frontiers | Frontiers in Physics

TYPE Original Research
PUBLISHED 22 December 2023
DOI 10.3389/fphy.2023.1325851

OPEN ACCESS

EDITED BY
Tao Shao,
Chinese Academy of Sciences (CAS), China

REVIEWED BY
Cheng Cheng,
Chinese Academy of Sciences (CAS), China
Lanlan Nie,
Huazhong University of Science and Technology, China

*CORRESPONDENCE
Miao Yan,
yanmiao@csu.edu.cn
Hui Gong,
feelgonghui@126.com

RECEIVED 22 October 2023
ACCEPTED 30 November 2023
PUBLISHED 22 December 2023

CITATION
Guo L, Yan M, Gong H, Zou Z and Henningsen A (2023), Application of non-thermal plasma in medicine: a bibliometric and visualization analysis. *Front. Phys.* 11:1325851. doi: 10.3389/fphy.2023.1325851

Application of non-thermal plasma in medicine: a bibliometric and visualization analysis

Linna Guo[1,2], Miao Yan[2,3]*, Hui Gong[2,3]*, Ziang Zou[4] and Anders Henningsen[5]

[1]Department of Stomatology, The Second Xiangya Hospital, Central South University, Changsha, China, [2]International Research Center for Precision Medicine, Transformative Technology and Software Services, Changsha, China, [3]Department of Pharmacy, The Second Xiangya Hospital, Central South University, Changsha, Hunan, China, [4]Department of Gynecology and Obstetrics, The Third Xiangya Hospital, Central South University, Changsha, China, [5]Division Regenerative Orofacial Medicine, University Department of Oral and Maxillofacial Surgery, Medical Center Hamburg-Eppendorf, Hamburg, Germany

Non-thermal plasma has been widely studied in medicine due to its beneficial effect with low thermal or other damages. Numerous medical research studies have been conducted using non-thermal plasma devices; yet, to date, there is no report summarizing this field as a whole. In this study, we aim to perform a bibliometric analysis to assess the state of research, current research priorities, and emerging trends in non-thermal plasma medicine over the last two decades. Publications related to non-thermal plasma medicine (2002–2022) were searched in Web of Science core collection. Bibliometric analysis and visualization was then performed using R-Bibliometrix and CiteSpace. A total of 725 publications related to non-thermal plasma were identified. The annual number of publications has increased continuously over the past two decades. n the field of non-thermal plasma medicine, Germany, China and the United States dominated. Of all institutions, Leibniz Institute for Plasma Science and Technology published the most papers. The journal with highest citation was JOURNAL OF PHYSICS D-APPLIED PHYSICS. Bekeschus Sander published the highest H-value of articles. "Inactivation", "Apoptosis", "Chronic Wound" is the primary focus area of non-thermal plasma medicine, "Differentiation", "Water", "Gene Expression" and "Cell Death" were the main keywords of the new research hotspots. In this study, bibliometric methods were used to analyze current research priorities and trends in non-thermal plasma medicine and to identify the countries, institutions, authors, and journals with the greatest influence in the field to enhance collaboration and learning.

KEYWORDS

non-thermal plasma, medicine, bibliometric analysis, Citespace, visualization

Introduction

In recent years, plasma has been widely studied and used in medicine. Non-thermal plasma is plasma generated by partial ionization of gases (with ionization degrees from 10^{-7} to 10^{-4}) at low temperatures ($\leq 10^4$ K), which allows its use with low thermal damage under certain conditions. Usually, non-thermal plasma generators produce a mixture of reactive species, such as reactive oxygen species (ROS) and reactive nitrogen species (RNS), in addition to charged particles and UV radiation. These reactive species have demonstrated various biological effects, including anti-microbial, anti-cancer, wound healing, tissue

regeneration, implant surface treatment, and anti-inflammatory activities [1, 2]. Consequently, plasma medicine has emerged as a new field for the use of non-thermal plasma in medical treatments [3]. Non-thermal plasma treatments are relatively painless, non-invasive, and do not require the use of harmful chemicals or radiation. Given the wide range of studies on non-thermal plasma medicine, organizing and summarizing the publications could help to advance the field and provide guidance to future researchers.

Understanding the developmental trends and new advancements in plasma medicine is critical. However, keeping up with the rapidly changing landscape of biomedical research is challenging. Bibliometric analysis provides a statistical and quantitative approach to visualize evidence from a large number of published studies, including data on keywords, citation reports, authors, affiliated countries, institutions, and journals [4, 5]. Despite the potential of bibliometric analysis, no study has examined global research collaborations, current research priorities, and development trends of non-thermal plasma medicine. To gain insights into the existing evidence and determine future research directions, it is critical to conduct a bibliometric analysis to assess global collaboration patterns and developmental trends in non-thermal plasma medicine.

Scientific publications are fundamental to the progress of academic exchange and clinical guidelines. Evaluative bibliometrics is a quantitative scientific discipline that uses various methods to assess research performance and enables the identification of influential publications and stimulation of new research ideas. It is important to recognize that bibliometric analysis differs from literature reviews in that the former offers quantitative information such as citation frequency, authorship, publication patterns, and research collaborations in a specific field, whereas the latter provides qualitative analysis of research literature. Despite numerous articles on bibliometric analysis in various fields, relatively few studies have been conducted in non-thermal plasma medicine. Although some reviews on plasma medicine are available, there are still gaps in quantitative analysis in this research area. Therefore, conducting bibliometric analyses is crucial to address this shortcoming, as it can provide critical data for defining research trends and facilitating future research directions.

In the present study, a comprehensive bibliometric analysis on non-thermal plasma medicine was performed and software (Citespace) was used to generate visualizations. The objective of this study was to methodically assess the research status, current research priorities, and emerging research trends in non-thermal plasma medicine over the past 20 years, highlight major achievements, and identify future research directions in the field.

Materials and methods

Search strategy and eligibility criteria

Scientific articles and literature on the topic of non-thermal plasma (or cold plasma) in medicine were searched using the Web of Science Core Collection (WoSCC), which includes the Science Citation Index Expanded and other citation indices. In this search, the search terms were TS = (non-thermal plasma OR cold plasma) AND TS = (medicine). The time span was from January 2002 to December 2022, and except for publications that did not contain unique content, articles written in languages other than English were excluded. As the data was obtained directly from the database, ethical approval is not required.

Bibliometric analysis

Data from these articles were imported and combined using bibliometrix package (version 2.2) in the R language. Several bibliometric analysis methods were used in our study, such as keyword co-occurrence analysis and historical direct citation analysis. In this study, CiteSpace (version 6.2. R2) was used to perform social network analysis and identify developmental dynamics, hotspots, future trends, and key points in the scientific literature on a given topic. Burst detection methodology was used to identify notable keywords or references that show a sudden increase in frequency over a given time period. n addition, a cluster analysis (co-citation) of references was performed based on the number of articles co-authored, allowing the formation of clusters of institutions or keywords that show greater collaboration within the same group. Network maps with nodes of varying sizes and colors were used to show variations in the number or frequency of published records between clusters of the same research topics. The strength of collaborations between nodes was indicated by lines, with thicker lines representing stronger collaboration. To further illustrate the data, an overlay visualization method was used in which the color of each node represents the institution or keyword that was published in the average year. Data was stored in Plain Text format with Full Record and Cited References in WoSCC and imported into CiteSpace for subsequent analysis.

Results

Brief description of the literature on non-thermal plasma medicine

By 31 December 2022, 765 articles were retrieved from the WOS database, of which 745 were published in 2002–2022 and 725 were in English. Among them, 591 research papers accounted for 81.5%; 130 were reviews, accounting for 17.9%, were included in the study. The top five WOS disciplines were applied physics (n = 151); physics of fluid plasmas (n = 108); biochemistry and molecular biology (n = 80); multidisciplinary chemistry (n = 72) and pharmacology and pharmacy (n = 60).

Productivity analysis

As shown in Figure 1, the number of research articles published in the field of non-thermal plasmas and medicine increased slowly from 2002 to 2011, with a sharp increase in 2012, and then stabilized. After 2015, there was a rapid growth trend, especially in 2020, when the number of published articles

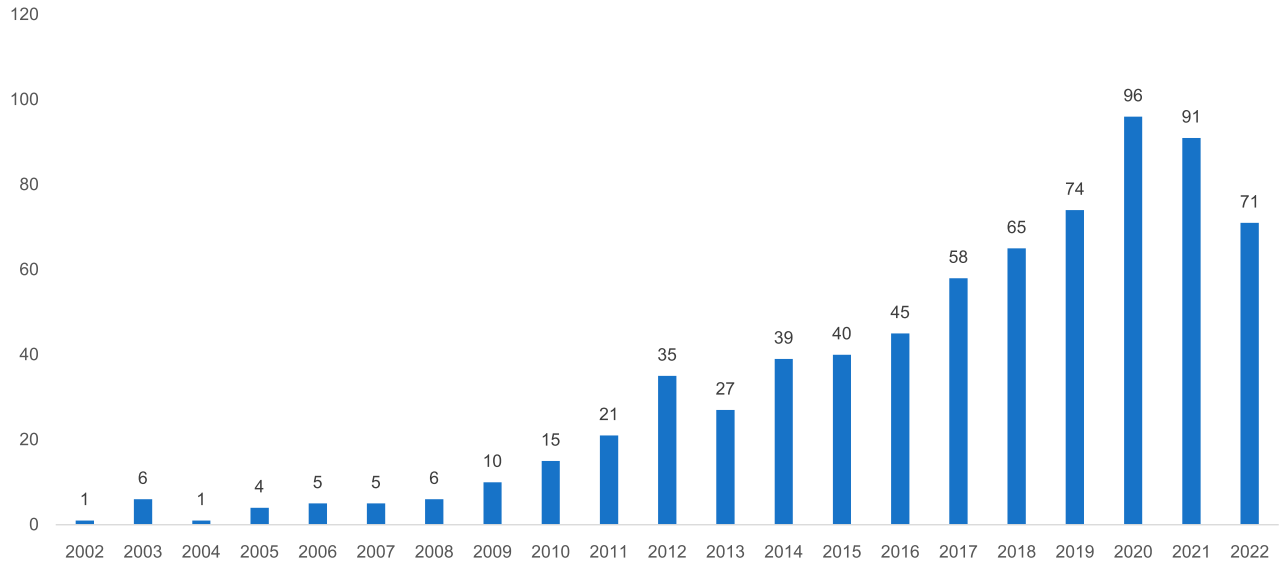

FIGURE 1
Annual scientific production in non-thermal plasma research.

TABLE 1 Top 10 productive countries concerning non-thermal plasma medicine.

Country	Documents n (%)	Citations	Average citations	Centrality
GERMANY	164 (0.229)	9,094	55.50	0.25
CHINA	117 (0.164)	2,551	21.80	0.01
United States	89 (0.124)	3,589	40.30	0.30
JAPAN	46 (0.064)	1,306	28.40	0.07
KOREA	34 (0.048)	599	17.60	0.01
IRAN	29 (0.041)	658	22.70	0.01
FRANCE	27 (0.038)	1,317	48.8	0.12
BELGIUM	18 (0.025)	476	26.40	0.29

reached 96, 96 times the number in 2002. From 2021 to 2022, the number of published articles decreased slightly, but the overall trend is upward, and the growth rate is generally exponential, indicating that international attention to research on nonthermal plasmas in medicine continues to increase and offers certain research prospects (Figure 1).

Countries and cooperation networks analysis

Since 2002, the literature on the research of non-thermal plasma in medicine has been published in 59 countries, mainly in the following few countries: Germany, China, and the United States. The number of publications and the frequency of citations are two dimensions for analyzing the strength of scientific research and reflect the attention and impact of a country or institution in a particular field. In terms of number of publications, the top five countries are Germany (n = 164), China (n = 117), the United States (n = 89), Japan (n = 46), and South Korea (n = 34). In terms of literature citations, the top five countries are Germany, the United States, China, France, and Japan. It is noteworthy that Germany, China, and the United States are among the top three countries in both number of publications and frequency of citations, proving that these three countries have strong scientific research capabilities in this area. Although France ranks seventh in the number of articles published, the average number of citations per article is high (Table 1).

Import the paper data into CiteSpace to perform a collaboration network analysis and calculate the centrality of these countries. As shown in Figure 2B and Table 1, the circle represents the country, and the darker the center color is, the earlier the document was published. The higher the centrality, the closer the cooperation with other countries. The circle with purple outer circles represents higher centrality. In China, the United States, and Germany, research on non-thermal plasma in medicine started earlier. The United States has the highest

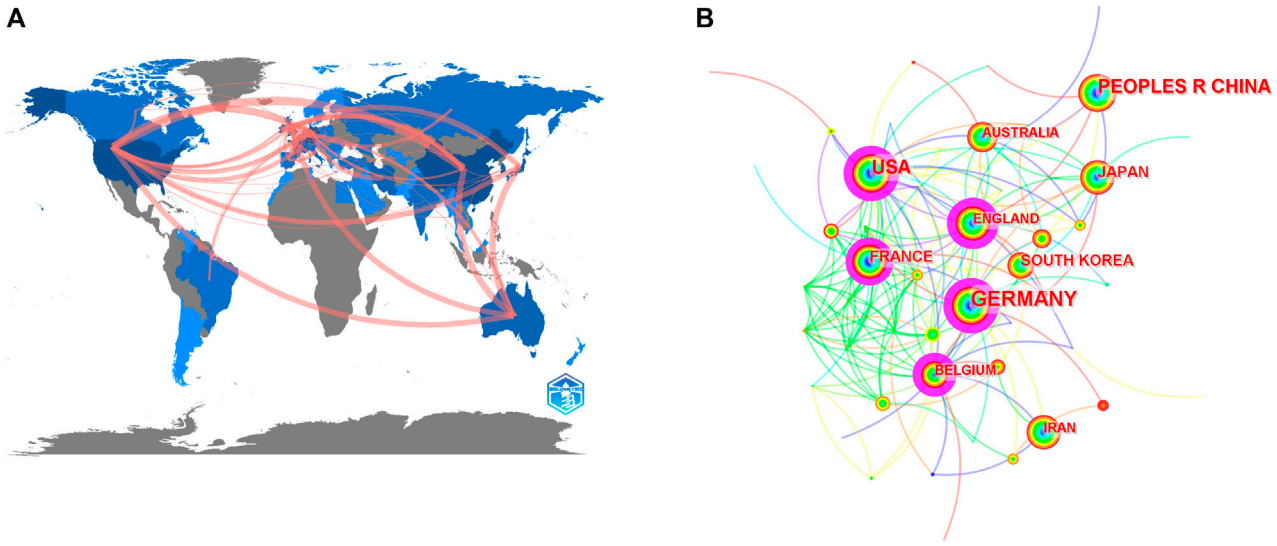

FIGURE 2
Leading countries in non-thermal plasma medicine. **(A)**: countries' collaboration world map. **(B)**: countries' cooperation network.

TABLE 2 Top 10 productive institutions concerning non-thermal plasma medicine.

Affiliation	Country	Publication counts
Leibniz Institute for Plasma Science and Technology INP	GERMANY	137
Univ Med Greifswald	GERMANY	108
George Washington Univ	United States	65
Nagoya Univ	JAPAN	58
Old Dominion Univ	VIRGINIA	43
Huazhong Univ Sci And Technol	CHINA	40
Kwangwoon Univ	KOREA	40
Greifswald Univ	GERMANY	37
Drexel Univ	United States	33

centrality score (0.30), followed closely by Belgium (0.29), Germany (0.25), the United Kingdom (0.22), and France (0.12), indicating that these countries pay more attention to international cooperation in this field. It is worth noting that Belgium has played an important role in the development of this field, although it ranks eighth in the number of published articles (Table 1). From the analysis diagram of national cooperation networks, it can be seen that the lines representing the connection between these countries and other countries is relatively thick, indicating that there is extensive cooperation between these countries (Figure 2).

Institutions and cooperation analysis

As shown in Table 2, the top ten institutions in non-thermal plasma medicine related research are listed. Leibniz Institute for Plasma Science and Technology INP has published significantly more documents than other institutions (n = 137), followed by George Washington University (n = 65), University Medicine Greifswald (n = 62), and Nagoya University (n = 58, Table2). A comprehensive analysis of the collaborative network between institutions or universities was performed. The larger the font in the cooperation network analysis table, the more contributions the institution makes in this field, the earlier it conducts relevant research (Figure 3). As shown in Figure 3, Leibniz Institute for Plasma Science and Technology INP, George Washington University, University Medicine Greifswald, Nagoya University have played an important role in the development of this field.

In network map, the cluster analysis of cooperation among institutes and the overlay visualization of the largest 5 clusters are shown in Figure 3. In the first place of centrality is Leibniz Institute of Plasma Science & Technology INP (0.14, Cluster2). The second one is the George Washington University (0.08, Cluster1). The third

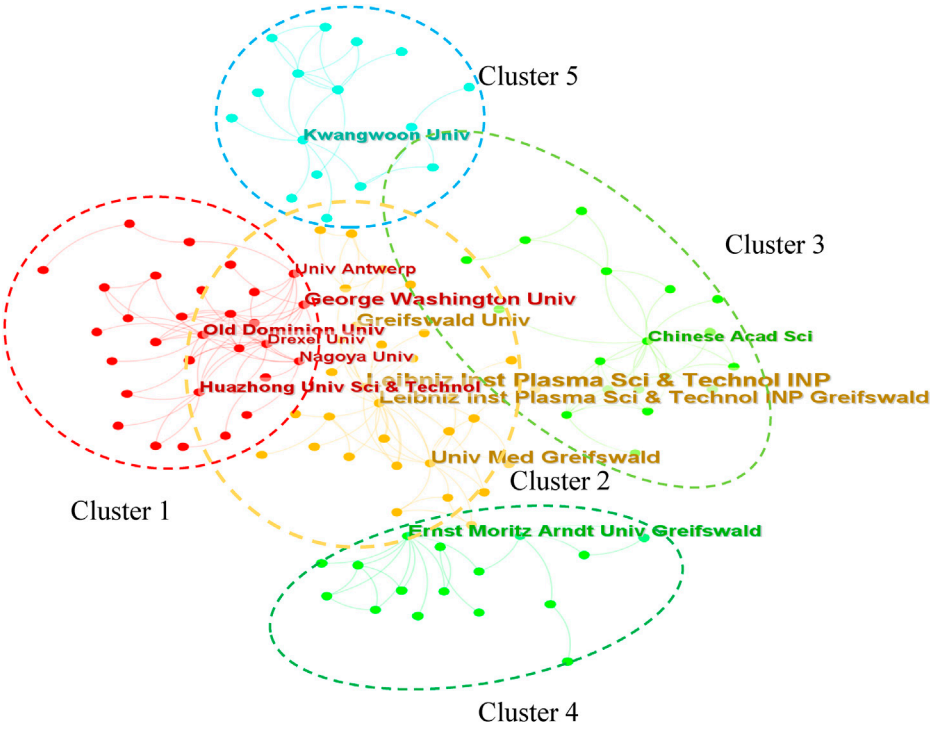

FIGURE 3
Visualization of active institutes and cluster analysis of cooperation among institutes.

TABLE 3 Top 10 most productive authors in non-thermal plasma medicine.

Author	Country	Institution	Counts	H_index	Citations
BEKESCHUS S	GERMANY	Leibniz Institute for Plasma Science and Technology INP	65	27	444
VON WOEDTKE T	GERMANY	Univ Med Greifswald	43	25	460
WELTMANN KD	GERMANY	Leibniz Institute for Plasma Science and Technology INP	41	26	271
WENDE K	GERMANY	Leibniz Institute for Plasma Science and Technology INP	26	20	250
SCHMIDT A	GERMANY	Leibniz Institute for Plasma Science and Technology INP	26	19	285
KEIDAR M	United States	George Washington Univ	21	13	56
EMMERT S	GERMANY	University of Rostock	20	13	116
SHIMIZU T	GERMANY	Max Planck Inst Extraterr Phys	15	12	162
METELMANN HR	GERMANY	Ernst Moritz Arndt Univ Greifswald	13	12	78
TANAKA H	JAPAN	Nagoya Univ	13	12	58

is Drexel University (0.06, Cluster1). The fourth is the Chinese Academy of Sciences (0.06, Cluster3). The fifth is the University Antwerpen (0.06, Cluster1).

Authors analysis

We then analyzed the authors of the published articles and found that the top five authors in terms of citation frequency were von Woedtke T (n = 460), Sander B (n = 444), Schmidt A (n = 285), Weltmann KD (n = 271), and Wende K (n = 250) The countries and institutions to which the author belong are listed in Table 4. Based on the H value of the cited articles, the top five authors are Sander B (27), Weltmann KD (26), von Woedtke T (25), Wende K (20), and Schmidt A (19) This shows that these five authors have a significant influence and have played an important role in the development of this field. It is worth noting that most of these authors were from Leibniz Institute for Plasma Science and Technology in Germany (Table 3).

With the function "Burst" it is possible to display the authors who are currently most active in this field. The details are shown in Figure 4.

FIGURE 4
Top 10 authors with the strongest citation bursts.

The analysis on the result of burst detection, non-thermal plasma in medicine have been actively studied by Zimmermann JL (Germany) since 2012. Sander B was the most active author in the field of non-thermal plasma in medicine in 2013 and his influence reached 9.54, ranking first. Emmert S (5.73) and Zimmermann JL (5.14) were second and third and were both active in 2012 and from 2020 to 2022 and 2012–2013, respectively. As a result, Sander B and Emmert S are not only possessed the strongest citation bursts, but also the top researchers in recent years. At the same time, Boeckmann L and Freud E have also been in the top ranks recently (Figure 4).

Journal analysis

The top 10 journals with the highest citation are listed in Table 4. The top five cited journals are JOURNAL OF PHYSICS D-APPLIED PHYSICS (n = 2,200), PLASMA PROCESSES AND POLYMERS (n = 1913), SCIENTIFIC REPORTS (n = 1,316), PLASMA SOURCES SCIENCE TECHNOLOGY (n = 1,262), and IEEE TRANSACTIONS ON PLASMA SCIENCE (n = 1,146). Impact factors (average in the past 5 years, IF) and Journal citation reports (JCR) are shown in Table 4. From the perspective of the H-value of the cited articles, the top five journals are PLASMA PROCESSES POLYMERS (H = 18), followed by JOURNAL OF PHYSICS D-APPLIED PHYSICS (H = 17), IEEE TRANSACTIONS ON PLASMA SCIENCE (13), PLASMA SOURCES SCIENCE&TECNOLOGY (12) and SCIENTIFIC REPORTS (12, Table 3). Therefore, comprehensive analysis of JOURNAL OF PHYSICS D-APPLIED PHYSICS and PLASMA PROCESSES AND POLYMERS has paid more attention to the research related to non-thermal plasma and medicine, and has great influence.

Research focus and frontiers analysis on the non-thermal plasma medicine

Research focus analysis

The word frequency and centrality of key words reflect the hot topics that researchers have focused on and studied over a period. Key words characterize the core meaning of an article, and conducting keyword analysis can profoundly capture the core content of this area. Centrality is a basic indicator for measuring the weight of nodes, reflecting their importance in the network. The greater the frequency of co-occurrence and the centrality of keywords, the greater the importance of the nodes. The analysis of the co-occurrence of keywords is shown in Figure 5A. The size of the nodes reflects the frequency of the keywords, with "medicine," "atmospheric pressure plasma," "inactivation," "argon plasma," and "dielectric barrier discharge" being the most common. The R-Bibliometrix package was used to draw a map of the keyword cloud (see Figure 5B). In Figure 5A, the nodes with purple outer circles were those with higher centrality, including "Apoptosis" (0.17), "Dielectric Barrier Discharge" (0.10), "Medicine" (0.08), "*In Vitro*" (0.08), and "Cancer" (0.08), which had higher centrality and frequency, indicating these key contents received attention in promoting and developing the field (Table 5). When the high-frequency keywords were further sorted and summarized, it was found that the research focus in the field of nonthermal plasma medicine from 2002 to 2022 was mainly concentrated in four categories. The keyword with the highest level of attention in cluster 1 is "Apoptosis", the keyword with the highest level of attention in cluster 2 is "Inactivation"; the keyword with the highest level of attention in cluster 3 is "Atmospheric Pressure Plasma"; and the keyword with the highest level of attention in cluster 4 is "Nitric Oxide" (Figure 5C).

TABLE 4 Top 10 core journals on non-thermal plasma medicine.

Journal	H_index	Counts	Citations	IF	JCR
PLASMA PROCESSES AND POLYMERS	18	32	1913	3.610	Q1
JOURNAL OF PHYSICS D-APPLIED PHYSICS	17	33	2,200	3.178	Q2
IEEE TRANSACTIONS ON PLASMA SCIENCE	13	21	1,146	1.354	Q4
PLASMA SOURCES SCIENCE TECHNOLOGY	12	21	1,262	4.434	Q1
SCIENTIFIC REPORTS	12	14	1,316	5.516	Q2
APPLIED PHYSICS LETTERS	11	13	554	3.816	Q2
JOURNAL OF ETHNOPHARMACOLOGY	11	18	150	5.242	Q1
APPLIED SCIENCES-BASEL	10	16	140	2.921	Q2
CANCERS	10	17	330	6.886	Q1
PLOS ONE	10	13	1,137	4.069	Q1

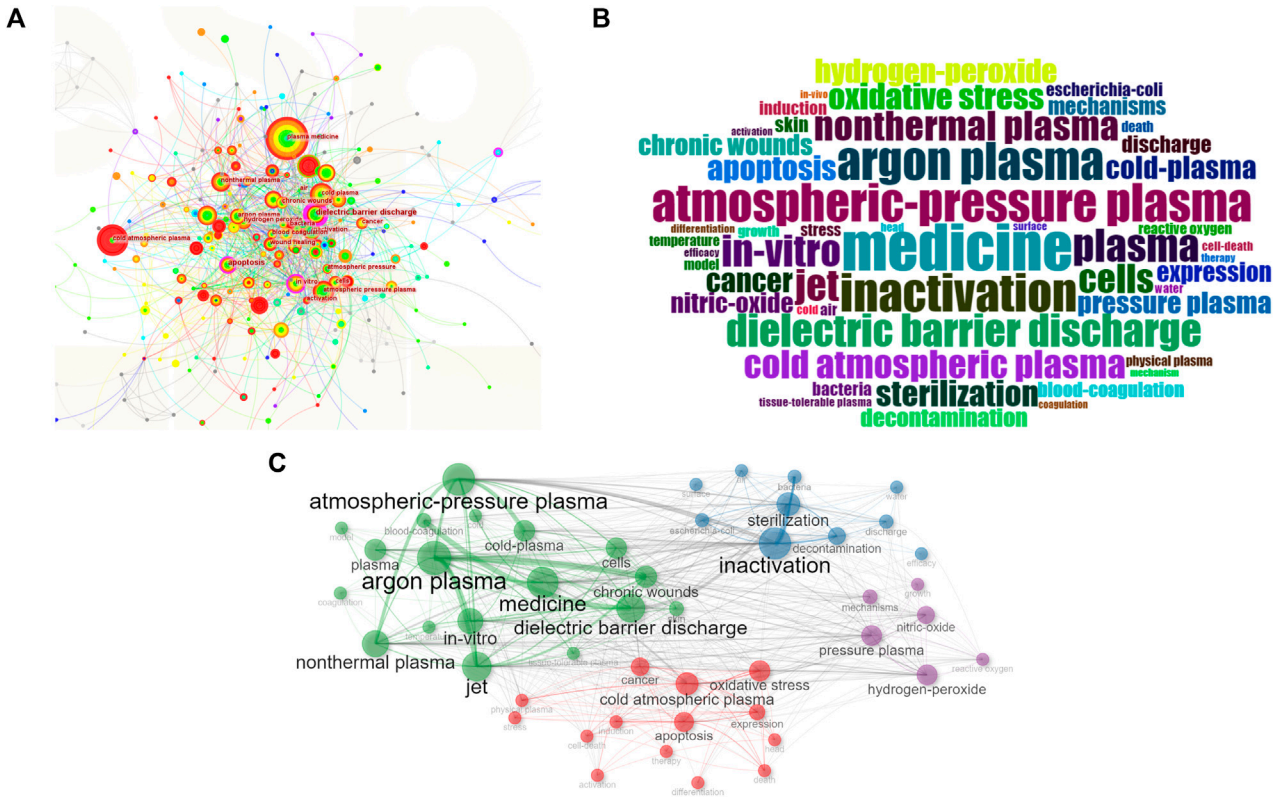

FIGURE 5
Visualization of keywords analysis. **(A)**: Keywords cooccurrence and centrality. **(B)**: Keyword cloud **(C)**: Mapping and clustering of keywords for non-thermal plasma medicine.

Research frontiers analysis

Keywords with the strongest citation bursts mean that the keywords appear more frequently or are cited more frequently in a relatively short period of time. Detection indicators of keyword citation frequency generally include intensity and age distribution, which reflect the vanguard and developing trend of research in a given period. Figure 6A lists the 20 keywords with the highest citation bursts. "Bacteria" appeared the earliest and lasted the longest (2008–2016), with a strength of 8.27, ranking second. During this period, "Inactivation", "Air", and "Sterilization" were also keywords with high attention. "Medicine" began to become a research hotspot for

TABLE 5 Top 10 highest centrality keywords.

Keywords	Centrality	Counts
Apoptosis	0.17	42
Assay	0.12	6
Growth	0.11	17
Human plasma	0.10	6
Dielectric barrier discharge	0.10	65
Plasma	0.09	27
Medicine	0.08	76
Cancer	0.08	38
In vitro	0.08	48
Involvement	0.08	3

many scientists after 2011 and continued until 2018, ranking first in terms of strength (10.79). During this period, "Synchronous Sound" (2013–2014, 3.77), "Cold" (2014–2017, 3.65), "Cell" (2015–2016, 3.38) received more attention. Over the past 5 years, "Differentiation" has received the most sustained attention from 2019 to 2022, with a strength of 3.26. In addition, "Water", "Trraditional Chinese Medicine", "Reactive Oxygen", and "Electric Field", "Path", "Cold Physical Plasma", "Reactive Oxygen Specifications", "Gene Expression", and "Cell Death" have also received much attention from scientists in the past 5 years.

In this article, the Bibliometrix package in the R language environment is used to describe the history of topic development using keywords (Thematic Map). The results show that "Inactivation", "Dterilization", and "Decontamination" are found in the "basic themes" area, indicating that they are fundamental concepts for research in this area. In Figure 6B, the analysis shows that "Apoptosis," "Cancer," and "Expression" were categorized under the "motor themes" area, whereas "Surface" and "Water" were classified as "emerging themes", indicating that researchers are relatively active in these areas which may have good prospects in the field of non-thermal plasma medicine.

Co-cited references analysis

E. Garfield (2004) introduced the concept of the historiographic map, which is a network diagram showing the major direct citations in a bibliographic collection in chronological order. The historical direct citation network of documents presents a diachronic shift of the mpst frequently cited documents on a timeline and reflects the replacement and evolution of research foci. The analysis of historical citation by Bibliometrix can provide two statistical indicators, the Local Citation Score (LCS) and the Global Citation Score (GCS), which represents the number of citations of documents in the current database and the total number of citations of documents in the entire web of science database, respectively. Not only is it possible to determine the influence of specific documents, but it is also possible to determine the relevance of specific documents between the visual analysis domain and other domains. Use the following command to obtain the historical cited network information of the literature [options (width = 130)] [histResults < − histNetwork (M, min citations = 2, sep = "; ")] [net < − histPlot (histResults, n = 10, size = 5, labelsize = 3)].

The analysis results of the historical direct citation network showed that there were 9 landmark documents in this field. Table 6 and Figure 7 summarize the relevant information of important documents in the historical cited network atlas. According to the statistics of the four articles numbered 1, 2, 3, 6 the LCS and GCS indexes are relatively high, indicating that these four articles had significant influence in the corresponding years and the research content is highly correlated with the relevant research on non-thermal plasma medicine.

Discussion

General information

In this study, the main areas of knowledge and emerging trends in non-thermal plasma medicine were analyzed using bibliometric analysis. Some breakthrough achievements were also identified by bibliometric methods. The results show that annual publications on non-thermal plasma generally show an upward trend. In addition,

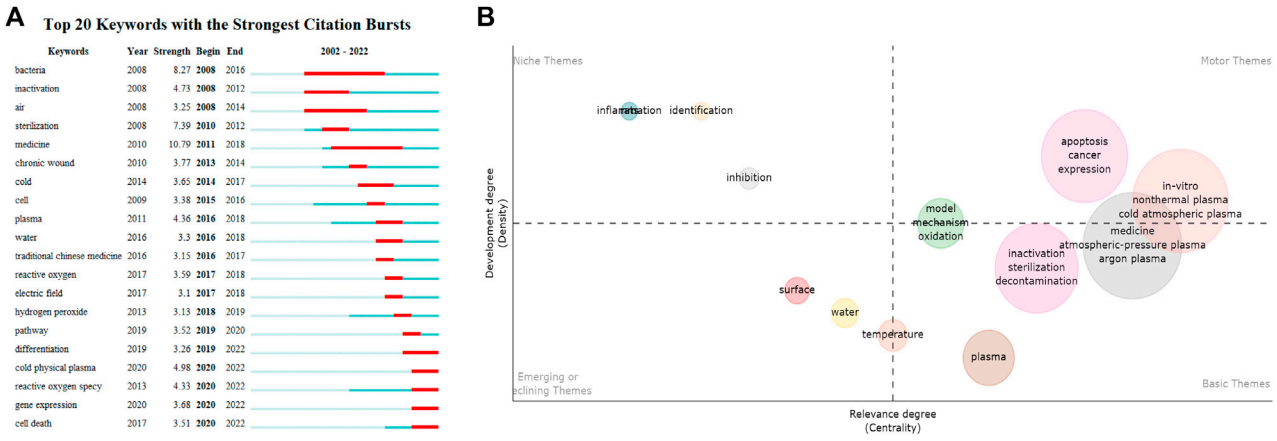

FIGURE 6
(A): Keywords with the strongest citation burst. **(B)**: Thematic Map of keywords in non-thermal plasma medicine.

TABLE 6 Nine Landmark documents in non-thermal plasma medicine.

Code	Title	Author	Journal	Country	Year	LCS	GCS
1	Endothelial cell proliferation is enhanced by low dose non-thermal plasma through fibroblast growth factor-2 release	KALGHATGI S	ANN BIOMED ENG	United States	2010	52	219
2	Antitumor effect of plasma treatment on u87 glioma xenografts: preliminary results	VANDAMME M	PLASMA PROCESS POLYM	FRANCE	2010	43	202
3	Effects of non-thermal plasma on mammalian cells	KALGHATGI S	PLOS ONE	United States	2011	74	385
4	Tissue tolerable plasma (TTP) induces apoptosis in pancreatic cancer cells *in vitro* and *in vivo*	PARTECKE LI	BMC CANCER	GERMANY	2012	43	180
5	Cold atmospheric plasma, a new strategy to induce senescence in melanoma cells	ARNDT S	EXP DERMATOL	GERMANY	2013	36	152
6	Non-thermal atmospheric-pressure plasma possible application in wound healing	HAERTEL B	BIOMOL THER	GERMANY	2014	52	270
7	A cold plasma jet accelerates wound healing in a murine model of full-thickness skin wounds	SCHMIDT A	EXP DERMATOL	GERMANY	2017	39	135
8	One year follow-up risk assessment in skh-1 mice and wounds treated with an argon plasma jet	SCHMIDT A	INT J MOL SCI	GERMANY	2017	36	65
9	Plasma medicine: a field of applied redox biology	VON WOEDTKE T	*IN VIVO*	GERMANY	2019	44	128

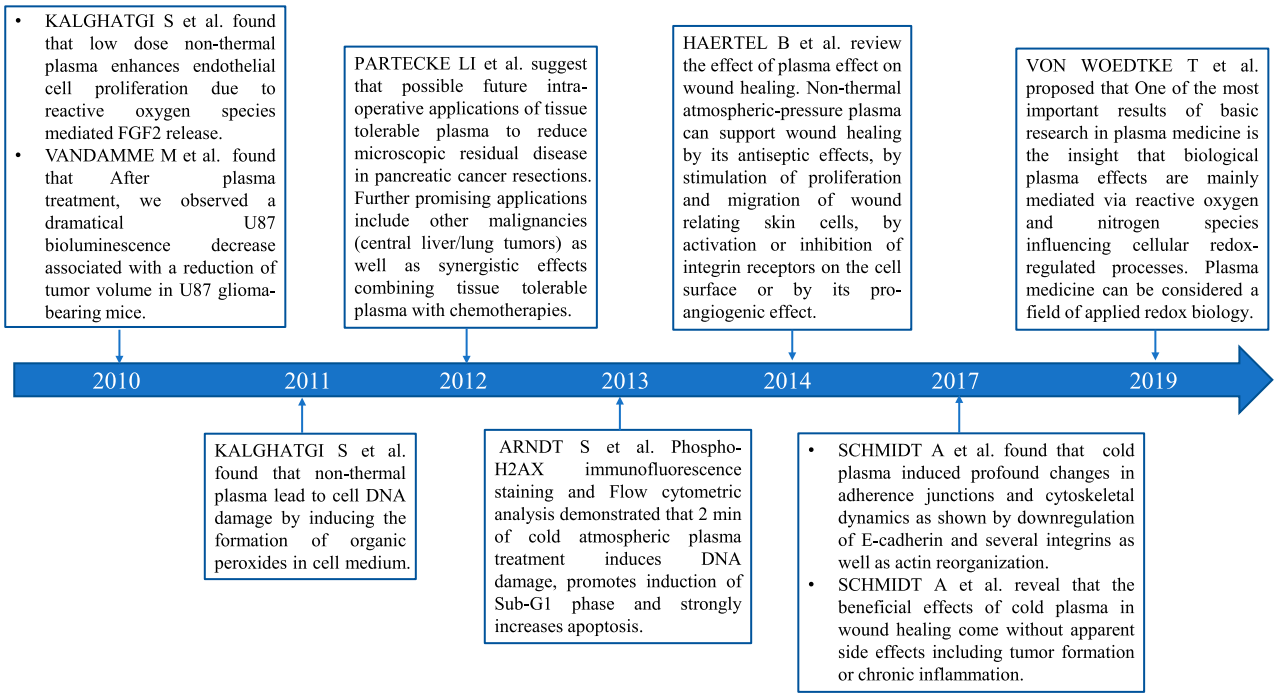

FIGURE 7
Timeline of part of landmark achievements in non-thermal plasma medicine research.

the geographic distribution of publications was determined on the country and affiliation of authors listed in the article using a datable method. In the field of non-thermal plasma medicine, institutions from Germany, the United States, and China dominate. The Leibniz Institute for Plasma Science and Technology INP, George Washington Univ, University Medicine Greifswald, Nagoya University have played an important role in the development of this field. From the production and influence perspective, Bekeschus S and von Woedtke T from Germany have been at the forefront in the last two decades. However, the aim of this study was not to obtain complete precision data from nonthermal plasma medicine, but to stimulate interest and encourage further investigation in this

field. This article can also provide researchers who have just entered this field with a quick overview of non-thermal plasma medicine and help them understand the latest trends.

The increase in publications in the field of non-thermal plasma medicine is most likely due to the introduction of several journals specializing in non-thermal plasmas and the increasing interest of researchers in professional and academic changes in the application of non-thermal plasmas in medicine. Among the top 10 journals, Plasma Processes and Polymers and Journal of Physics D-Applied Physics had by far the highest number of published articles and the highest H-index, indicating that these two journals were the most popular journals for scientists working on nonthermal plasma medicine during 2002–2022. These journals are highly coveted by researchers worldwide as they show case the latest advancements and noteworthy discoveries in non-thermal plasma medicine research. In recent years, both Plasma Processes and Polymers and Journal of Physics D-Applied Physics have focused on investigating the use of plasma-activated water (PAW) and its potential use in the treatment of cancer. At the same time, these journals have also been focusing on the role of non-thermal plasma in combating the coronavirus or pathogenic microbes and the impact of non-thermal plasma treatment on the surface properties of biomaterials, which is consistent with the result of Thematic Map. As shown in thematic map, “Surface” and “Water” are the emerging themes; “Apoptosis”, “Cancer” and “Expression” are the motor themes.

Current esearch otspots

Based on the analysis of keywords and seminal documents in the field, we were able to categorize the research in non-thermal plasma medicine into three major hotspots, which are described below.

(1) Mechanistic insights into the inactivation of microorganisms by non-thermal plasma.

Non-thermal plasma has been studied as a method for inactivating various types of microorganisms, including bacteria, viruses, and fungi [6, 7]. The antimicrobial properties of NTP have been extensively studied. One of the main advantages of NTP is that it can effectively kill microorganisms without the use of antibiotics. This is particularly important given the increasing prevalence of antibiotic-resistant bacteria. NTP has been shown to be effective in killing antibiotic-resistant bacteria, including MRSA and *K. pneumoniae* [8]. The mechanism by which NTP modulates gene expression in antibiotic-resistant bacteria is thought to involve the generation of reactive oxygen species (ROS) and reactive nitrogen species (RNS). These species can cause oxidative stress and DNA damage in bacteria, leading to changes in gene expression and potentially affecting bacterial growth and biofilm formation [9]. Additionally, NTP may also be used in combination with traditional antibiotics to increase their efficacy.

In addition, NTP can be used as a sterilization method in the medical field, where it is able to sterilize medical equipment and surfaces in hospitals and clinics. It is also used in the food and beverage industry to sterilize packaging materials and to treat liquids, such as juices and wines. It is an alternative to traditional sterilization methods that use heat, radiation, or chemicals, and is particularly useful in situations where these methods may not be practical or effective.

(2) Non-thermal plasma induced apoptosis in cancer cells: A promising therapy for cancer treatment

Non-thermal plasma has been shown to induce apoptosis, the programmed cell death of damaged or abnormal cells. This method has been studied extensively in cancer research, as it has shown potential as a non-invasive and selective treatment for cancer cells. Non-thermal plasma apoptosis involves the use of ionized gases to produce a unique combination of reactive species, such as reactive oxygen and nitrogen species, that can induce apoptosis in target cells. These reactive species can cause damage to the cell membrane, DNA, and other cellular components, leading to the activation of apoptotic pathways. Landmark documents 2, 3, 4 and 5 were about effects of non-thermal plasma on cell apoptosis and cancer treatment. Specifically, Vandamme et al. performed a study to evaluate the potential antitumor effect of an *in vivo* plasma treatment (A pulsed DBD with μs pulses at moderate power) on a U87-luc glioma tumor and found that the plasma treatment was safe for mice and decrease associated with a reduction of tumor volume in mice with U87 glioma [10]. Kalghatgi et al. found that non-thermal plasma may lead to cell DNA damage by inducing the formation of organic peroxides in cell medium [11]. Subsequently, Partecke et al. showed that up to 10 s of NTP treatment can induce apoptosis and causes cell death in pancreatic cancer cells *in vitro* without negative effects on surrounding healthy tissues [12], indicating that non-thermal plasma apoptosis is its selectivity towards cancer cells, as normal cells are less susceptible to the effects of non-thermal plasma. Additionally, non-thermal plasma can be used in a localized manner, minimizing damage to surrounding healthy tissue. Further research by Arndt et al. found that exposure to cold atmospheric plasma for a duration of 2 min can result in DNA damage and may trigger the induction of Sub-G1 phase, and may significantly enhances the rate of apoptosis [13], which further elucidated the mechanism of NTP in treating cancer by inducing apoptosis. Further investigation is warranted to comprehensively elucidate the underlying mechanisms of non-thermal plasma cancer treatment and to optimize its effectiveness and safety in clinical settings.

(3) Non-Thermal Plasma: A Novel Approach to Wound Healing

Wound healing with non-thermal plasma (NTP) is a rapidly developing area in biomedical engineering. It is a promising approach for promoting tissue regeneration and repairing chronic wounds that are resistant to conventional therapies. Landmark documents 1, 6, 7 and 8 were on wound healing or tissue regeneration. In recent years, interest in the use of NTP for wound healing has increased due to its many benefits, such as its ability to accelerate wound closure, stimulate angiogenesis, and enhance antimicrobial activity [14]. Kalghatgi S et al. showed that low dose non-thermal plasma enhances endothelial cell proliferation due to reactive oxygen species mediated FGF2 release [15]. Schmidt A et al. found that exposure to cold plasma resulted in significant alterations to adherence junctions and

cytoskeletal dynamics [16]. In particular, downregulation of E-cadherin and several integrins and reorganization of actin were observed. Despite these changes, the authors found that the use of cold plasma in wound healing showed favorable results without obvious adverse effects such as tumor formation or chronic inflammation. This suggests that cold plasma may be a promising therapeutic approach for wound healing without significant safety concerns, including tumor formation or chronic inflammation [16, 17]. The researchers found that NTP may induce the release of growth factors and cytokines, which in turn can promote cell migration, proliferation, and differentiation. This study sheds light on the underlying mechanisms of NTP wound healing and provides insight into potential future applications.

A recent study by Maryam et al. examined the effects of NTP treatment on wound healing in a diabetic mouse model [18]. The results showed that NTP treatment significantly improved wound healing compared to the control group by promoting angiogenesis and increasing collagen deposition. This study highlights the potential of NTP as a therapeutic option for diabetic wounds, which are notoriously difficult to treat.

With the deepening of research on plasma and the development of plasma medical equipment, plasma has been applied in some clinical practice. For example, Plason, a low-temperature plasma device (PLASMA Poration ™, Los Angeles, CA) has been applied to promote wound healing and skin regeneration. It produces nitrogen oxide active particles that can accelerate wound healing, inflammation repair, and regulate cell function. Especially for acute inflammation, such as sensitive muscle symptoms in the acute phase, after laser treatment, after mesodermal treatment, sensitivity to ointment, dermatitis, *etc.*, significant effects can be observed. In addition, V-PRO maX® Low Temperature Sterilization System, a hydrogen peroxide low-temperature plasma equipment (STERIS, Ohio, United States), is commonly used for sterilization of surgical instruments, and is favored by people due to its simple operation and short sterilization time, which can significantly improve efficiency and reduce costs. It is essential to note that while there is promising preclinical research indicating the potential benefits of cold plasma in various medical applications, the translation to widespread clinical use is still an ongoing process.

Future frontiers

Based on this overview of the timeline of research topics and keywords for non-thermal plasma medicine, it is predicted that three research topics are likely to be of great importance in the future, as follows.

(1) Non-thermal plasma activated water: A potential therapeutic agent in medicine

Non-thermal plasma activated water is a novel technology that is attracting increasing attention in medicine. Plasma-activated water is produced by exposing water to a non-thermal plasma that generates various reactive oxygen and nitrogen species that can be used in biomedical fields such as infection control, wound healing, and cancer therapy. One recent study conducted by Qing H et al. investigated the effect of plasma activated water on the oral bacteria *streptococcus* mutans and found that the plasma activated water can have immediate antimicrobial effects on oral bacteria of S. mutans in both planktonic and biofilm forms [19]. Another study showed that plasma activated water may be a new and effective method for promoting wound healing by reducing the number of wound bacteria without side effects [20]. In addition, plasma-activated water has also been studied for its use in selective treatment of cancer cells. In a study by Subramanian et al. it was shown that the viability of human breast cancer cells (MDA-MB-231) after treatment with plasma-activated water was significantly lower than that of healthy fibroblast cells from mice [21]. Plasma activated water retains its potency against cancer cells after 14 days of refrigerated storage. Non-thermal plasma-activated water therefore has broad potential applications and good prospects in the medical field, but its safety and quality control need to be further confirmed.

(2) Non-thermal plasma promotes cell differentiation: Mechanisms and applications

Non-thermal plasma that promotes cell differentiation is a new technology that has the potential to revolutionize the field of stem cell research and regenerative medicine. Non-thermal plasma is potentially capable of inducing stem cell differentiation into specific cell types without the use of chemical triggers or genetic manipulation. A recent study by Byul-Bora Choi et al. investigated the use of cold no-ozone plasma to induce differentiation of human periodontal ligament (PDL) cells into osteoblasts [22]. The results showed a significant increase in the expression of genes related to osteoblast differentiation, indicating the potential of non-thermal plasma treatment as a method for inducing bone regeneration. Another recent study by Mime K et al. investigated the potential of non-thermal atmospheric-pressure plasma in promoting mesodermal differentiation of human induced pluripotent stem cells (hiPSCs) [23]. The results showed that plasma-treated hiPSCs exhibited suppression of ectoderm genes such as WNT1 and increased expression of mesoderm genes in embryoid bodies (EBs), suggesting that plasma treatment may be a useful tool to guide the fate of pluripotent stem cells while maintaining genomic integrity. Despite the promising results, there are still some challenges to overcome in the application of non-thermal plasma differentiation. The mechanisms underlying non-thermal plasma induced differentiation and its potential applications in the clinical setting need to be further explored.

(3) Enhancing the biocompatibility of surfaces using non-thermal plasma

NTP can generate various reactive species, including reactive oxygen and nitrogen species, ultraviolet radiation, and electric fields, which can modify the surface properties of materials. In medicine, NTP activated surfaces have been used to improve biocompatibility, prevent bacterial colonization, and promote tissue regeneration. For example, NTP treatment can improve the hydrophilicity of materials like titanium, zirconia and PEEK, which can promote cell adhesion, proliferation, and osteogenic differentiation of dental pulp stem cells [24, 25]. Chaichi et al. utilized a handheld cold plasma generator to alter the surface characteristics of two commonly employed biomaterials: the metallic Ti6Al4V and the nonmetallic

GUR1020 polymer, which are frequently utilized in joint and disc replacement applications. They found a remarkable 60-fold decrease in tribological wear rates for the plasma-coated samples, coupled with a 2- to 3-fold enhancement in biocompatibility properties as compared to their noncoated counterparts [26]. Additionally, NTP can generate a variety of reactive species that can destroy bacterial membranes, leading to their inactivation. Therefore, NTP activated surfaces have been used to reduce the risk of bacterial infections associated with medical devices such as catheters and implants [27].

The effect of non-thermal plasma on biocompatibility can also be elucidated from the perspective of the direct interaction between the active particles generated at the treated interface and biological tissue. Lee et al. found that anti-psoriatic impact of cold plasma was related to the suppression of inflammatory cytokine expression, modulation of CD4 T cell differentiation, and the induction of PD-L1 expression [28]. Furthermore, researchers found that cold plasma treated medium were able to lead to the increase of the cell-ECM adhesion and cell proliferation, which was mostly attributed to the enhancement of the production and activity of integrin proteins [29]. Therefore, the surface modification of biomaterials by non-thermal plasma and the impact of active substances released from the plasma treated surfaces on cells can both lead to an increase in their biological properties.

(4) The exploration of mechanism of current research hotspots concerning gene expression and pathway.

Bibliometric analysis of keyword bursts revealed that "Pathway", "Reactive Oxygen Species", and "Gene Expression" are currently among the trending topics in non-thermal plasma medicine research, suggesting that exploring the mechanisms behind current research priorities is a pioneering area of research. For example, Fetamah et al. demonstrated that *Candida* albicans growth and virulence factors, as well as HSP90 gene expression, can be inhibited by the application of cold atmospheric plasma, suggesting that nonthermal plasma has therapeutic potential for the treatment of C. albicans-induced fungal infections [30]. The study provides insight into the inhibitory effects and mechanisms of non-thermal plasma on microorganisms, particularly through changes in gene expression. Furthermore, Jung et al. investigated the mechanism of non-thermal plasma-induced apoptosis in cancer cells and found that non-thermal plasma activates EGR1/GADD45α signaling by inducing ROS, leading to apoptotic cell death in thyroid cancer cell through a novel mechanism [31]. Similarly, Hwang et al. discovered that non-thermal plasma promotes hair growth by activating the Wnt/β-catenin signaling pathway in dermal papilla cells, revealing the mechanism behind non-thermal plasma promoting tissue regeneration [32]. Therefore, elucidating the mechanisms behind the current hotspots from the perspectives of "signaling pathways", "reactive oxygen species" and "gene expression" remains an important research focus.

Limitations and strength

This study has particular strengths. First, for the first time, we have performed a bibliometric analysis of publications on non-thermal plasma medicine using Bibliometrix Package and CiteSpace. This analysis provides clinicians and scholars with a comprehensive guide on non-thermal plasma medicine. Secondly, we utilized two tools (CiteSpace and Bibliometrix Package) to perform our investigation simultaneously. CiteSpace is a widely used bibliometric analysis tool that provides better insights into evolving research priorities and trends.

This study also has certain limitations. First, the search strategy was exclusively focused on nonthermal plasma medicine, which may have resulted in the omission of some relevant studies, although efforts were made to broaden the search terms. Second, most of the results were obtained using machine algorithms, which may have limited ability to identify nuances that human reviewers might identify. Finally, emerging areas of research related to nonthermal plasma medicine may have been overlooked by the search strategy of this study, possibly due to the limitations of the machine algorithms.

In summary, NTP has great potential for various medical applications, such as cancer treatment, disinfection, wound healing, implant surface treatment and tissue regeneration engineering. It offers advantages such as non-invasiveness, no radiation, low temperature, and selective action, making it a promising new therapeutic modality. Despite the promising outlook, there are still some challenges in NTP medicine. One challenge is the lack of standardized protocols for NTP treatment, which can vary depending on the type of plasma source, treatment duration, and power settings. Additionally, the safety of NTP for wound healing in humans still needs to be thoroughly investigated. Additionally, the cost of NTP technology needs to be reduced to improve its feasibility and sustainability in the medical field.

Conclusion

Based on this bibliometric analysis, it was determined that research in the field of plasma medicine is promising, as publications in this area are increasing exponentially. Inactivation of microorganisms, apoptosis in cancer cells and wound healing are the current focus areas of non-thermal plasma medicine. On the other hand, improving the biocompatibility of surfaces, activating water, and promoting cell differentiation are the hotspots of this field, which could have a broad research perspective in the future.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding authors.

Author contributions

LG: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Software, Supervision, Validation, Writing–original draft, Writing–review and editing. MY: Conceptualization, Resources, Supervision, Validation, Visualization, Writing–review and editing. HG: Formal Analysis, Investigation,

Methodology, Project administration, Resources, Software, Supervision, Visualization, Writing–original draft. ZZ: Formal Analysis, Methodology, Resources, Software, Writing–review and editing. AH: Methodology, Project administration, Visualization, Writing–review and editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work was supported by the Hunan Provincial Natural Science Foundation of China (No. 2023JJ40817), and the Scientific Research Launch Project for new employees of the Second Xiangya Hospital of Central South University.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

1. Kalghatgi S, Kelly CM, Cerchar E, Torabi B, Alekseev O, Fridman A, et al. Effects of non-thermal plasma on mammalian cells. *PLoS One* (2011) 6(1):e16270. doi:10.1371/journal.pone.0016270

2. Haertel B, von Woedtke T, Weltmann KD, Lindequist U. Non-thermal atmospheric-pressure plasma possible application in wound healing. *Biomol Ther (Seoul)* (2014) 22(6):477–90. doi:10.4062/biomolther.2014.105

3. Kaushik NK, Kaushik N, Linh NN, Ghimire B, Pengkit A, Sornsakdanuphap J, et al. Plasma and nanomaterials: fabrication and biomedical applications. *Nanomaterials (Basel)* (2019) 9(1):98. doi:10.3390/nano9010098

4. Agarwal A, Durairajanayagam D, Tatagari S, Esteves SC, Harlev A, Henkel R, et al. Bibliometrics: tracking research impact by selecting the appropriate metrics. *Asian J Androl* (2016) 18(2):296–309. doi:10.4103/1008-682x.171582

5. Keathley-Herring H, Van Aken E, Gonzalez-Aleu F, Deschamps F, Letens G, Orlandini PC. Assessing the maturity of a research area: bibliometric review and proposed framework. *Scientometrics* (2016) 109(2):927–51. doi:10.1007/s11192-016-2096-x

6. Baldanov BB, Ranzhurov TV, Semenov AP, Gomboeva SV. Cold atmospheric argon plasma jet source and its application for bacterial inactivation. *J Theor Appl Phys* (2019) 13(2):95–9. doi:10.1007/s40094-019-0326-3

7. Wiegand C, Beier O, Horn K, Pfuch A, Tölke T, Hipler UC, et al. Antimicrobial impact of cold atmospheric pressure plasma on medical critical yeasts and bacteria cultures. *Skin Pharmacol Physiol* (2014) 27(1):25–35. doi:10.1159/000351353

8. Kim CK, Kim H, Kim HJ, Cho SB. Antibacterial and anticandidal effects of atmospheric-pressure, non-thermal, nitrogen- and argon-plasma pulses. *Dermatol Ther* (2021) 35(2):e15222. doi:10.1111/dth.15222

9. Scholtz V, Vaňková E, Kašparová P, Premanath R, Karunasagar I, Julák J. Non-thermal plasma treatment of eskape pathogens: a review. *Front Microbiol* (2021) 12:12. doi:10.3389/fmicb.2021.737635

10. Vandamme M, Robert E, Pesnel S, Barbosa E, Dozias S, Sobilo J, et al. Antitumor effect of plasma treatment on U87 glioma xenografts: preliminary results. *Plasma Process Polym* (2010) 7(3-4):264–73. doi:10.1002/ppap.200900080

11. Koutsopoulos S, Kalghatgi S, Kelly CM, Cerchar E, Torabi B, Alekseev O, et al. Effects of non-thermal plasma on mammalian cells. *PLoS ONE* (2011) 6(1):e16270. doi:10.1371/journal.pone.0016270

12. Partecke LI, Evert K, Haugk J, Doering F, Normann L, Diedrich S, et al. Tissue Tolerable Plasma (TTP) induces apoptosis in pancreatic cancer cells *in vitro* and *in vivo*. *BMC Cancer* (2012) 12(1):473. doi:10.1186/1471-2407-12-473

13. Arndt S, Wacker E, Li Y-F, Shimizu T, Thomas HM, Morfill GE, et al. Cold atmospheric plasma, a new strategy to induce senescence in melanoma cells. *Exp Dermatol* (2013) 22(4):284–9. doi:10.1111/exd.12127

14. Haertel B, Tv W, Weltmann K-D, Lindequist U. Non-thermal atmospheric-pressure plasma possible application in wound healing. *Biomolecules Ther* (2014) 22(6):477–90. doi:10.4062/biomolther.2014.105

15. Kalghatgi S, Friedman G, Fridman A, Clyne AM. Endothelial cell proliferation is enhanced by low dose non-thermal plasma through fibroblast growth factor-2 release. *Ann Biomed Eng* (2009) 38(3):748–57. doi:10.1007/s10439-009-9868-x

16. Schmidt A, Bekeschus S, Wende K, Vollmar B, von Woedtke T. A cold plasma jet accelerates wound healing in a murine model of full-thickness skin wounds. *Exp Dermatol* (2017) 26(2):156–62. doi:10.1111/exd.13156

17. Schmidt A, Woedtke T, Stenzel J, Lindner T, Polei S, Vollmar B, et al. One year follow-up risk assessment in SKH-1 mice and wounds treated with an argon plasma jet. *Int J Mol Sci* (2017) 18(4):868. doi:10.3390/ijms18040868

18. Amini M, Jahandideh A, Dehghanpisheh P, Momeni M, Asghari A. Comparative study of histological change after local treatments with zinc oxide, infrared rays, ultraviolet rays, and cold plasma in rat model of diabetic foot. *Indian J Surg* (2020) 82(6):1094–9. doi:10.1007/s12262-020-02143-9

19. Yu Q, Wang Y, Chen M, Sun H, Yu H, Dong X, et al. The antimicrobial property of plasma activated liquids (PALs) against oral bacteria Streptococcus mutans. *Dental* (2021) 3(1). doi:10.35702/dent.10007

20. Xu D, Wang S, Li B, Qi M, Feng R, Li Q, et al. Effects of plasma-activated water on skin wound healing in mice. *Microorganisms* (2020) 8(7):1091. doi:10.3390/microorganisms8071091

21. Subramanian PSG, Jain A, Shivapuji AM, Sundaresan NR, Dasappa S, Rao L. Plasma-activated water from a dielectric barrier discharge plasma source for the selective treatment of cancer cells. *Plasma Process Polym* (2020) 17(8):1900260. doi:10.1002/ppap.201900260

22. Choi B-B, Choi J-H, Kang T-H, Lee S-J, Kim G-C. Enhancement of osteoblast differentiation using No-ozone cold plasma on human periodontal ligament cells. *Biomedicines* (2021) 9(11):1542. doi:10.3390/biomedicines9111542

23. Kobayashi M, Tomoda K, Morihara H, Asahi M, Shimizu T, Kumagai S. Non-thermal atmospheric-pressure plasma potentiates mesodermal differentiation of human induced pluripotent stem cells. *Heliyon* (2022) 8(12):e12009. doi:10.1016/j.heliyon.2022.e12009

24. Guo L, Zou Z, Smeets R, Kluwe L, Hartjen P, Gosau M, et al. Attachment and osteogenic potential of dental pulp stem cells on non-thermal plasma and UV light treated titanium, zirconia and modified PEEK surfaces. *Materials* (2022) 15(6):2225. doi:10.3390/ma15062225

25. Guo L, Smeets R, Kluwe L, Hartjen P, Barbeck M, Cacaci C, et al. Cytocompatibility of titanium, zirconia and modified PEEK after surface treatment using UV light or non-thermal plasma. *Int J Mol Sci* (2019) 20(22):5596. doi:10.3390/ijms20225596

26. Chaichi A, Prasad A, Kootta Parambil L, Shaik S, Hemmasian Ettefagh A, Dasa V, et al. Improvement of tribological and biocompatibility properties of orthopedic materials using piezoelectric direct discharge plasma surface modification. *ACS Biomater Sci Eng* (2019) 5(5):2147–59. doi:10.1021/acsbiomaterials.9b00009

27. Lee J-H, Jeong W-S, Seo S-J, Kim H-W, Kim K-N, Choi E-H, et al. Non-thermal atmospheric pressure plasma functionalized dental implant for enhancement of bacterial resistance and osseointegration. *Dental Mater* (2017) 33(3):257–70. doi:10.1016/j.dental.2016.11.011

28. Lee YS, Lee MH, Kim HJ, Won HR, Kim CH. Non-thermal atmospheric plasma ameliorates imiquimod-induced psoriasis-like skin inflammation in mice through inhibition of immune responses and up-regulation of PD-L1 expression. *Sci Rep* (2017) 7(1):15564. doi:10.1038/s41598-017-15725-7

29. Liedtke KR, Freund E, Hackbarth C, Heidecke C-D, Partecke L-I, Bekeschus S. A myeloid and lymphoid infiltrate in murine pancreatic tumors exposed to plasma-treated medium. *Clin Plasma Med* (2018) 11:10–7. doi:10.1016/j.cpme.2018.07.001

30. Ebrahimi-Shaghaghi F, Noormohammadi Z, Atyabi SM, Razzaghi-Abyaneh M. Inhibitory effects of cold atmospheric plasma on the growth, virulence factors and HSP90 gene expression in Candida albicans. *Arch Biochem Biophys* (2021) 700:108772. doi:10.1016/j.abb.2021.108772

31. Jung SN, Oh C, Chang JW, Liu L, Lim MA, Jin YL, et al. EGR1/GADD45α activation by ROS of non-thermal plasma mediates cell death in thyroid carcinoma. *Cancers (Basel)* (2021) 13(2):351. doi:10.3390/cancers13020351

32. Hwang JH, Lee HY, Chung KB, Lee HJ, Kim J, Song K, et al. Non-thermal atmospheric pressure plasma activates Wnt/β-catenin signaling in dermal papilla cells. *Sci Rep* (2021) 11(1):16125. doi:10.1038/s41598-021-95650-y