible electronics, piezoelectric materials, and mathematical models. While research areas that are still relatively new and have room for further exploration include *triboelectricity, piezoelectricity, nanogenerators (smart materials), ultrasonics (ultrasounds), internet of things, biosensors, and solar cells (solar energy).*

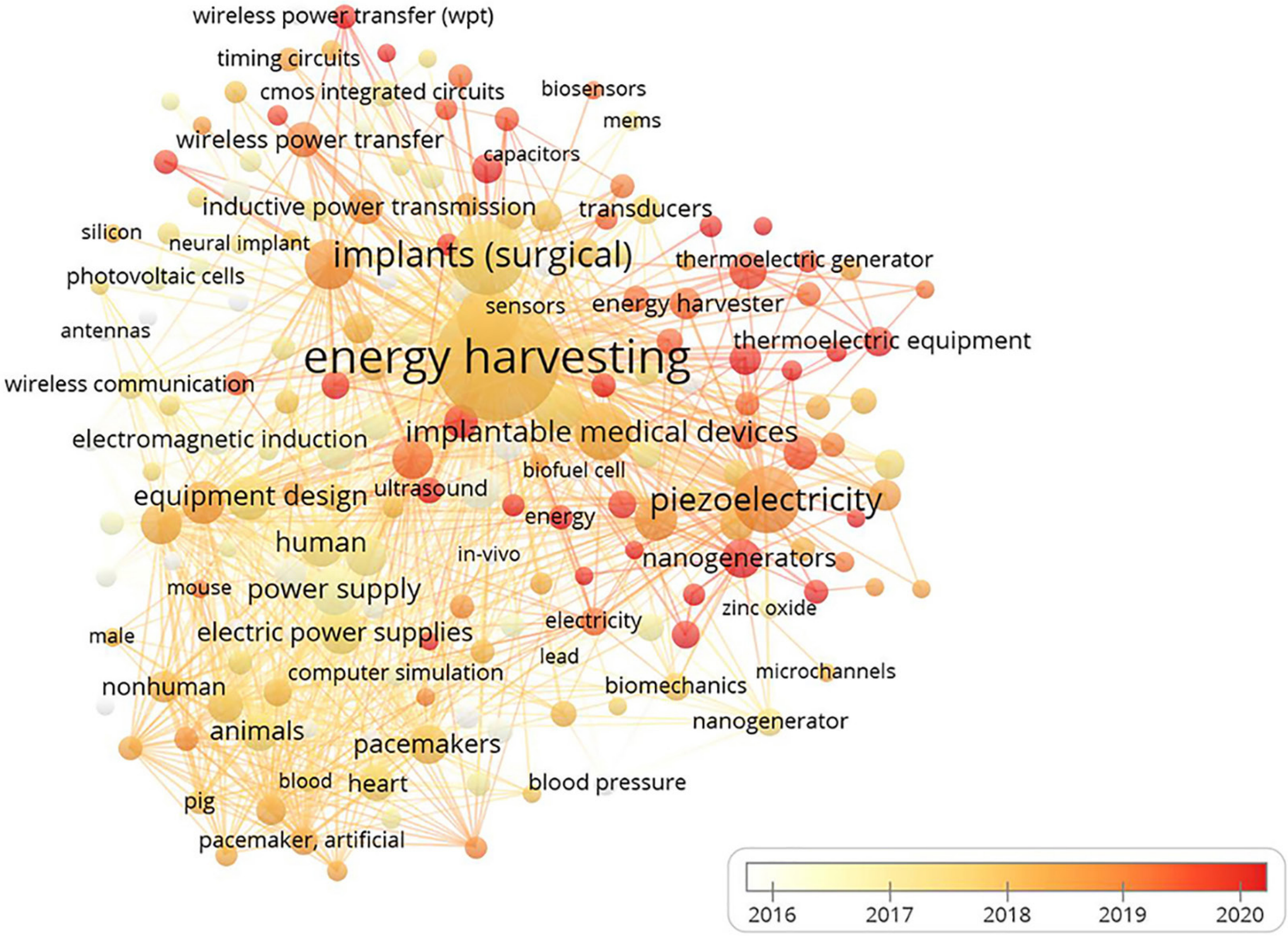

Fig. 4. The research timeline focuses on the exploration of in-body communication exploiting light as a medium at the Centre for Wireless Communications, University of Oulu, Finland

As seen in these keywords, i.e., “piezoelectricity,” “triboelectricity,” and “solar cells” (widely known as PV cells), they can be distinguished as methods for EH. Among these methods, PV cells can generate energy within the microwatt range, typically ranging from tens to hundreds of microwatts, despite the typically small available harvesting area (in the mm^2 scale) [65–68]. PV cells remain a significant area of interest, particularly in extending the lifespan of IMDs. They possess remarkable energy conversion efficiency, operate as a renewable energy source, and exhibit promising output power [4]. Previous studies have indicated that commercial PV cells can power pacemakers [69] and in-body sensors [21]. Additionally, experiments conducted on animal models, such as mice [70] and pigs [71], in vitro have also demonstrated the potential of PV cells for powering devices under the skin. However, there are challenges related to the penetration of light into the tissue, as light energy is absorbed and scattered, which limits deeper penetration and requires larger energy harvesting devices [72]. A study by [73] using simulation techniques revealed that almost all light is absorbed at a depth of 6 mm. Furthermore, the depth of light penetration decreases for shorter wavelengths, especially for wavelengths below 900 nm. A study [74] revealed that biological tissues exhibit two optimal windows of optical transparency: 650–950 nm and 1000–1350 nm, which are in the NIR region. NIR light has the potential to efficiently power embedded PV cells because it can penetrate the skin and has reduced scattering loss. A study by [75] demonstrated that PV cells can produce a power of 100 μW/mm^2 when exposed to an 808 nm light source, while another study successfully harvested 11.84mW using an 850 nm NIR light [76].

Despite its advantages in power generation, the transmission of NIR light directly to the human body must be carefully regulated in accordance with standards (received optical power) due to its potential to harm biological tissue and its damaging effects on the skin caused by its heating properties [29–31]. The successful results indicate that PV cells can serve as a viable energy source for various IMDs, such as pacemakers, retinal stimulators, and hearing aids. From the perspective of an energy harvesting device, a specialized PV cell should be designed to effectively capture NIR light, which has a narrow spectrum. This is because commercial PV cells are typically designed to operate across a wide range of light wavelengths. Using NIR light to simultaneously transfer energy and data is a promising area of research. This study explores the use of PV cells as both a data receiver and an energy harvester. This research field aims to introduce a novel approach and open new perspectives, emphasizing the use of light for in-body communication systems, particularly NIR light. To the best of our knowledge, this groundbreaking discovery was initially made by [28].

The term “smart materials” can be interpreted by authors in two ways: as a special material and its composition, and as system miniaturization. These interpretations are based on the authors’ perspective. Many scholars are striving to decrease the size and weight of IMDs while maintaining sufficient energy capacity for their power sources. At the same time, EH devices also need to be miniaturized to enable integration with small IMDs. Miniaturization is one of the open areas in this research field, as elaborated in references [77–80]. The process of miniaturization involves more than simply reducing the size of these devices; it also entails finding solutions for the decreased power output, often necessitating new design strategies. It will bring new challenges for fabrication, packaging, and wireless communication. Advancements in micromachining techniques, electronic engineering, medicine, and material science have enabled the creation of smaller IMDs that are more durable and offer improved functionality integrated with EH systems. On the other hand, the availability and intensity of ambient energy sources within the human body are limited and fluctuate, thereby restricting the amount of power that can be extracted. There is a strong motivation to maximize the use of NIR light for both illumination and data transmission. One potential approach in this area is the development of implantable PV cells as energy harvesters, specifically for use in in-body devices. For this reason, it becomes imperative to use special materials.

The concept of “biocompatibility” is also a theme explored in this topic, as it is grouped in Cluster 2. This metric is crucial in designing an IMD system to ensure the safety of biological tissues [81]. In future research, IMDs incorporating implanted PV cells should prioritize biocompatibility, as the electrical conductivity of human body tissues must be strictly considered. If there is direct contact between the electronic circuits within IMDs (e.g., implanted PV cells) and the tissues, it may result in a short circuit and consequent harm to the tissue [82], [83].

Finally, this study has successfully identified five clusters of co-occurring keywords using VOS Viewer. These clusters can provide valuable guidance and direction for future research in related fields, helping to understand the structure of the knowledge map and identify areas that need in-depth investigation and further exploration in the near future.

4 CONCLUSION AND FUTURE STUDIES

4.1 Conclusion

This study uses bibliometric methods to analyze the research on EH for IMDs from its beginning in 2008 to October 2023. The findings indicate a growing trend in EH for IMDs research, with a total of 250 articles retrieved from the Scopus database. When it comes to the number of publications on EH for IMD research, the highest contributors are from the United States, with authors from China, University Hospital Bern, and Nano Energy, respectively. The most cited article is authored by Safaei et al. with a paper entitled “A Review of Energy Harvesting Using Piezoelectric Materials: State-of-the-Art a Decade Later (2008–2018).” In terms of research collaboration using co-author analysis by country, the USA and China have demonstrated outstanding performance. Future research collaborations in EH for IMDs could be carried out in the top three countries, namely the United States, China, or South Korea. On the other hand, it can be conducted with scholars who have received the most publications and citations. Researchers can consider publishing their work in nanoenergy (in the field of science), *IEEE Access* (covering various disciplines), or *IEEE Transactions on Biomedical Circuits and Systems* (in the field of engineering). Given the potential benefits of EH in prolonging the lifespan of IMD batteries and reducing the necessity for repetitive surgeries, it is anticipated that research on EH for IMDs will continue to expand in the future. The results of the VOS Viewer analysis, which is based on the evolution of keywords by year and the number of keywords, indicate that future research should prioritize the following areas: nanogenerators, smart materials, triboelectricity, ultrasounds, ultrasonics, Internet of Things, biosensors, piezoelectric, solar cells, and solar energy. The other one is biocompatibility.

4.2 Future studies

In future research, scholars have the potential to conduct more extensive analyses by utilizing VOS Viewer. For example, they can analyze co-authorship (including authors, organizations, and countries), citation, bibliographic coupling, and co-citation, in conjunction with other tools such as BibliometriX. This study is limited by using Scopus as the primary database for literature searches, which may lead to the exclusion of valuable works not indexed by Scopus but by other databases, such as Google Scholar, WOS, Dimensions, etc. Our literature search strategy was carefully defined and conducted, focusing on keywords related to biomedical implants or implantable devices and their variations or derivatives. However, some articles might use alternative terminology (nomenclature) that is not covered in our nomenclature lists, and therefore may not be included in our searches. This study is also limited by the challenge of sorting multiple keywords with identical definitions, as the refinements of the keywords could influence perceptions. The study did not directly sort all the obtained articles to determine their alignment with the search keywords. However, despite these limitations, there are still significant opportunities for further investigation and expanding the scope of this research. Another constraint that affects the dataset is the precision of the data acquired as a result of Scopus updates in the articles indexing. Conducting the same search strategy on different dates may produce slightly different outcomes. To illustrate, the findings obtained by other researchers after October 6, 2023, differed from those incorporated in this investigation. Nevertheless, we do not see this as a limitation that compromises the reproducibility of our study, as it is an inherent characteristic of Scopus' functioning. Moreover, all bibliometric studies acknowledge and address this issue of data accuracy [63], rendering it inconsequential.

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