Heliyon 10 (2024) e27399

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Two Decades' advancements and Research trends in needle-type Sensor technology: A scientometric analysis

Guangyi Yang [a], Wenjing Xu [a,*], Botan Xu [b], Yi Yang [c], Pengwei Li [a], Aotian Yu [a], Simin Ning [a], Qixuan Fu [a], Rong Zhang [d], Xiaohan Liu [e]

[a] School of Acupuncture-Moxibustion and Tuina, Beijing University of Chinese Medicine, Beijing 102488, China
[b] School of Nursing, Beijing University of Chinese Medicine, Beijing 102488, China
[c] School of Chinese Medicine, Beijing University of Chinese Medicine, Beijing 102488, China
[d] The Third Clinical Medical College, Beijing University of Chinese Medicine, Beijing 102488, China
[e] School of Life Sciences, Beijing University of Chinese Medicine, Beijing 102488, China

A R T I C L E I N F O

Keywords:
Needle-type sensor
CiteSpace
Scientometric
Knowledge graph
Biomedical engineering

A B S T R A C T

Needle-type sensor, characterized by its slender, elongated shape, is a promising sensing method due to its rapid response, high sensitivity, and portability. Recently, the needle-type sensor technology has garnered increasing attention, leading to its accelerated development and extensive use in medical and healthcare, environmental monitoring, and geosciences. However, there remains a need for a comprehensive review of existing research. Here, we utilize scientometric analysis, which is booming recently, to conduct a comprehensive investigation of the needle-type sensor field. This analysis covers various aspects, including annual trends, journals, institutions, countries, disciplines, authors, references, and keywords of 136,667 publications from the Web of Science Core Collection (WoSCC) database spanning from January 1, 2004, to January 1, 2024. Additionally, we identify current hotspots, frontiers, and predict future trends. Eventually, three research hotspots are refined: multidisciplinary materials science, sensor miniaturization and integration, and biomedical engineering, indicating that further investigations may focus on creating biocompatible materials to enhance sensing properties, optimizing sensor structure through miniaturization and integration methods, and improving clinical applications in biomedical engineering. This work may facilitate the development of needle-type sensors.

1. Introduction

Needle-type sensor is a promising sensing method known for its high sensitivity, straightforward analytical procedures, rapid detection speed, portability, and potential for on-site or in-situ detection [1]. This sensor, commonly characterized by its slender and elongated shape, exhibits a pivotal role in monitoring and collecting data in diverse fields by providing precise and real-time measurements [2,3]. The needle-type sensors' ability to sense various parameters such as temperature [4], pressure [5], and biochemical changes [6] accurately in a localized manner makes them indispensable in healthcare, where they are utilized in medical procedures such as minimally invasive surgeries and continuous patient monitoring [4]. Moreover, needle-type sensors find applications ranging

* Corresponding author.
E-mail address: jingwenxu2013@pku.edu.cn (W. Xu).

https://doi.org/10.1016/j.heliyon.2024.e27399
Received 5 November 2023; Received in revised form 27 February 2024; Accepted 28 February 2024
Available online 7 March 2024

from heavy metals to gas monitoring, enabling precise measurements in challenging and constrained environments [7,8].

The needle-type sensors have witnessed remarkable advancements in recent years, driven by innovations in materials, fabrication techniques, and sensing mechanisms. Therefore, within the continually expanding landscape of scientific research, it is crucial to understand the dynamics of knowledge dissemination, collaboration patterns, and the impact of scholarly work. This is why scientometric analysis emerges as a powerful tool, offering insights into the intricate web of scientific communication by analyzing publications and their contained information [9]. It holds immense significance in contemporary academia and research management by identifying emerging trends and performing the evaluation of research status, thereby aiding researchers in understanding the current frontiers of the field and making informed research decisions [10]. While scientometric analyses have been conducted on various sensors, including electrochemical sensors, electrochemiluminescence sensing, and sensor-based rehabilitation [2,11,12], a similar study on needle-type sensors is yet to be done.

CiteSpace, a Java-based scientometric software invented by Prof. Chaomei Chen, stands as one of the most popular software in the field of information visualization and knowledge mapping [13]. It provides a systematic approach to analyze and visualize the evolution and impact of scientific research, aiding researchers in gaining valuable insights into their respective fields [14].

In this study, we investigate the historical evolution, current status, and the latest trends in-depth by manually analyzing the knowledge graph generated by CiteSpace software. The analysis covers annual trends, journals, institutions, countries, disciplines, authors, references, and keywords of the included publications. Through this study, we will furnish a comprehensive overview of the preceding research and identify potential directions in the field of needle-type sensors, as well as underscore the significance of needle-type sensors in advancing scientific development and facilitating technological innovation.

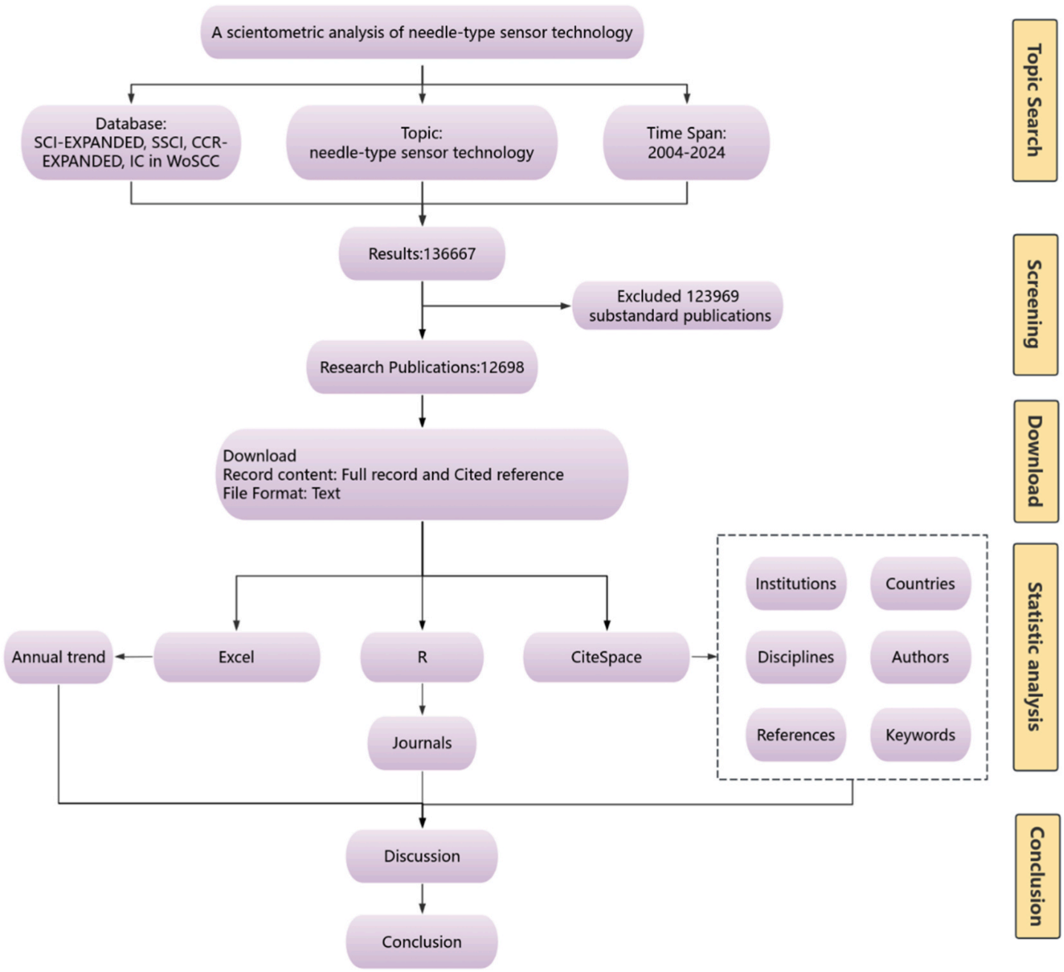

Fig. 1. Flow chart of the scientometric analysis in this paper.

2. Data sources and analysis methods

2.1. Data sources

We opt for the Web of Science Core Collection (WoSCC) database, which is widely acclaimed as the world's largest and most reliable database [11], to conduct our publication search. To ensure comprehensive data retrieval, the search formula "TS = Needle-type sensor OR TS= Needle-type sensors OR TS= Sensing needle OR TS= Sensing needles OR TS= Probe sensor OR TS= Probe sensors OR TS = Microneedle sensor OR TS = Microneedle sensors OR TS= Needle detecting OR TS= Needle detectings OR TS= Probe detecting OR TS= Probe detectings" is employed and indexed in SCI-EXPANDED, SSCI, CCR-EXPANDED, and IC. The retrieved publications span from January 1, 2004, to January 1, 2024, with no language restrictions.

2.2. Inclusion and exclusion criteria

We incorporate reviews and articles focusing on needle-type sensors, ensuring their accessibility. Nonetheless, the duplicate publications and those with incomplete information are excluded from our analysis.

2.3. Study selection

Both authors (G. Yang and Y. Yang) screen all retrieved publications independently based on the inclusion and exclusion criteria. Any disagreements are resolved through consensus or a third-party arbitrator (W. Xu).

2.4. Analysis method

The included publications are exported in RefWorks format and renamed as "download_XX." Excel and the bibliometrix package in R software [15–17] are used to calculate the number of journals and publications. Then, the data is imported into the CiteSpace software with time slices set from 2004 to 2024, where each slice represents one year; the selection criteria is set to be "Top N = 20", indicating the top 20 levels of most cited or frequent items per slice. Each level could comprise several qualified nodes. The Pathfinder and Pruning sliced networks algorithms are used for optimal visual results in graph pruning, with other settings at default. Subsequently, the CiteSpace software is employed to analyze the annual trend, journals, disciplines, authors, institutions, countries, references, and the keywords of the included publications. The knowledge graph generated by the software is refined to improve the result presentation. Within the graph, node connections represent collaborations among research entities and node size correlates with the frequency of their occurrences. Finally, all the graphs are exported in PDF format for subsequent analysis. The entire scientometric research process is illustrated in Fig. 1.

3. Results

A total of 136667 publications are retrieved from the WoSCC database. After screening, 12698 publications meeting the criteria are included in the study, consisting of 11700 articles and 476 reviews. All included publications are exported by January 1, 2024.

3.1. Annual trend

The annual publication trend can reflect the significance attributed to a specific subject [18]. Fig. 2 illustrates the publication and

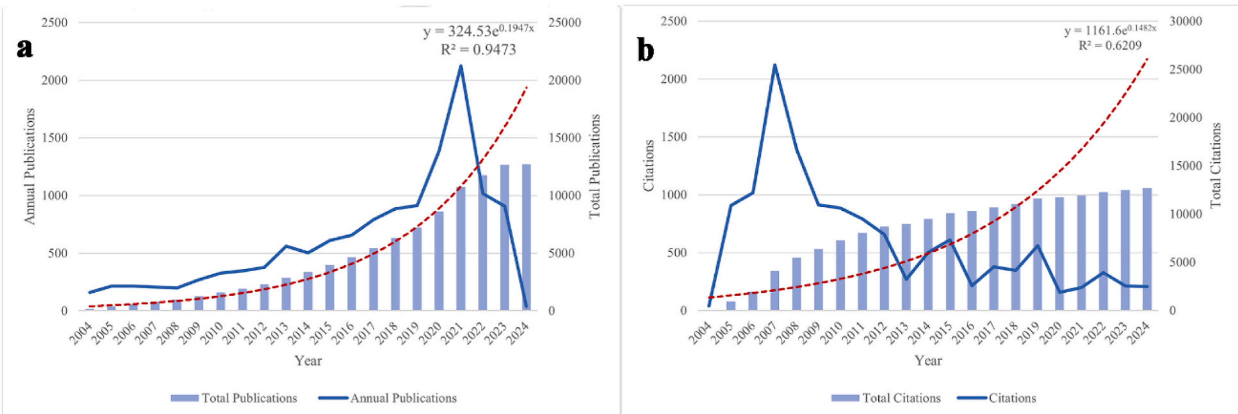

Fig. 2. The annual trends of publications and citations. The annual trend of publications (a), and the annual trend of citations (b), respectively.

citation trends related to needle-type sensor research spanning the years from 2004 to 2024. The number of publications related to needle-type sensors demonstrates a consistent rise, with a noticeable acceleration before 2021 but encounters a development bottleneck in recent years. However, citations exhibit a substantial increase alongside the number of published papers before 2007, and since then, there has been an extended period of decline.

Fig. 2 depicts the three-stage evolution of paper publication and citation trends. (1) The initial period (2004–2008): annually, fewer than 250 papers are published, totaling under 1000. Despite this, citations significantly increase, peaking at 2123 in 2007, as these publications are regarded as the foundation of the field. (2) The expansion period (2009–2019): during this period, the average number of annual publications is more than 250, with a rapid growth rate. By 2019, the cumulative total surpasses 7000, marking needle-type sensors' rising scholarly interest. (3) Boom period (2020–2023): annually, publications notably surpass 1000, peaking in 2021 with over 2000 articles. Concurrently, the total publications exceeded 10000, indicating a surge in research activity. According to the trend line of the total number of publications (represented by the dotted line in Fig. 2a), it is expected that the annual number of publications will still rise in the next few years. According to the trend line of the total number of citations (represented by the dotted line in Fig. 2b), the frequency of citations has the willingness to increase in the next few years.

3.2. Journal

Within the total of 1790 journals publishing relevant studies, the top 10 journals with the highest number of needle-type sensors-related publications are displayed in Fig. 3, which play a vital role in disseminating academic knowledge. These ten journals publish 20.633% of all the studies on needle-type sensors. The three highest-ranked journals from this selection are Sensors and Actuators B: Chemical, Sensors, and IEEE Sensors Journal. These three journals yield 666, 404, and 327 publications on needle-type sensors, accounting for 5.245%, 3.182%, and 2.575% of the total publications retrieved, respectively.

Table 1 displays the top 10 journals with most citations, which have a significant impact on the advancement of this field, representing 53.95% of all citations in the dataset. Regarding the JCR divisions, 9 of these ten journals are classified in Q1 and 1 in Q2, indicating the importance of needle-type sensors in the corresponding field. Among the journals in this field, Sensors and Actuators B: Chemical holds the highest number of citations, with 666 publications being cited a total of 4971 times, averaging 7.46 citations per publication. Analytical Chemistry comes next in rank (with 200 articles cited 4104 times, averaging 20.52 citations per publication), followed by Journal of the American Chemical Society (with 39 articles cited 3678 times, averaging 94.3 citations per publication).

3.3. Country/region

The country/region co-occurrence network depicted in Fig. 4 demonstrates that 53 countries/regions have engaged in needle-type sensor research. The top five countries with most publications are People's Republic of China (4181 counts), the USA (1889 counts), India (1225 counts), Japan (675 counts), and South Korea (650 counts). Evidently, the People's Republic of China and the USA have dominated the development of this field compared to other nations, signifying their heightened focus on needle-type sensing.

Centrality, which is defined by the count of shortest paths traversing a node in a network, illustrates the connecting role of nodes directly and reflects its significance for promoting coordinated development between regions. The top 5 are England (0.3), USA (0.22), Germany (0.19), France (0.19), and Japan (0.18), indicating their central role of international scientific research collaboration. In addition, it is worth noting that England secures the first position for centrality, but ranks 7th for publications' number, suggesting its important role in cooperation and great potential for future development.

3.4. Institution

The analysis of institutional cooperation (Fig. 5) shows that a total of 292 institutions have conducted researches in the field of

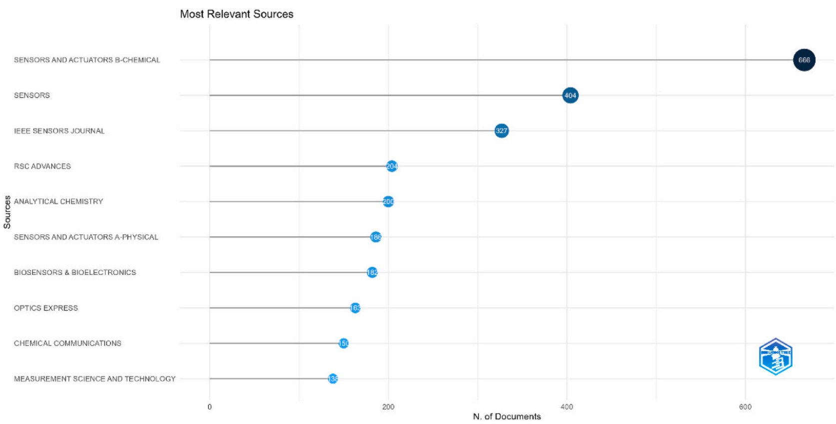

Fig. 3. Top 10 journals of publications.

Table 1
Top 10 journals with most citations.

Rank	Journal	Counts	Category (JCR)	Rank	Journal	Counts	Category (JCR)
1	Sensors and Actuators B: Chemical	4971	Q1	6	Analytica Chimica Acta	2641	Q1
2	Analytical Chemistry	4104	Q1	7	Angewandte Chemie-international Edition	2606	Q1
3	Journal of the American Chemical Society	3678	Q1	8	Chemical Reviews	2599	Q1
4	Chemical Communications	2970	Q2	9	Science	2532	Q1
5	Biosensors & Bioelectronics	2918	Q1	10	Talanta	2532	Q1

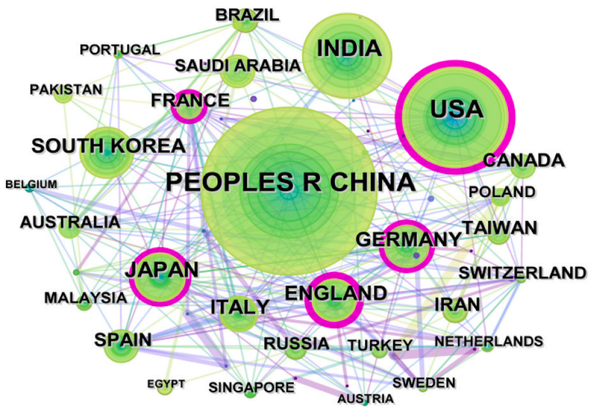

Fig. 4. Country co-occurrence network.

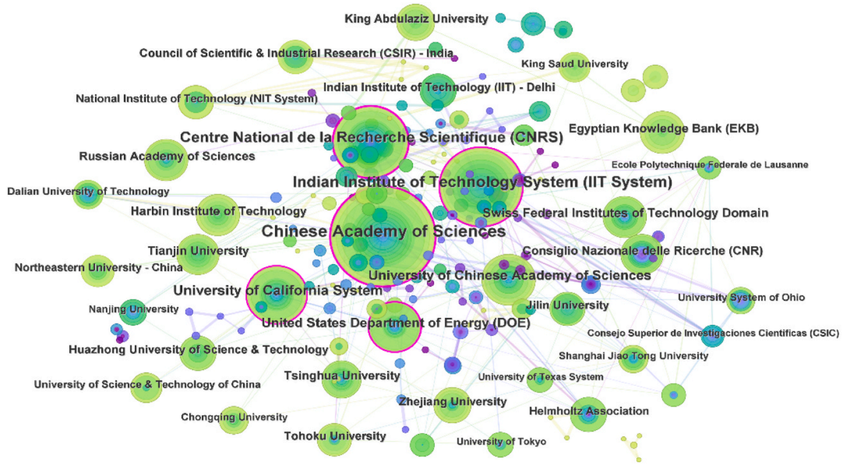

Fig. 5. Institution co-occurrence network.

needle-type sensors. Among them, the top 5 institutions with the highest number of publications are the Chinese Academy of Sciences (477 counts), Indian Institute of Technology System (IIT System) (321 counts), Centre National de la Recherche Scientifique (CNRS) (255 counts), University of California System (177 counts), and United States Department of Energy (DOE) (133 counts). The top 5 institutions with the highest centralities are CNRS (0.28), Chinese Academy of Sciences (0.22), United States Department of Energy (DOE) (0.17), University of California System (0.15), and Indian Institute of Technology System (IIT System) (0.11).

By examining the connections between nodes, we can gain a clear and intuitive understanding of institutional collaboration. As shown in Fig. 5, there are six institutions occupying a dominant position in inter-agency cooperation in this field: The Chinese Academy of Sciences-represented, the IIT System, the CNRS, the University of California System, the University of Chinese Academy of Sciences, and DOE. This indicates their significant scientific research capacity and academic influence in the field, which can be considered as a potential research partner for other institutions.

3.5. Author

The results of the author co-occurrence analysis (Fig. 6) demonstrate that a total of 957 authors have contributed to the research. According to the Price Law: $N \approx 0.749 \times N_{max}^{1/2}$ Nmax is the publications of the top contributing author)[19], since Gupta BDholds the highest publication count (60 counts), we can get $N \approx 5$. Thus, there are 98 core authors with a cumulative total of 951 publications, constituting 34.8% of the total publications. As the percentage is less than 50%, we can conclude that the formation of a core author group has not yet transpired. Therefore, to foster the advancement of the field, greater collaborative endeavors should be embraced.

There are 4 obvious cooperative teams in Fig. 6. The Harun SW team leads in terms of publications, while the Zhang Yu team shares the highest number of researchers. Harun SW's team primarily researches fiber optic sensors for the identification of human metabolites and biological signals such as uric acid, glucose, and electrocardiogram signals [20–22]. The team represented by Zhang Yu is devoted to the development and improvement of optical fiber sensors [23–25]. Zhao Yong's team's current research interests appear to center around developing innovative fiber optic sensors by utilizing unique materials and structures to enhance sensitivity, selectivity, and other performance for various applications, including environmental monitoring and gas detection [26,27]. The team, led by Liu Bin, focuses on the development of advanced sensing technologies, the study of triboelectric effects in various materials, and the exploration of new applications for these technologies in industry and research [28].

Co-cited authors are those referenced authors who are concurrently cited by other works [29]. This serves as a straightforward approach to identify authors with profound influence to the field. There are 235 authors with a total of 9765 citations. Table 2 presents the top 10 authors by citation count, where Wang Y is at the forefront with 572 citations, followed by Wang J (568 citations), Zhang Y (506 citations), Liu Y (500 citations), and Zhang J (427 citations), among others.

3.6. Discipline

Fig. 7 illustrates the disciplinary network of needle-type sensors. As depicted in the figure, needle-type sensors encompass a wide range of fields, with "Chemistry, analytical" being the most prominently representative, as needle-type sensors is an important method to detect and quantify specific chemical species. It is followed by "instrument & instrumentation" due to its inherent nature of needle-type sensors as sense instruments. "Physics, applied", and "Engineering, electrical & electronic" occupy the third and fourth position, respectively. "Materials Science, Multidisciplinary" holds the fifth position due to its important role in improving sensor performance and the exceptional sensing capabilities of the molecules with nano or micro scale. It is worth noting that all five categories make their first appearance in 2004.

When we examine the subject centrality, "Materials Science, Multidisciplinary" exhibits the highest centrality (0.34), followed by "Engineering, Mechanical" (0.32), and "Nanoscience & Nanotechnology" (0.25). This suggests that multidisciplinary material holds promise for the future development of needle-type sensors and that the integration of disciplines and the development of new materials are significant in this field.

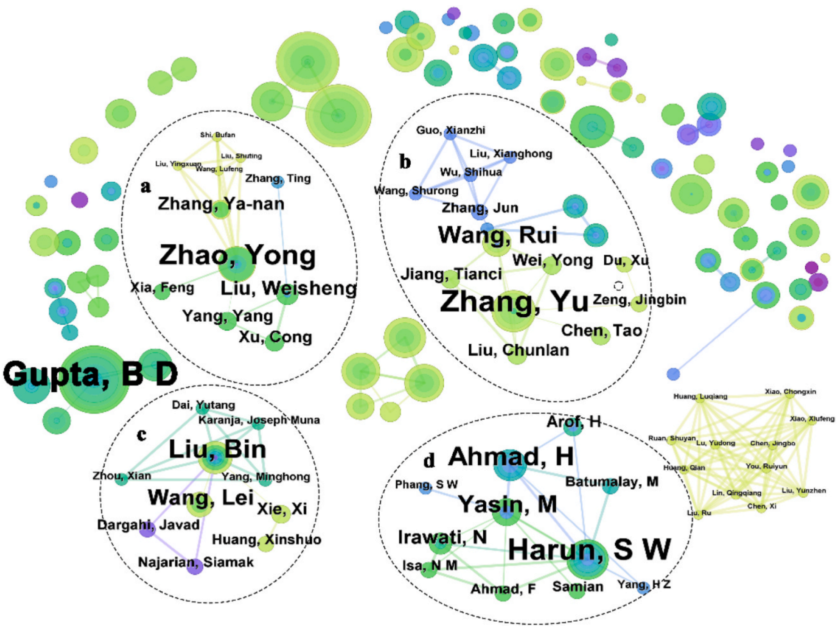

Fig. 6. Author co-occurrence network with 4 obvious cooperative teams (a-d).

Table 2
Top 10 cited authors.

Rank	Author	Citations	Rank	Author	Citations
1	Wang Y	572	6	Li Y	391
2	Wang J	568	7	Zhao Y	391
3	Zhang Y	506	8	Liu J	356
4	Liu Y	500	9	Zhang X	294
5	Zhang J	427	10	Wang L	286

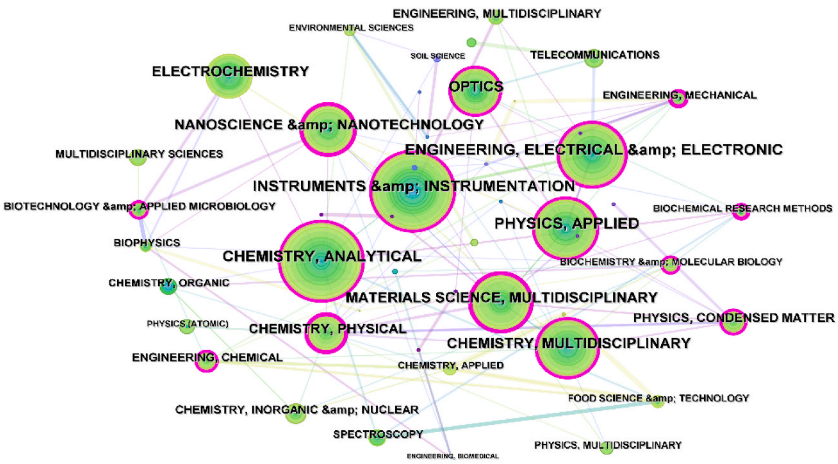

Fig. 7. Discipline category network.

3.7. Keywords

3.7.1. Keywords co-occurrence

Keywords reflect the core concept of the publications, and keywords co-occurrence analysis could be employed to investigate the emergence and dissemination of hotspots in a specific research area [30]. Fig. 8 shows the keywords co-occurrence network, consisting of 318 nodes and 1112 links. Following the consolidation of synonyms, the top 5 keywords by frequency are: sensor (1957 counts),

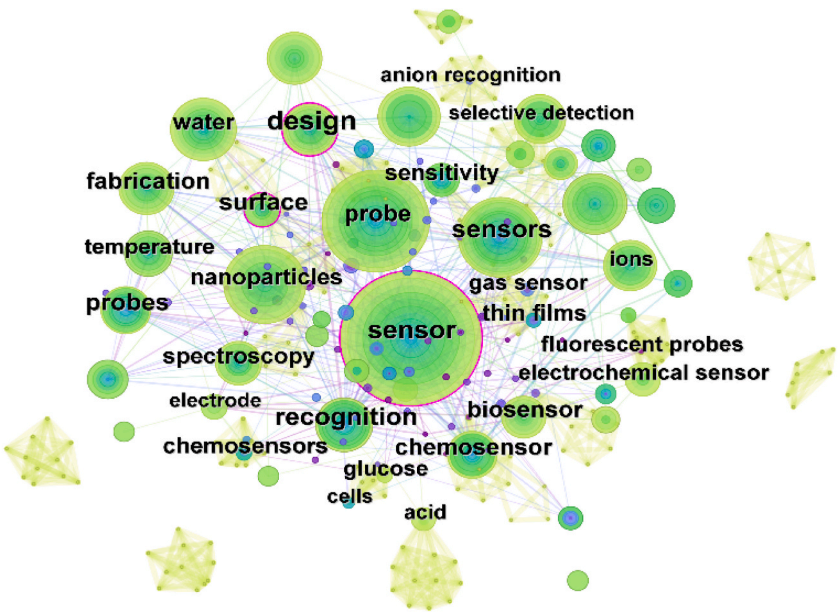

Fig. 8. Keyword co-occurrence network.

probe (1219 counts), nanoparticles (768 counts), water (500 counts), and fluorescent probe (434 counts).

Reviewing the publications related to the high-frequency occurrence keywords, the following could be observed: (1) Manufacturing of needle-type sensors for detection equipment is the current research focus, especially in the field of bioengineering, such as monitoring blood sugar [31], skin humidity [32], and disease markers [33]. (2) Needles are mostly coated with nanoparticles, which have a high surface area enabling fast and reversible responses [34]. (3) Needle-type biosensors have attracted increasing attention, as it is the most mentioned type of sensor (268 counts) in the analysis, indicating broad prospects for development.

3.7.2. Keywords cluster

The analysis of the keyword cluster is based on the log-likelihood rate (LLR) algorithm and results in 14 keyword clusters (Fig. 9a). We judge the significance of the cluster by the Q value (modularity) and the S value (silhouette) [35]. The Q value is 0.8128 (greater than 0.3), which means that the network is significant. Additionally, the S value is 0.9173 (greater than 0.7), affirming the high reliability of clustering results.

By reviewing Fig. 9b, the clusters could be broadly divided into 3 categories: structure-related (#2 surface, #6 trivial and nontrivial logic circuits, #7 charge density, #15 carbon nanotubes, #16 quantum dots); technology-related (#0 sensor, #1 electrochemical sensor, #4 gas sensor, #8 microneedles, #9 chemosensors, #10 modal probe sensor, #14 multifunctional sensor); application-related (#3 spectroscopy, #5 acid, #11 on off, #12 in vivo analysis, #13 copper detection, #17 dinotefuran).

3.7.3. Keywords burst

The term "keywords burst" signifies a substantial surge in keyword frequency over a period, indicating an increased focus on the topic [36]. Fig. 10 displays the top 25 keywords with the strongest citation bursts. As keyword bursts represent research hotspots at specific times, they can be divided into three distinct periods. From 2004 to 2011, the primary focus of researchers is on the structural design. From 2012 to 2019, the focus shifts to in-vivo detection, with the concurrent use of fluorescent probes to boost sensor sensitivity. From 2020 to 2024, colorimetric detection begins garnering interest among researchers for its cost-effectiveness, simplicity, and efficiency, emerging as a recent hotspot [37]. The hotspots mentioned above will exhibit their profound influence on future development.

3.8. Reference

We find a total of 1418 references with 4797 citations in the included publications. Table 3 shows the 10 most-cited references, which are considered fundamental to the development of subsequent researches.

By summarizing the top 5 cited papers, we find that Hu ZC (2014) [38] emerges as the most frequently referenced (93 citations) source. This work provides a comprehensive overview of metal-organic frameworks (MOFs), emphasizing their structural diversity, tunability, and potential applications. Besides, it underlines the versatility of MOFs by introducing their applicability in areas such as gas storage, separation, catalysis, and drug delivery. Yang YM (2013) [39] reviews the application of chemodosimeters in bioimaging. These compounds emit light upon reacting with specific substances, rendering them valuable for visualizing and analyzing intricate biological structures within living cells and organisms. Furthermore, the article elucidates the operational principles and fabrication techniques of luminescent chemodosimeters, emphasizing their crucial role in the detection of heavy metal cations, which are acknowledged as hazardous pollutants. Lustig WP (2017) [40] investigates deeper into a specific subclass of MOFs known as luminescent metal-organic frameworks (LMOFs). This paper extends the discussion on LMOFs by detailing their use in sensing applications. It outlines the recent developments in this field since 2014, focusing on how LMOFs can be used to sense and detect environmental pollutants, toxins, and other significant substances. The document underscores the importance of luminescence-based detection and how various interactions within the MOF structure can lead to changes in emission spectra, useful for sensing applications. Carter KP

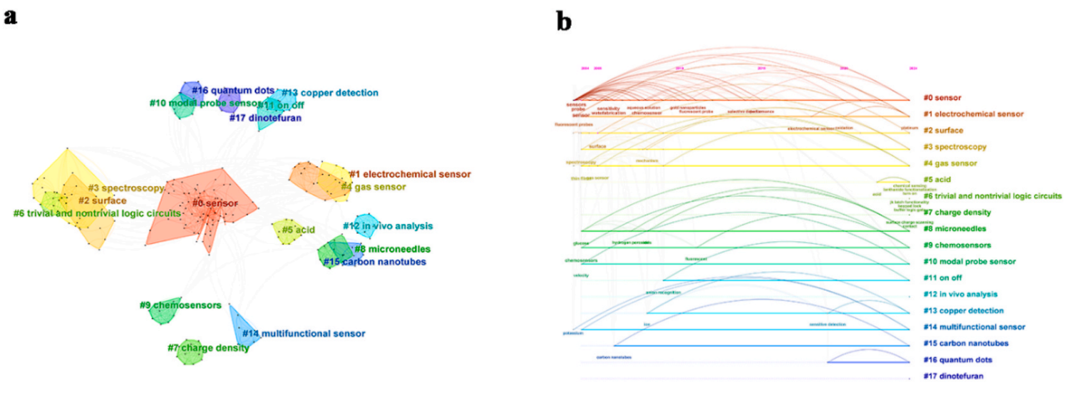

Fig. 9. Keywords cluster network. The keywords are divided into 18 clusters of different colors according to the LLR algorithms (a), the timeline and detailed information of each cluster (b). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

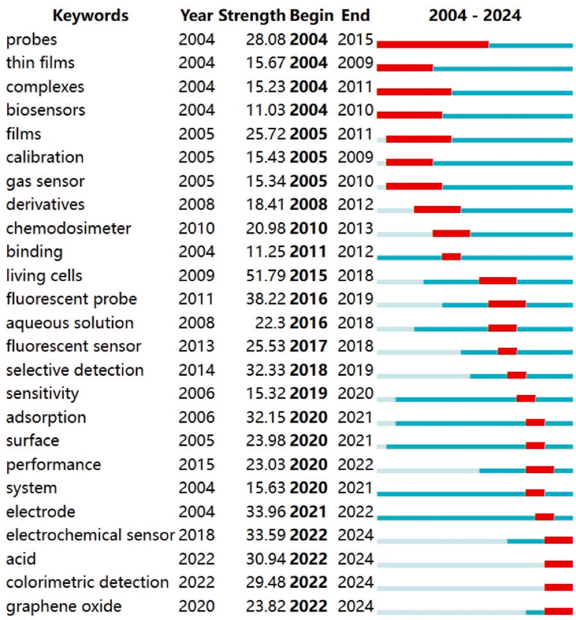

Fig. 10. Top 25 keywords with the strongest citation burst.

Table 3
Top 10 cited references.

Rank	Title	First author	Journal	Publication year	citations
1	Luminescent metal-organic frameworks for chemical sensing and explosive detection [38]	Hu ZC	Chemical Society Reviews	2014	93
2	Luminescent Chemodosimeters for Bioimaging [39]	Yang YM	Chemical Reviews	2013	61
3	Metal-organic frameworks: functional luminescent and photonic materials for sensing applications [40]	Lustig WP	Chemical Society Reviews	2017	55
4	Fluorescent Sensors for Measuring Metal Ions in Living Systems [41]	Carter KP	Chemical Reviews	2014	53
5	Fluorescent and colorimetric sensors for detection of lead, cadmium, and mercury ions [42]	Kim HN	Chemical Society Reviews	2012	51
6	Sensors for the optical detection of cyanide ion [43]	Xu Z	Chemical Society Reviews	2010	50
7	Luminescent Functional Metal-Organic Frameworks [44]	Cui YJ	Chemical Reviews	2012	49
8	Lanthanide Organic Framework as a Regenerable Luminescent Probe for Fe^{3+} [45]	Xu H	Inorganic Chemistry	2015	44
9	Tools and tactics for the optical detection of mercuric ion [46]	Nolan EM	Chemical Reviews	2008	42
10	Metal-Organic Framework Materials as Chemical Sensors [47]	Kreno LE	Chemical Reviews	2012	41

(2014) [41] offers an exhaustive overview of fluorescent sensors' application and evolution in detecting and quantifying metal ions within biological systems. This study details the primary characteristics of metal ion fluorescent sensors, focusing on their photophysical attributes and signal modulation mechanisms. Additionally, it classifies sensors employed in live-cell imaging into molecular, genetically encoded, and hybrid probes. The review highlights critical factors to consider when integrating sensors into biological systems, including influences on intracellular sensor concentration, buffering, and localization. Building upon previous basic research, Kim HN (2012) [42] focuses on the development of fluorescent and colorimetric sensors for selectively detecting metal ions and classifying them into various categories based on their receptors, including small molecule-based sensors, calixarene-based chemosensors, BODIPY-based chemosensors, polymer-based chemosensors, DNA functionalized sensing systems, protein-based sensing systems, and nanoparticle-based sensing systems. The work highlights this field's interdisciplinary approach, integrating chemistry, biology, and materials science to address a crucial environmental challenge.

Deeper analysis of the highly cited papers revealed the following hotspots: (1) Optimize the design of needle-type sensors, including choosing suitable conductive materials and reducing sensor size; (2) improve the performance of needle-type sensors, including accuracy, efficiency, and minimally invasive measurement of biomarkers.

4. Summary and prospects

4.1. Research status

Researches on needle-type sensor technologies have undergone a continuously increasing period before entering a boom period with a large number of related publications emerging in recent years. As the most frequently cited journal, Sensors and Actuators B: Chemical also publishes the majority of related papers. The People's Republic of China is at the forefront of research with 4181 publications, while England occupies a central position due to its research influence. The Chinese Academy of Sciences is the foremost publishing institution, with Gupta BD as the principal author. While,the most cited author is Wang Y and the most cited reference is finished by Hu ZC (2014) [38], indicating their high impact in this field.

4.2. Research hotspots and frontiers

Through the keywords and references analysis, we identify the following three research hotspots, which are regarded as the potential future trends in the needle-type sensors.

4.2.1. Biomedical engineering

Biomedical engineering (BME) is a youthful interdisciplinary field which blends the principles and methodologies from engineering, biology, chemistry, physics, and computer science to devise innovative healthcare and medical science solutions [48]. With a primary commitment to enhancing human health and well-being, these innovations find applications in diagnosing, treating, and preventing diseases and eventually improving the overall quality of life for people worldwide [49].

The prominent team led by Harun SW has conducted comprehensive and pertinent research on biomedical engineering topics, which has achieved the highest centrality ranking through discipline analysis. Additionally, reference analysis highlights biomedical engineering as a recent hotspot, indicating a strong potential for future research orientation in the field of biomedical engineering.

In previous studies, needle-type sensors have been widely applied in many aspects of biomedical usage due to their sharp tips, which facilitate cell/organ penetration by inducing highly localized stress [50]. Naghavi AH et al. [51] have developed a biomedical imaging system based on ultrawideband microwave radar, capable of detecting strokes within the human head by inserting a series of body-matched microsensors. This method has enabled real-time visualization of bleeding areas during biopsies and increased the likelihood of identifying clots within the head region. Furthermore, the innovative application of needle-type sensors in various diagnostic and monitoring tasks has been seen. The microneedles (MNs), which are primarily used to facilitate transdermal drug delivery and uptake of interstitial fluid in a minimally invasive manner to the skin [52,[53]], have the potential to revolutionize how medications are administered and how bodily fluids are sampled for medical analysis, as these devices can create channels through the stratum corneum and thus facilitate efficient drug delivery to the dermis. Therefore, driven by the significantly expanded application in the field of BME, there exist a lot of electrochemical-based devices like glucometers, immunosensors, and devices for monitoring carcinogenic chemicals, mutagenic chemicals, and endocrine-disrupting compounds [54]. In tissue engineering, biosensors have become crucial tools for disease diagnosis benefiting from the tiny size of needle-type sensors. They are selective, sensitive, and rapid, offering a more advanced alternative to traditional ELISA analytical technology and capitalizing on the ability to monitor micro biophysiological signals in real-time and on-site by integrating biological, chemical, and physical technologies [55].

Moreover, there has been progress in needle-based electrical impedance spectroscopy. Liu, J et al. [56] have developed a system that classifies different tissue types using impedance measurements taken with a modified needle. This technology is visualized through a MATLAB Graphical User Interface based on the spatial sensitivity distribution of the needle, offering a new dimension in tissue analysis. Besides, with the rapid development of surgical robotics, the sensor has also received the attention of researchers as one of the important components. For example, Soudan M et al. [57] have developed a micro-force sensor that can provide haptic feedback and quantify robotic surgery mechanics and dynamics for precise tissue stress measurement during surgery. Besides, needle-type sensors are of great significance in promoting the scientific and quantitative research of acupuncture and moxibustion, which are effective traditional Chinese medicine treatment methods, through offering real-time monitoring of in vivo physiological changes during the acupuncture process [58].

However, despite the significant progress mentioned above, needle-type sensors face several challenges as well. For example, the biocompatibility of materials employed in needle-type sensors is critical to prevent adverse reactions in biological settings, such as in vivo devices. Furthermore, the still relatively large size of needle-like sensors compared to biological tissues, coupled with the lack of flexibility, may make them potentially harmful to the human body [59]. The cost and scale of production limit the widespread industrialization of MNs, which is another significant barrier to their adoption on a larger scale [60].

Therefore, optimizing the materials and the design of the needle-type sensors is of great significance to ensure their outstanding properties (for example, minor damage, accurate measurement, and rapid response), which may lay the foundation for clinical applications in the field of bioengineering in the future.

4.2.2. Multidisciplinary materials science

Multidisciplinary materials science is a field that utilizes physics, chemistry, metallurgy, and other disciplines to examine the properties and applications of materials [61]. Multidisciplinary materials science ranks the highest in centrality among all disciplines. Furthermore, there is a total of 1603 obtained publications related to needle-type sensors for multidisciplinary materials science. All of these demonstrate that multidisciplinary materials science is receiving increasing attention.

There are several popular choices for needle-type sensors including carbon fibers, platinum/iridium (Pt/Ir), tungsten, ZnO, polymers, quartz, ceramics, and nanomaterials. Carbon fibers, known for their excellent electrical conductivity, biocompatibility, and mechanical strength, are suitable for detecting low neurotransmitter concentrations like dopamine [62]. Pt/Ir electrodes are widely used in neural and physiological monitoring due to their excellent corrosion resistance and stable electrochemical properties. Furthermore, Pt/Ir electrodes' integrity maintained over extended periods will facilitate their chronic implantation [63]. Tungsten needles are known for their durability, mechanical strength, and good electrical conductivity, making them suitable for applications requiring robust electrodes or for long-term sensing [64]. Additionally, as demonstrated in the studies conducted by T. Gao and T. Wang, the ZnO electrode shows an impressive performance for gas sensing, attributed to its pronounced gas sensitivity [65]. Polymers, flexible and often biocompatible, can be molded into complex shapes and are usually cheaper than metal or silicon-based sensors [66]. The quartz's excellent chemical resistance, good biocompatible, and good thermal stability make it useful in microfluidic devices [67]. Ceramics, which are highly stable, resistant to high temperatures, and chemically inert, are usually used in harsh environments where other materials may fail [68]. Nanomaterials can provide high sensitivity, electrical conductivity, and unique mechanical properties, which facilitate them leading the cutting-edge of sensor technology [69].

Given that the aforementioned materials may have some shortcomings, for example, carbon fiber electrodes are prone to fouling, Pt/Ir electrodes are costly, while tungsten electrodes may exhibit electrode drift, it is essential to further develop biocompatible materials that enhance the safety and durability of needle-type sensors within the body.

4.2.3. Miniaturization and integration

In this section, we introduce methods for decreasing the dimensions of needle-type sensors and enhancing their functionality. As stated in the research [70], microneedle technologies have the potential to expand wearable health monitoring capabilities from physiology to biochemistry. Additionally, decreasing the needle size is effective in reducing patient discomfort during medical applications.

Miniaturization of needle-type sensors often relies on Micro-Electro-Mechanical Systems (MEMS) technology. MEMS enables the fabrication of tiny, high-precision sensors with dimensions on the microscale. The key steps in MEMS-based miniaturization include lithography, etching, and thin-film deposition techniques [72]. Besides, advances in nanotechnology have further pushed the boundaries of miniaturization. By leveraging nanomaterials like carbon nanotubes and nanowires, researchers have developed needle-type sensors with diameters on the nanoscale. These sensors exhibit exceptional sensitivity and can access previously unreachable spaces within biological tissues or industrial equipment [34].

Meanwhile, as one of the most common of integration method, combining multiple needle-type sensors into arrays allows for simultaneous measurement of multiple parameters [73]. The arrays are particularly useful in medical diagnostics, where they can provide comprehensive information about a patient's condition. Besides, the integration, which allows materials with exceptional sensing properties to be fused with other needle device, will enable the device to function as a sensor while carrying out other purpose. Kim Jiseok et al., for instance, explore the integration of pressure sensors with printed organic thin-film transistors for flexible and large-area tactile sensing applications [71]. And according to the result of keywords brust analysis, the design of sensors, which mainly focuses on the miniaturization and integration process, become the hotspot from 2004 to 2011.

From the above findings, it is evident that miniaturization and integration will promote the creation of superior needle-type sensors, which is important for the development of needle-type sensors, especially for the medical application.

5. Conclusion

This study comprehensively explores the research hotspots and frontiers of needle-type sensor technology using scientometric analysis. Drawing from the findings, the following predictions are put forth for the future advancement of this field: (1) Further develop biocompatible materials to enhance the sensing properties of needle-type sensors; (2) Optimize the structure of the needle-type sensors by miniaturization and integration methods; (3) Apply needle-type sensors in the field of bioengineering.

6. Strength and Limitation

Based on scientometric analysis, this study aims to provide readers and researchers with relevant information on needle-type sensing research in a visual way. Therefore, it is convenient for researchers to understand the research progress, research hotspots, and frontiers in such a rapidly developing field. At the same time, we have also studied the collaboration of different countries, institutions, authors, and disciplines. Potential partnerships and reliable information about advancements, frontiers, and potential research trends in this field can be provided to scientists and funding agencies.

However, this study has limitations. Firstly, though the WoSCC database is recognized as the most extensive database in the world, it is still possible to miss the publication and cause publication bias. For this reason, we make our search formula as comprehensive as possible and expand our inclusion as much as possible by means of two-person back-to-back screening. Then, though we have not restricted language in our retrieval strategy, language bias is inevitable because English language has been the predominant language in the Web of Science database. Therefore, the sources of research information can be expanded in the future to analyze the research hotspots and trends in this field comprehensively.

Data availability statement

The data associated with this study have not been deposited in a publicly available repository, as all research data are included within the article. Further inquiries can be directed to the corresponding author.

CRediT authorship contribution statement

Guangyi Yang: Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Wenjing Xu:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Botan Xu:** Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Yi Yang:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Pengwei Li:** Visualization, Software, Project administration, Methodology. **Aotian Yu:** Visualization, Software, Methodology, Investigation. **Simin Ning:** Software, Methodology, Data curation. **Qixuan Fu:** Writing – original draft, Visualization. **Rong Zhang:** Visualization, Software, Resources. **Xiaohan Liu:** Software, Formal analysis.

Declaration of competing interest

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

Acknowledgments

This study is supported in part by grants from the High-Level Talent Project, Beijing University of Chinese Medicine (2022-XJ-KYQD-004).The table of contents in this paper is accomplished in FigDraw.The author would like to express sincere thanks to the mentor Wenjing Xu for her patient guidance and selfless help in this work.

References

[1] H. Han, D. Pan, F. Pan, X. Hu, R. Zhu, A functional micro-needle sensor for Voltammetric determination of iron in coastal waters, Sensor. Actuator. B Chem. 327 (2021) 128883.

[2] X. Yu, H. Wang, X. Ning, R. Sun, H. Albadawi, M. Salomao, A.C. Silva, Y. Yu, L. Tian, KohA, C.M. Lee, A. Chempakasseril, P. Tian, M. Pharr, J. Yuan, Y. Huang, R. Oklu, J.A. Rogers, Needle-shaped ultrathin piezoelectric microsystem for guided tissue targeting via mechanical sensing, Nat. Biomed. Eng. 2 (2018) 165–172.

[3] L. Rivas, S. Dulay, S. Miserere, L. Pla, S.B. Marin, J. Parra, E. Eixarch, E. Gratacós, M. Illa, M. Mir, J. Samitier, Micro-needle implantable electrochemical oxygen sensor: ex-vivo and in-vivo studies, Biosens. Bioelectron. 153 (2020) 112028.

[4] J. Park, D.I. Cha, Y. Jeong, H. Park, J. Lee, T.W. Kang, H.K. Lim, I. Park, Real-time internal steam pop detection during radiofrequency ablation with a radiofrequency ablation needle integrated with a temperature and pressure sensor: preclinical and clinical pilot tests, Adv. Sci. 8 (2021).

[5] S.-W. Kim, G.-Y. Oh, K.-I. Lee, Y.-J. Yang, J.-B. Ko, Y.-W. Kim, Y.-S. Hong, A highly sensitive and flexible capacitive pressure sensor based on alignment Airgap dielectric, Sensors 22 (2022) 7390.

[6] T. Guo, F. Liu, X. Liang, X. Qiu, Y. Huang, C. Xie, P. Xu, W. Mao, B.-O. Guan, J. Albert, Highly sensitive detection of urinary protein variations using tilted fiber grating sensors with plasmonic nanocoatings, Biosens. Bioelectron. 78 (2016) 221–228.

[7] Y. Li, H. Han, C. Wang, Y. Liang, D. Pan, H. Wang, An antifouling gel-protected Iridium needle sensor: long-term, on-site monitoring of copper in seawater, Chemosphere 313 (2023) 137366.

[8] Y. Liu, B. Zhou, W. Wang, J. Shen, W. Kou, Z. Li, D. Zhang, L. Guo, C. Lau, J. Lu, Insertable, scabbarded, and Nanoetched silver needle sensor for hazardous element depth profiling by laser-induced breakdown spectroscopy, ACS Sens. 7 (2022) 1381–1389.

[9] A. Ninkov, J.R. Frank, L.A. Maggio, Bibliometrics: methods for studying academic publishing, Perspectives on Medical Education 11 (2021) 173–176.

[10] D. Xu, Y.-L. Wang, K.-T. Wang, Y. Wang, X.-R. Dong, J. Tang, Y.-L. Cui, A scientometrics analysis and visualization of depressive disorder, Curr. Neuropharmacol. 19 (2021) 766–786.

[11] X. Liu, S. Zhao, L. Tan, Y. Tan, Y. Wang, Z. Ye, C. Hou, Y. Xu, S. Liu, G. Wang, Frontier and hot topics in electrochemiluminescence sensing technology based on CiteSpace bibliometric analysis, Biosens. Bioelectron. 201 (2022) 113932.

[12] S. Facciorusso, S. Spina, R. Reebye, A. Turolla, R.S. Calabrò, P. Fiore, A. Santamato, Sensor-based rehabilitation in neurological diseases: a bibliometric analysis of research trends, Brain Sci. 13 (2023) 724.

[13] C. Chen, Z. Hu, S. Liu, H. Tseng, Emerging trends in regenerative medicine: a scientometric analysis in*citespace*, Expet Opin. Biol. Ther. 12 (2012) 593–608.

[14] C. CiteSpace Chen, A Practical Guide for Mapping Scientific Literature, Nova Science Publishers, Inc., New York, 2016.

[15] M. Aria, C. Bibliometrix Cuccurullo, An R-tool for comprehensive science mapping analysis, Journal of Informetrics 11 (2017) 959–975.

[16] C. Cuccurullo, M. Aria, F. Sarto, Foundations and trends in Performance Management. A twenty-five years bibliometric analysis in business and Public Administration domains, Scientometrics 108 (2016) 595–611.

[17] C. Cuccurullo, M. Aria, F. Sarto, Twenty years of research on performance management in business and public administration domains, Acad. Manag. Proc. 2013 (2013) 14270.

[18] A. Jahanshahi, M. Lopes, M. Brandão, E.A. De Castro, Development of bioenergy technologies: a scientometric analysis, Hel iyon 9 (2023).

[20] M. Yasin, M. Zulkarnaen, Y.G.Y. Yhuwana, Samian, A.H. Zaidan, S.W. Harun, Bundled plastic optical fiber based sensor for ECG Signal Detection, Optik 203 (2020) 164077.

[21] N. Irawati, S.W. Harun, S. Adwan, M. Alnowami, H. Ahmad, Pmma microfiber coated with al-doped zno nanostructures for detecting uric acid, Microw. Opt. Technol. Lett. 57 (2015) 2455–2457.

[22] A. Lokman, H. Arof, S.W. Harun, Dumbbell shaped inline mach–zehnder interferometer for glucose detection, Measurement 59 (2015) 167–170.

[23] C. Liu, C. Liu, Y. Wei, C. Shi, R. Wang, X. Wang, P. Ren, Y. Tang, Z. Liu, Y. Zhang, Highly sensitive SPR curvature sensor based on graded-index fiber, Opt Lett. 48 (2023) 3135.

[24] Y. Wei, C. Liu, C. Liu, C. Shi, Z. Ren, Z. Ran, T. Jiang, R. Wang, X. Wang, Y. Zhang, Z. Liu, Multichannel directional recognition SPR curvature sensor based on D-type double-clad multimode fiber, IEEE Sensor. J. 22 (2022) 21719–21726.

[25] Z. Liu, B. Zhao, Y. Zhang, Y. Zhang, C. Sha, J. Yang, L. Yuan, Optical fiber temperature sensor based on Fabry-Perot interferometer with photopolymer material, Sensor Actuator Phys. 347 (2022) 113894.
[26] Z. Lin, R. Lv, Y. Zhao, J. Zhao, X. Hu, R. Liu, A simple integrated interferometer for salinity and temperature measurement, IEEE Trans. Instrum. Meas. 72 (2023) 1–7.
[27] Y. Liu, Y. Zhang, S. Liu, B. Shi, L. Wang, Y. Zhao, Fiber optic room temperature ethanol sensor based on ZnSnO3/Tio 2 with UV radiation sensitization, Sensor. Actuator. B Chem. 399 (2024) 134814.
[28] T. Liu, W. Mo, X. Zou, B. Luo, S. Zhang, Y. Liu, C. Cai, M. Chi, J. Wang, S. Wang, D. Lu, S. Nie, Liquid–solid triboelectric probes for real-time monitoring of sucrose fluid status, Adv. Funct. Mater. 33 (2023).
[29] Y.-H. Chen, M.-Q. Yin, L.-H. Fan, X.-C. Jiang, H.-F. Xu, T. Zhang, X.-Y. Zhu, Bibliometric analysis of traditional Chinese medicine research on heart failure in the 21st century based on the WOS database, Hel iyon 9 (2023).
[31] L. Zhao, Z. Wen, F. Jiang, Z. Zheng, S. Lu, Silk/polyols/god microneedle based electrochemical biosensor for continuous glucose monitoring, RSC Adv. 10 (2020) 6163–6171.
[32] G. Bahuguna, V.S. Adhikary, R.K. Sharma, R. Gupta, Ultrasensitive organic humidity sensor with high specificity for healthcare applications, Electroanalysis 32 (2019) 76–85.
[33] Ö. Erdem, I. Eş, G.A. Akceoglu, Y. Saylan, F. Inci, Recent advances in microneedle-based sensors for sampling, diagnosis and monitoring of chronic diseases, Biosensors 11 (2021) 296.
[34] A. Choe, D. Qin, A.M. Yu, E. Chung, A. Jhunjhunwala, J.A. Rose, S.Y. Emelianov, PH-responsive ratiometric photoacoustic imaging of polyaniline nanoparticle-coated needle for targeted cancer biopsy, Photoacoustics 31 (2023) 100500.
[35] C. Chen, CiteSpace II: detecting and visualizing emerging trends and transient patterns in scientific literature, J. Am. Soc. Inf. Sci. Technol. 57 (2006) 359–377.
[36] H. Lin, X. Wang, M. Huang, Z. Li, Z. Shen, J. Feng, H. Chen, J. Wu, J. Gao, Z. Wen, F. Huang, Z. Jiang, Research hotspots and trends of bone defects based on web of science: a Bibliometric analysis, J. Orthop. Surg. Res. (2020) 15.
[37] Z. Golsanamlu, J. Soleymani, A. Gharekhani, A. Jouyban, In-situ preparation of norepinephrine-functionalized silver nanoparticles and application for colorimetric detection of Tacrolimus in plasma samples, Hel iyon 9 (2023).
[38] Z. Hu, B.J. Deibert, J. Li, Luminescent Metal-organic frameworks for chemical sensing and explosive detection, Chem. Soc. Rev. 43 (2014) 5815–5840.
[39] Y. Yang, Q. Zhao, W. Feng, F. Li, Luminescent chemodosimeters for bioimaging, Chem. Rev. 113 (2012) 192–270.
[40] W.P. Lustig, S. Mukherjee, N.D. Rudd, A.V. Desai, J. Li, S.K. Ghosh, Metal–organic frameworks: functional luminescent and photonic materials for sensing applications, Chem. Soc. Rev. 46 (2017) 3242–3285.
[41] K.P. Carter, A.M. Young, A.E. Palmer, Fluorescent sensors for measuring metal ions in living systems, Chem. Rev. 114 (2014) 4564–4601.
[42] H.N. Kim, W.X. Ren, J.S. Kim, J. Yoon, Fluorescent and colorimetric sensors for detection of lead, cadmium, and Mercury ions, Chem. Soc. Rev. 41 (2012) 3210–3244.
[43] Z. Xu, X. Chen, H.N. Kim, J. Yoon, Sensors for the optical detection ofcyanide ion, Chem. Soc. Rev. 39 (2010) 127–137.
[44] Y. Cui, Y. Yue, G. Qian, B. Chen, Luminescent functional metal–organic frameworks, Chem. Rev. 112 (2011) 1126–1162.
[45] H. Xu, H.-C. Hu, C.-S. Cao, B. Zhao, Lanthanide Organic Framework as a regenerable luminescent probe for $Fe3+$, Inorg. Chem. 54 (2015) 4585–4587.
[46] E.M. Nolan, S.J. Lippard, Tools and tactics for the optical detection of Mercuric Ion, Chem. Rev. 108 (2008) 3443–3480.
[47] L.E. Kreno, K. Leong, O.K. Farha, M. Allendorf, R.P. Van Duyne, J.T. Hupp, Metal–organic framework materials as chemical sensors, Chem. Rev. 112 (2011) 1105–1125.
[48] X. Gao, Frontiers in biomedical engineering, Adv. Funct. Mater. 30 (2020).
[49] H.R. Weed, Biomedical engineering - practice or research? IEEE (Inst. Electr. Electron. Eng.) Trans. Biomed. Eng. BME-22 (1975) 110–114.
[50] B. Liu, X. Yi, Y. Zheng, Z. Yuan, J. Yang, J. Yang, X. Yu, L. Jiang, C. Wang, A review of Nano/micro/milli needles fabrications for biomedical engineering, Chin. J. Mech. Eng. 35 (2022).
[51] A.H. Naghavi, H.R. Hassani, D. Oloumi, Improving the probability of stroke detection inside the human head using wideband polarimetric synthetic aperture radar imaging, Int. J. RF Microw. Computer-Aided Eng. 2023 (2023) 1–9.
[52] S. Wang, M. Zhao, Y. Yan, P. Li, W. Huang, Flexible monitoring, diagnosis, and therapy by microneedles with versatile materials and devices toward multifunction scope, Research 6 (2023).
[53] L.K. Vora, A.H. Sabri, P.E. McKenna, A. Himawan, A.R. Hutton, U. Detamornrat, A.J. Paredes, E. Larrañeta, R.F. Donnelly, Microneedle-based biosensing, Nature Reviews Bioengineering 2 (2023) 64–81.
[54] J. Wu, H. Liu, W. Chen, B. Ma, H. Ju, Device integration of electrochemical biosensors, Nature Reviews Bioengineering 1 (2023) 346–360.
[55] Y.-C.E. Li, I.-C. Lee, The current trends of biosensors in tissue engineering, Biosensors 10 (2020) 88.
[56] J. Liu, Ö. Atmaca, P.P. Pott, Needle-based electrical impedance imaging technology for Needle Navigation, Bioengineering 10 (2023) 590.
[57] M. Soudan, S.L. King, S. Chung, P.J. Brown, Development and validation of a 3DOF force sensing tool for in-situ surgical robotics, J. Med. Biol. Eng. 43 (2023) 332–338.
[58] H. Chang, M. Huo, Q. Zhang, M. Zhou, Y. Zhang, Y. Si, D. Zhang, Y. Guo, Y. Fang, Flexible needle-type microbiosensor for real-time monitoring traditional acupuncture-mediated adenosine release in vivo, Biosens. Bioelectron. 235 (2023) 115383.
[59] C. Li, L. Zhang, X. Zhang, G. Liu, J. Zhao, A compliant actuator for steering the needle within tissue with feedback of FBG-based shape sensing, Sensor Actuator Phys. 356 (2023) 114340.
[60] H. Lu, S. Zada, L. Yang, H. Dong, Microneedle-based device for biological analysis, Front. Bioeng. Biotechnol. (2022) 10.
[61] M.A. McEvoy, N. Correll, Materials that couple sensing, actuation, computation, and communication, Science (2015) 347.
[62] R.K. Poduval, S. Noimark, R.J. Colchester, T.J. Macdonald, I.P. Parkin, A.E. Desjardins, I. Papakonstantinou, Optical fiber ultrasound transmitter with electrospun carbon nanotube-polymer composite, Appl. Phys. Lett. 110 (2017).
[63] N. Zakaria, Y. Mohd, L.Y. Chin, M.N. Jalil, Z.M. Zain, Poly-ortho-phenylenediamine modified pt/IR microelectrode as impedimetric biosensor, Int. J. Electrochem. Sci. 16 (2021) 210736.
[64] X. Liu, G. Chen, P. Zhou, Y. Xu, X. Li, Z. Cui, J. Cui, Z. Hai, Q. Chen, D. Sun, High-temperature and wide-range anemometer based on plasma glow discharge, IEEE Sensor. J. 22 (2022) 3067–3073.
[65] T. Gao, T.H. Wang, Synthesis and properties of multipod-shaped zno nanorods for gas-sensor applications, Appl. Phys. A 80 (2004) 1451–1454.
[66] R. Pradeep, V. Siva, M.A. Jothi, A. Murugan, A. Shameem, S. Sanjana, E. Hemnath, A. G Al-Sehemi, Structural, surface morphological and dielectric studies of Guanidinium Salt Incorporated Poly (ethylene oxide)/poly (vinyl pyrrolidone) solid polymer electrolytes, Hel iyon (2024) 10.
[67] S. Klangprapan, B. Choke-arpornchai, P.A. Lieberzeit, K. Choowongkomon, Sensing the classical swine fever virus with molecularly imprinted polymer on Quartz Crystal Microbalance, Hel iyon 6 (2020).
[68] M. Mesrar, A. Elbasset, N.-S. Echatoui, F. Abdi, T. Lamcharfi, Microstructural and high-temperature dielectric, piezoelectric and complex impedance spectroscopic properties of k0.5bi0.5tio3 modified NBT-BT lead-free ferroelectric ceramics, Hel iyon 9 (2023).
[69] S. Malik, J. Singh, R. Goyat, Y. Saharan, V. Chaudhry, A. Umar, A.A. Ibrahim, S. Akbar, S. Ameen, S. Baskoutas, Nanomaterials-based biosensor and their applications: a Review, Hel iyon (2023) 9.
[70] Y. Li, H. Zhang, R. Yang, Y. Laffitte, U. Schmill, W. Hu, M. Kaddoura, E.J. Blondeel, B. Cui, Fabrication of sharp silicon hollow microneedles by deep-reactive ion etching towards minimally invasive diagnostics, Microsystems & Nanoengineering 5 (2019).
[71] J. Kim, T. Nga Ng, W. Soo Kim, Highly sensitive tactile sensors integrated with organic transistors, Appl. Phys. Lett. 101 (2012) 103308.
[72] A. Eidi, Design and evaluation of an implantable MEMS based biosensor for blood analysis and real-time measurement, Microsyst. Technol. 29 (2023) 857–864.
[73] S.N. Mustaffa, N. Md Yatim, A.R. Abdul Rashid, N. Md Yatim, V. Pithaih, N.S. Sha'ari, A.R. Muhammad, A. Abdul Rahman, N.A. Jamil, P.S. Menon, Visible and angular interrogation of Kretschmann-based SPR using hybrid AU–zno optical sensor for hyperuricemia detection, Hel iyon (2023) 9.