A Scientometric Analysis of Photodynamic and Laser Medicine Research: Knowledge Structure, Collaboration Networks, and Thematic Evolution

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Abstract:
Photodynamic and laser medicine has rapidly developed into an interdisciplinary research field integrating photonics, laser technology, nanotechnology, biomedical imaging, and clinical medicine; however, its global knowledge structure and thematic evolution remain insufficiently understood. This study aimed to provide a comprehensive scientometric analysis of global research on photodynamic and laser medicine from 1990 to 2026 by examining its knowledge structure, collaboration networks, and thematic evolution. Bibliographic records were retrieved from the Web of Science Core Collection and analyzed using the Bibliometrix/Biblioshiny package in R. Performance analysis, collaboration network analysis, keyword co-occurrence, thematic mapping, density visualization, and trend topic analysis were employed. A total of 3,924 publications were identified, with an annual growth rate of 16.01%. China was the leading contributor in publication output, whereas the United States showed the highest citation impact and international collaboration. Keyword co-occurrence analysis revealed three major thematic clusters centered on photodynamic therapy, nanomedicine and drug delivery, and biomedical imaging. Trend analysis indicated a shift from fundamental photochemical mechanisms toward nanotechnology-enabled, imaging-guided, and clinically oriented applications. Overall, photodynamic and laser medicine is characterized by increasing integration of therapeutic and diagnostic approaches, with future development likely to depend on interdisciplinary collaboration across photonics, nanotechnology, biomedical imaging, and precision medicine.

Keywords: Photodynamic therapy; Laser medicine; Scientometric analysis; Bibliometric mapping; Knowledge structure; Thematic evolution

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1. Introduction

In recent decades, the development of light-based technologies in optics and photonics has brought profound transformations to medical sciences, biomedical engineering, and therapeutic technologies[1-3]. The rapid advancement of optical technologies has not only enabled innovative imaging, diagnostic, and disease monitoring techniques but has also facilitated the emergence of a new generation of minimally invasive, targeted, and intelligent therapeutic approaches[4, 5]. The increasing role of optical technologies in medicine has led to the formation of an interdisciplinary field in which optics, laser physics, photonics, materials science, biomedical engineering, and clinical sciences converge[6, 7].

Light, as one of the most fundamental tools in modern medicine, now extends far beyond its traditional role in imaging and tissue visualization and has become an effective therapeutic agent[8]. The interaction between light and biological tissues enables a wide range of diagnostic and therapeutic processes. Advances in optical technologies and precise control of light parameters such as wavelength, intensity, exposure time, and energy delivery have expanded the applications of light in medicine from conventional techniques toward personalized and intelligent therapies[9, 10].

In this context, the development of laser technology and the emergence of medical photonics have played a pivotal role in transforming modern medicine[11, 12]. Lasers, due to their coherence, Monochromaticity, directionality, and high focusing capability, have become essential tools in surgery, ophthalmology, dermatology, dentistry, oncology, and targeted therapies[13]. Simultaneously, the growth of photonic technologies and the emergence of subfields such as Nanophotonics, Biophotonics, and optoelectronics have led to the development of advanced diagnostic and therapeutic systems that improve precision, reduce side effects, and enhance treatment efficacy[14-16].

One of the most prominent emerging fields in this domain is PDT, which utilizes a combination of light, oxygen, and photosensitizing agents to selectively destroy target cells[17-19]. Due to its minimally invasive nature, spatial selectivity, and reduced damage to healthy tissues, PDT has gained significant attention in recent years. It is now widely applied in the treatment of various cancers, skin disorders, ophthalmic diseases, drug-resistant infections, and vascular conditions[20, 21].

The expansion of PDT has contributed to the broader field of photodynamic medicine, which encompasses not only therapeutic applications but also imaging, diagnostics, photosensitizer design, nanocarriers, light delivery systems, and photonic technologies[22-24]. At the same time, the development of laser medicine and other light-based therapies has further blurred the boundaries between optics, photonics, and medical sciences, leading to a highly interconnected interdisciplinary research domain[25].

The rapid growth of these fields has resulted in a substantial increase in scientific production in recent years. Thousands of articles, systematic reviews, patents, emerging technologies, and scientific collaborations have been published in the areas of light-based therapies, laser medicine, and PDT[26]. While this expansion reflects the dynamism of the field, it has also made it increasingly difficult to understand its knowledge structure, identify key actors, detect research trends, and anticipate future directions[27].

In response to this challenge, scientometric methods have emerged as powerful tools for analyzing knowledge structures, collaboration networks, scientific trends, and intellectual mapping of research fields[28-30]. These approaches, including citation analysis, co-citation analysis, co-word analysis, and science mapping techniques, provide

a macroscopic view of the development of scientific domains and help reveal emerging research trajectories[31-33].

Despite the rapid growth of research in photodynamic therapy, laser medicine, and light-based therapies, a comprehensive understanding of the intellectual structure, collaboration patterns, thematic clusters, and emerging trends in this field is still lacking. Most previous studies have focused on clinical, technological, or narrative reviews, while fewer studies have systematically examined the global knowledge structure using scientometric approaches[34, 35]. This gap limits informed decision-making in research planning, scientific policy, and technological development.

Accordingly, the present study aims to conduct a scientometric analysis of research on photodynamic therapy, laser medicine, and light-based therapeutic approaches. Using data retrieved from the Web of Science Core Collection and applying science mapping techniques, this study seeks to identify global research trends, influential authors and countries, collaboration networks, thematic structures, and emerging research fronts in this rapidly evolving interdisciplinary field.

2 .Methodology

This study employed a scientometric approach to investigate the intellectual structure, collaboration patterns, thematic evolution, and publication trends in photodynamic and laser medicine research. The methodological framework was designed according to established principles of bibliometric and science mapping studies.

Bibliographic records were retrieved from the Web of Science Core Collection (WoSCC) on 8 June 2026. WoSCC was selected as the data source because of its high-quality bibliographic metadata, standardized citation indexing, and comprehensive coverage of peer-reviewed scientific literature, making it one of the most widely used databases for scientometric research [36]. The literature search was conducted using the Topic (TS) field, including titles, abstracts, author keywords, and Keywords Plus. The following search strategy was applied: TS = ("photodynamic therapy" OR "photodynamic medicine" OR PDT OR "optical therapeutics" OR "laser medicine" OR "light therapy" OR "light-based therapy" OR "photonic medicine"). The search was restricted to records indexed in the Science Citation Index Expanded (SCI-Expanded) and Emerging Sources Citation Index (ESCI) databases, published between 1990 and 2026, categorized as Article or Review Article, and written in English. The final search conducted on 8 June 2026 identified 3,924 eligible records, which were exported for subsequent scientometric analyses.

Although other bibliographic databases, such as Scopus and PubMed, also provide valuable scientific records, WoSCC was selected due to its standardized citation structure, reliable bibliographic information, and compatibility with advanced science mapping tools, particularly Bibliometrix/Biblioshiny [27, 28].

Before analysis, the retrieved records were screened and standardized to improve data consistency. Duplicate records were removed, and variations in author names, institutional affiliations, and keywords were normalized. Synonymous terms and acronyms were unified to prevent fragmentation of the conceptual structure. For example, different expressions referring to PDT were standardized into a single preferred term.

Data analysis was conducted using Microsoft Excel and the Bibliometrix package with its Biblioshiny web interface in R. Performance analysis was performed to evaluate

annual scientific production, citation impact, countries, institutions, and collaboration patterns.

Conceptual structure analysis included keyword co-occurrence analysis, thematic density mapping, trend topic analysis, and strategic thematic mapping. In the co-occurrence network, node size represents keyword frequency, colors indicate thematic cluster membership, and link thickness represents the strength of relationships among keywords.

The co-word analysis was based on author keywords. Keywords were selected according to their occurrence frequency, and the network was normalized using the Association Strength method. Thematic clusters were identified using the Louvain clustering algorithm implemented in Bibliometrix.

Strategic thematic mapping was performed using Callon's centrality and density indicators. Centrality reflects the importance and external connections of a theme within the scientific field, whereas density represents the internal development and cohesion of a thematic cluster.

To evaluate the developmental trajectory and life cycle of photodynamic and laser medicine research, a logistic growth model was fitted to cumulative annual publication data.

The logistic model is expressed as:

$$P(t) = \frac{K}{1+e^{-r(t-t_0)}} \tag{1}$$

- ($P(t)$) is the cumulative number of publications at time (t);
- (K) represents the carrying capacity (maximum expected publication volume);
- (r) denotes the intrinsic growth rate; and
- (t_0) is the inflection point corresponding to the year of maximum growth.

Model parameters were estimated using nonlinear least-squares regression. Model performance was evaluated using the coefficient of determination (R^2). The fitted model yielded an R^2 value of 0.949, indicating an excellent fit to the observed publication trend. The estimated carrying capacity was 6,423 publications, suggesting that approximately 61.1% of the projected scientific capacity of the field has currently been achieved. The model further identified 2024 as the estimated peak growth year, after which publication output is expected to continue increasing but at a gradually declining growth rate.

2.1 Theoretical Background

In recent years, the rapid development of photodynamic therapy (PDT), laser medicine, and biomedical photonics has been accompanied by an increasing number of scientometric studies. However, previous bibliometric literature has largely focused on isolated disease categories or specific technological applications, leaving the broader intellectual architecture of the field unmapped.

Among the studies focusing on technological and material innovations, Cheng et al. (2022) conducted one of the earliest comprehensive bibliometric analyses on global cancer PDT, identifying nanotechnology as a major driving force and highlighting the dominant contributions of China and the United States [36]. Following this trajectory of targeted delivery systems, Zhou et al. (2022) investigated the evolution of 5-

aminolevulinic acid (5-ALA) applications, demonstrating a progressive shift from conventional photosensitizers toward multifunctional nanocarriers and integrated diagnostic–therapeutic platforms [37]. Furthermore, evaluating the long-term integration of optical technologies into oncology, Li et al. (2023) performed a thirty-year scientometric analysis of photoacoustic imaging, identifying precision medicine and multidisciplinary collaboration as critical emerging frontiers [38].

In parallel, a substantial body of bibliometric research has examined specialized clinical and anatomical applications. Focusing on localized infections, de Araujo et al. (2022) demonstrated continuous publication growth and expanding clinical interest in PDT as an adjunctive treatment for endodontics [39]. In the field of dermatology, Huang et al. (2024) analyzed two decades of research using Cite Space, reporting a strong shift toward advanced photosensitizers and technology-oriented therapeutic approaches [40]. This clinical mapping has recently extended to aggressive visceral malignancies, where Wang et al. (2025) presented a three-decade analysis of PDT for glioblastoma, showcasing a transition from basic laboratory research toward translational applications [41]. Similarly, Zhang et al. (2025) and Wen et al. (2026) independently investigated publication trends in gastric and colorectal cancers, respectively, with both teams identifying targeted combination therapies and precision oncology as the principal emerging directions[42, 43]. Contributed to the global mapping of skin oncology, Issrani et al. (2026) emphasized the critical role of international scientific cooperation in advancing skin cancer phototherapy [44].

Despite the valuable insights provided by these investigations, their collective scope remains highly compartmentalized within individual clinical conditions or isolated modalities. Consequently, a critical knowledge gap persists, as no previous study has comprehensively examined the global knowledge structure, collaboration networks, and overarching thematic evolution across the entire interdisciplinary spectrum of photomedicine and laser technology.

To bridge this gap, the present study provides a holistic science-mapping analysis based on the Web of Science Core Collection from 1990 to 2026. By integrating advanced publication modeling, strategic diagrams, and thematic density visualizations, this work moves beyond isolated bibliometric counts to deconstruct the macro-evolutionary trajectory of the entire discipline. The principal novelty and scientific contribution of this research lie in its capacity to unveil the hidden intellectual boundaries and transitional hot topics bridging physics-driven laser advancements and biology-driven phototherapy. By transforming fragmented literature into a definitive, data-driven roadmap, this study offers essential strategic guidance for funding agencies, clinicians, and multidisciplinary researchers to optimize future investments and target high-impact collaborative frontiers in next-generation light-based therapeutics.

3 . Results and Discussion

3.1 Overview of the Dataset and General Characteristics

A total of 3,924 publications retrieved from the Web of Science Core Collection were included in the analysis, and their main bibliometric characteristics are presented in Figure 1.

According to Figure 1 and the main information dashboard, the dataset comprises 3,924 scientific publications published between 1990 and 2026 across 1,490 different

sources, including journals, books, and other scholarly outlets. The annual growth rate of 16.01% reflects the dynamic nature of this research area and the increasing attention it has received from the scientific community. The average age of the documents is 7.5 years, indicating that a substantial proportion of the literature is relatively recent and up to date. Furthermore, the average number of citations per document is 48.29, which is a considerable figure and demonstrates the significant scientific impact of publications in this field.



Fig. 1. Main Information and Bibliometric Characteristics of the Retrieved Dataset

In terms of document types, research articles (n = 2,114) and review articles (n = 1,418) constitute the largest share of the dataset, suggesting a balanced distribution between the production of new knowledge and the synthesis of existing evidence. The participation of more than 20,000 authors, with an average of approximately six authors per publication (5.99), highlights the collaborative nature of research in this domain. Moreover, the international co-authorship rate of 26.4% indicates the existence of extensive global research networks and underscores the importance of international collaboration in advancing research on photodynamic therapy, laser medicine, and optical therapeutics.

3.1.1 Leading Authors in Photodynamic and Laser Medicine Research

To evaluate the key contributors shaping photodynamic and laser medicine research, the dataset was analyzed based on author productivity, local citations, and academic impact (H-index). Table 1 outlines the top 10 most influential authors evaluated across these three-core metrics. Highlighting these prolific researchers identifies the key scientific hubs driving this domain and underscores the scholars whose findings provide a foundation for ongoing research.

As presented in Table 1, Gasser, Gilles emerges as the most prominent researcher in this field across all evaluated metrics, holding the top position in total publication volume (26 documents), local citations (138 citations), and overall scholarly impact (H-index = 18). He is closely followed by Karges, Johannes (22 documents, H-index = 17) and Chen, Yu (19 documents, 119 local citations, H-index = 16), forming a highly active core of researchers driving modern advances in this discipline.

3.1.2 Leading Institutions in Photodynamic and Laser Medicine Research

Table 1. Top 10 Most Prolific and Influential Authors in Photodynamic and Laser Medicine Research Ranked by Publication Volume, Local Citations, and H-Index.

Impact Measure: H	Authors	Local Citations	Authors	N. of Documents	Authors	
18	GASSER GILLES	138	GASSER, GILLES	26	GASSER, GILLES	1
17	KARGES JOHANNES	119	CHEN, YU	22	KARGES, JOHANNES	2
16	CHEN YU	101	KARGES, JOHANNES	19	CHEN, YU	3
14	TANG BEN ZHONG	74	DING, DAN	16	TANG, BEN ZHONG	4
12	CHEN XIAOYUAN	68	PENG, XIAOJUN	14	AEBISHER, DAVID	5
11	PENG XIAOJUN	67	KIM, JONG SEUNG	13	ABRAHAMSE, HEIDI	6
11	YOON JUYOUNG	60	SHI, JIANLIN	13	CHEN, XIAOYUAN	7
10	LIU BIN	60	YOON, JUYOUNG	13	LIU, BIN	8
9	ABRAHAMSE HEIDI	53	CHEN, XIAOYUAN	13	PENG, XIAOJUN	9
9	DING DAN	51	EL-SAYED, MOSTAFA A.	12	BARTUSIK-AEBISHER, DOROTA	10

Introductory paragraph: To evaluate the institutional landscape driving research in photodynamic and laser medicine, the dataset was analyzed to identify the most productive universities and research centers. Table 2 presents the top 10 institutions based on total publication count. Examining institutional productivity provides insights into the primary centers of scientific leadership and resource allocation within this domain.

As shown in Table 2, the Chinese Academy of Sciences leads global institutional production with a total of 254 publications, followed by major U.S. academic entities including the University of California System (205 documents) and Harvard University (171 documents). Prestigious European and Asian institutions, such as the Centre National de la Recherche Scientifique (CNRS) (134 documents) and the National University of Singapore (96 documents), also feature prominently among the top contributors.

3.1.3 Leading Journals in Photodynamic and Laser Medicine Research

To identify the core publication venues shaping photodynamic and laser medicine research, the dataset was analyzed based on journal publication volume. Table 3 lists the top 10 most prolific academic journals disseminating research in this field. Examining these key publication outlets highlights the primary academic channels through which core methodologies, innovative therapies, and breakthrough findings are shared among researchers.

As presented in Table 3, Photodiagnosis and Photodynamic Therapy serves as the single most prolific journal in this domain, leading with 67 published documents. This is followed by high-impact multidisciplinary and materials-focused journals, including Coordination Chemistry Reviews (46 documents), Nanoscale (41 documents), ACS Nano (40 documents), and Advanced Materials (39 documents).

Table 2. Top 10 Most Productive Institutional Affiliations in Photodynamic and Laser Medicine Research

N. of Documents	Institutions
254	CHINESE ACADEMY OF SCIENCES
205	UNIVERSITY OF CALIFORNIA SYSTEM
171	HARVARD UNIVERSITY
134	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE (CNRS)
112	UNIVERSITY OF TEXAS SYSTEM
103	HARVARD UNIVERSITY MEDICAL AFFILIATES
97	EGYPTIAN KNOWLEDGE BANK (EKB)
96	NATIONAL UNIVERSITY OF SINGAPORE
91	UNIVERSITY OF LONDON
88	STANFORD UNIVERSITY

Table 3. Top 10 Most Prolific Journals in Photodynamic and Laser Medicine Research.

N. of Documents	Sources
67	PHOTODIAGNOSIS AND PHOTODYNAMIC THERAPY
46	COORDINATION CHEMISTRY REVIEWS
41	NANOSCALE
40	ACS NANO
39	ADVANCED MATERIALS
38	INTERNATIONAL JOURNAL OF MOLECULAR SCIENCES
37	JOURNAL OF BIOMEDICAL OPTICS
35	ACS APPLIED MATERIALS & INTERFACES
35	BIOMATERIALS
34	JOURNAL OF MATERIALS CHEMISTRY B

The distribution of published literature across these top sources reflects a strong interdisciplinary nature, spanning specialized clinical/photomedicine journals (e.g., Photo diagnosis and Photodynamic Therapy, Journal of Biomedical Optics) alongside high-impact journals in nanoscience, materials engineering, and chemistry (e.g., Biomaterials, ACS Applied Materials & Interfaces). This highlights how advancements in photodynamic therapy rely heavily on cross-disciplinary innovation at the intersection of material design, chemistry, and clinical application.

3.2 Publication Growth Dynamics and Logistic Model Forecast

A longitudinal visualization of scientific production in the field is presented to illustrate its publication growth pattern over the study period (Figure 2).

The field showed very limited publication activity in the 1990s, followed by rapid exponential growth after 2010, reaching a peak of 412 publications in 2025. The logistic growth model ($R^2 = 0.949$) indicates that the field is in the maturity phase, having achieved 61.1% of its estimated saturation capacity ($K = 6.423$), with the peak growth year

identified around 2024. Although scientific output is expected to continue increasing, the growth rate is projected to gradually slow as the field approaches saturation.

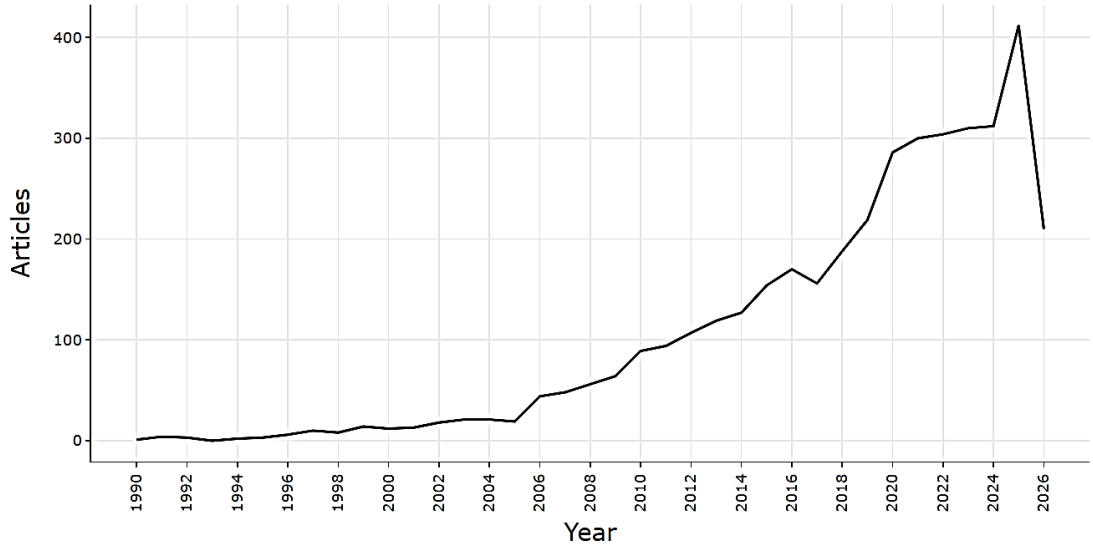


Fig. 2. Growth Trend of Publications in Photodynamic and Laser Medicine Research (1990–2026)

3.3 Leading Countries in Scientific Production and Citation Performance

The distribution of scientific production, citation impact, and collaboration patterns among the leading contributing countries is presented in Figure 3.

The country productivity and citation impact charts illustrate the global distribution of scientific influence and the intense competition among nations in this research field. In terms of publication output, China ranks first by a substantial margin; however, a large proportion of its publications are classified as Single Country Publications (SCP), indicating that much of its research is conducted domestically. In contrast, the United States, which ranks second in publication output, exhibits a notably high proportion of Multiple Country Publications (MCP), highlighting its central role in international collaboration networks and scientific diplomacy. From the perspective of research impact, measured by total citations, the United States leads with 56,089 citations, slightly surpassing China with 52,313 citations. Following these two scientific powerhouses, South Korea, India, and the United Kingdom occupy the subsequent positions with a considerable gap in both productivity and citation performance.

3.4 Evolution of Research Topics and Emerging Trends

To identify the temporal evolution of research interests and emerging topics, a trend topic analysis was conducted based on the occurrence of author keywords over time, as presented in Figure 4.

The trend topics analysis illustrates the evolution of research interests within the field over time. During the period from 2009 to 2012, research attention was primarily focused on fundamental concepts such as nanocrystals and evidence-based medicine. Between 2018 and 2021, the emphasis shifted toward photodynamic therapy, imaging, and nanoparticles, reflecting the growing integration of optical technologies and therapeutic applications. More recently, from 2023 onward, topics such as biomedical applications, nanomaterials, and bioimaging have emerged as the most prominent research themes.

This trend suggests a transition from fundamental material development toward translational research, clinical applications, and multidisciplinary biomedical innovations.

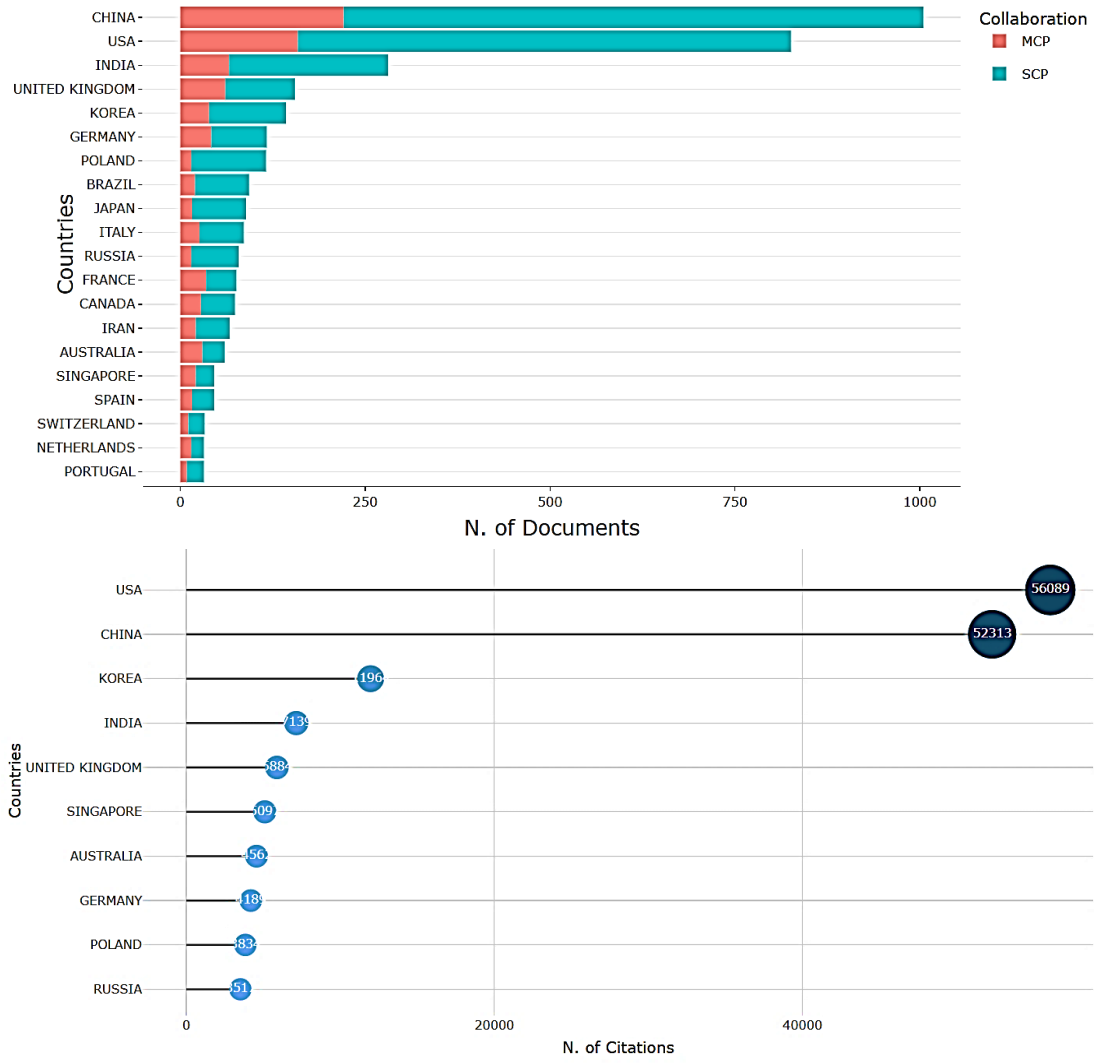


Fig. 3. Scientific Production and International Collaboration Patterns by Country.

3.5 Knowledge Structure and Conceptual Network of Photodynamic and Laser Medicine Research Based on Co-Word Network Analysis

The knowledge structure of photodynamic and laser medicine research was explored through keyword co-occurrence analysis, which identifies the major thematic clusters and reveals the conceptual relationships among research topics, as illustrated in Figure 5.

Based on the clustering results, the knowledge structure of photodynamic and laser medicine research is organized into three major interconnected thematic clusters. The red cluster is centered on photodynamic therapy, the largest node in the network, and includes key concepts such as photosensitizer, singlet oxygen, reactive oxygen species, and apoptosis, representing the fundamental photochemical and biological mechanisms

underlying PDT. The blue cluster is organized around drug delivery and cancer, encompassing concepts such as nanoparticles, nanomedicine, theranostics, precision medicine, and imaging, highlighting the strong emphasis on nanotechnology-based drug delivery systems and targeted cancer therapy. The green cluster, located in the upper-left region of the network, contains concepts including biosensors, bioimaging, and biomedical applications, reflecting research focused on diagnostic technologies and complementary biomedical applications. A prominent feature of the network is the strong linkage between photodynamic therapy and the cancer and drug delivery nodes, indicating that the integration of nanotechnology with photodynamic therapy for precision cancer treatment constitutes the dominant and rapidly evolving research direction within the field.

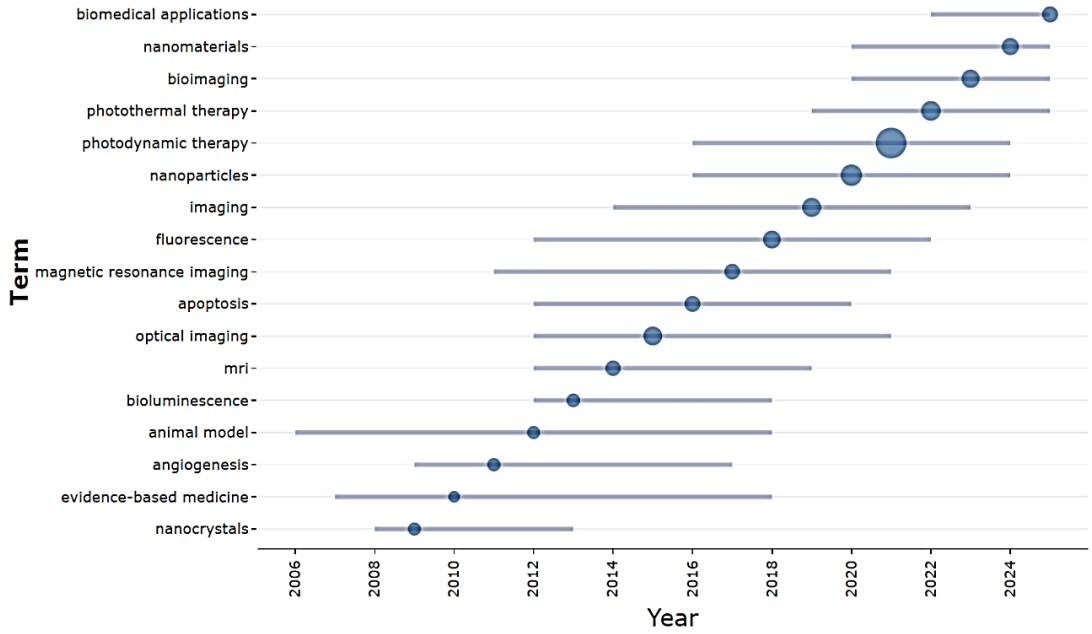


Fig. 4. Evolution of Research Topics in Photodynamic and Laser Medicine.

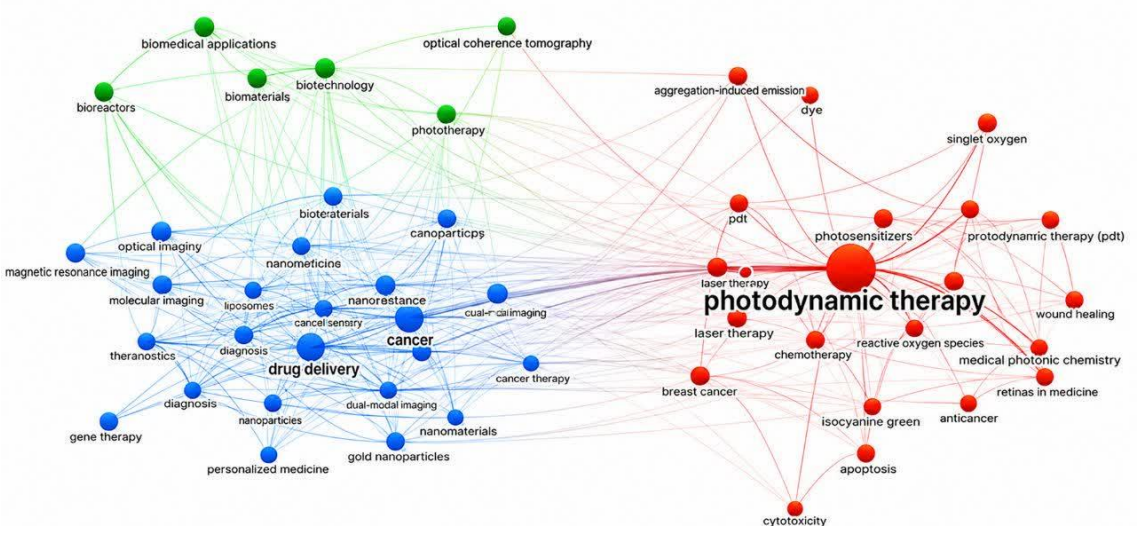


Fig. 5. Knowledge Structure of Photodynamic and Laser Medicine Research.

3.6 Thematic Structure and Research Hotspots in Photodynamic and Laser Medicine

To further identify the most concentrated and influential research topics, a thematic density map was generated based on keyword co-occurrence patterns (Figure 6).

The density visualization illustrates the relative concentration and intensity of research topics across the field. Warmer colors, particularly red and yellow, indicate regions with higher keyword density and greater research intensity, whereas cooler colors, including green and blue, represent lower-density areas associated with emerging, specialized, or less extensively investigated topics. The results reveal a clear dual-core structure within the knowledge landscape. On the right side of the map, a highly dense and central hotspot is formed around photodynamic therapy (PDT), where the term appears within a strong red region, indicating the highest concentration of research activity. This hotspot is closely associated with key mechanistic and biochemical concepts, including photosensitizers, singlet oxygen, reactive oxygen species, apoptosis, and wound healing, reflecting substantial research attention to the fundamental photochemical and photobiological mechanisms of PDT and the optimization of light-activated therapeutic agents.

In contrast, the left side of the map is dominated by a second major hotspot centered on drug delivery and cancer, closely associated with nanomedicine, nanotechnology, theranostics, imaging, precision medicine, and nanomaterials such as gold nanoparticles and quantum dots. This region represents the translational and application-oriented dimension of the field, highlighting the development of nanotechnology-enabled systems for controlled drug delivery, precise tumor diagnosis, and targeted cancer therapy. In addition, peripheral and lower-density regions include topics such as biosensors, optical coherence tomography, and aggregation-induced emission, which appear in lighter-colored areas and therefore represent relatively emerging, specialized, or niche research directions. Overall, the density map demonstrates that photodynamic therapy remains the principal research hotspot, while drug delivery and cancer constitute a second major concentration of research activity, indicating a strong convergence between fundamental photobiological mechanisms and nanotechnology-enabled clinical applications in photodynamic and laser medicine.

3.7 Strategic Diagram for Assessing the Maturity of Thematic Clusters

To evaluate the maturity and strategic importance of the major research themes, a thematic map based on centrality and density indicators was generated, as shown in Figure 7.

The maturity and development status of research themes were assessed based on two complementary dimensions: density and centrality. Density reflects the degree of internal development, conceptual coherence, and cohesion of a thematic cluster, indicating how strongly the keywords within a theme are interconnected. Centrality represents the degree of external interaction and importance of a theme within the overall knowledge structure of the research field. Therefore, themes characterized by high density and high centrality can be interpreted as highly developed and influential research areas because they demonstrate both strong internal development and significant connections with other scientific themes. In contrast, themes with high centrality but lower density may represent

fundamental or broadly connected research areas that have not yet achieved a highly specialized internal structure.

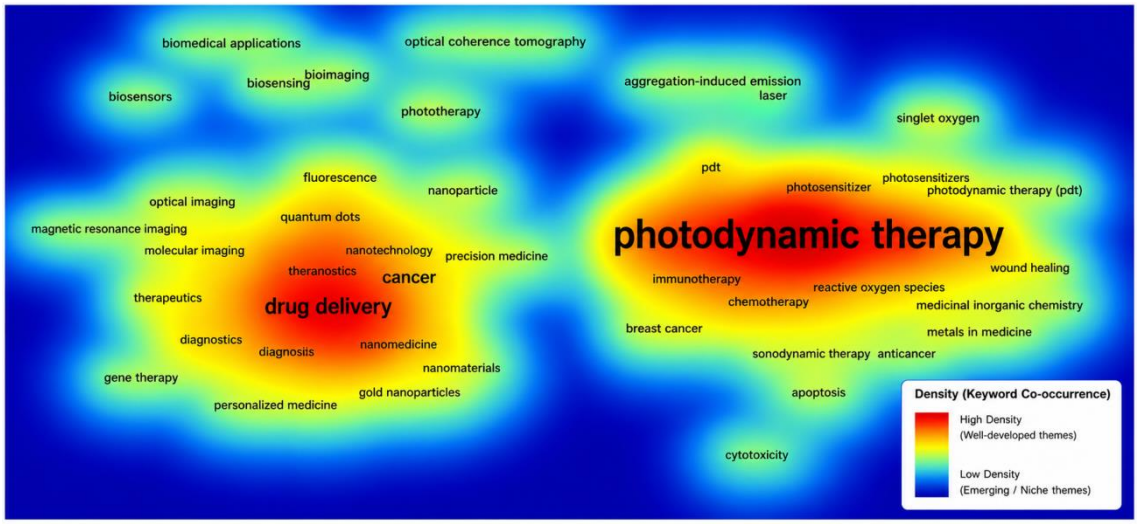


Fig.6. Density visualization map of keyword co-occurrence in photodynamic and laser medicine. Warmer colors (red–yellow) indicate higher keyword density and research intensity, whereas cooler colors (green–blue) represent lower-density and emerging research topics. The density scale represents the relative concentration of co-occurring keywords

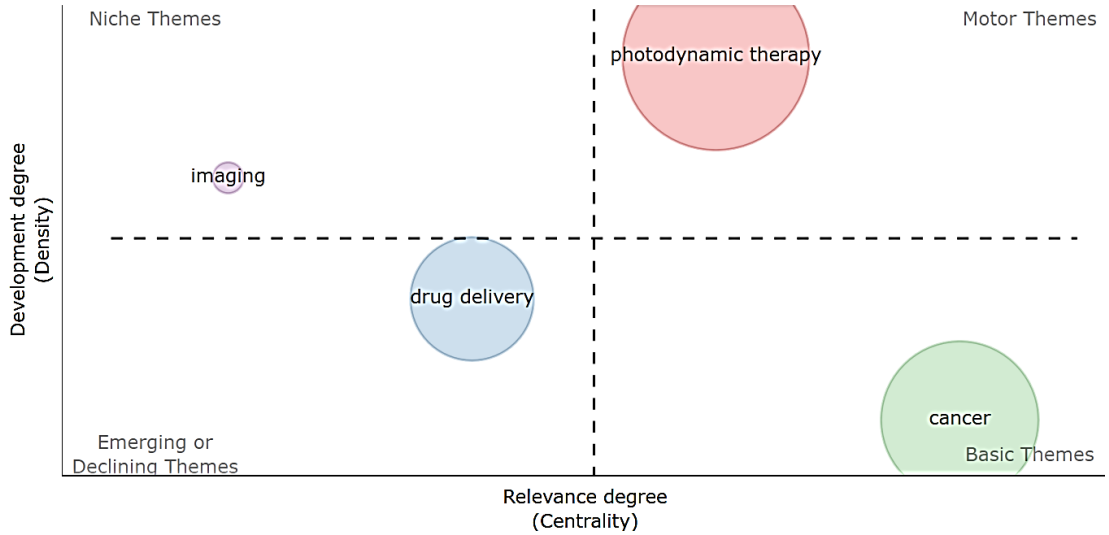


Fig. 7. Strategic Diagram of Thematic Cluster Maturity in Photodynamic and Laser Medicine Research

The thematic map evaluates the position and status of key concepts in the field based on two dimensions: density (degree of development) on the vertical axis and centrality (degree of relevance and importance) on the horizontal axis.

In the upper-right quadrant (Motor Themes), PDT is positioned with relatively high density and centrality, suggesting that it represents a highly developed and influential research theme that plays an important role in shaping the intellectual structure of photodynamic and laser medicine. This position indicates strong internal conceptual development as well as extensive connections with other research areas.

In the lower-right quadrant (Basic Themes), cancer appears with high centrality but lower density. This finding suggests that cancer represents a fundamental and widely connected research context within the field, serving as a major clinical application area, although it does not display the same level of internal thematic specialization as motor themes.

In the upper-left quadrant (Niche Themes), imaging is positioned as a highly developed but relatively specialized theme. Its location indicates strong internal development and conceptual cohesion, while its limited centrality suggests fewer connections with other major thematic areas.

Finally, drug delivery is located near the boundary between the Emerging and Basic Themes quadrants, indicating that this area represents a dynamic and evolving research direction that is becoming increasingly integrated with broader themes such as Nanomedicine, targeted therapy, and photodynamic applications

4. Limitations

Despite providing a comprehensive scientometric overview of photodynamic and laser medicine research, this study has several limitations. First, the analysis was based exclusively on the Web of Science Core Collection (WoSCC). Although WoSCC offers high-quality standardized bibliographic records and reliable citation data, the use of a single database may have resulted in coverage bias, as some relevant publications indexed in databases such as Scopus or PubMed may not have been included. Future studies may combine multiple databases to achieve a more comprehensive representation of the field.

Second, citation-based indicators should be interpreted with caution because citation counts may be influenced by publication age, disciplinary citation practices, and accumulated scientific visibility rather than solely reflecting current research impact. This issue is particularly relevant for recent publications from 2025–2026, which have had limited time to receive citations.

Finally, this study was limited to English-language publications classified as Article and Review Article, which may have introduced language and document-type bias. Future research incorporating additional databases, broader document types, and multilingual records may provide a more complete understanding of the global evolution of photodynamic and laser medicine research.

5. Conclusion

This study provides a comprehensive scientometric overview of the knowledge structure, collaboration networks, and thematic evolution of research in photodynamic and laser medicine from 1990 to 2026. Unlike previous bibliometric investigations that have mainly focused on specific diseases or individual clinical applications, this study offers an integrated perspective on the broader intellectual development and research dynamics of the field.

The findings indicate that research in photodynamic and laser medicine has experienced sustained growth in scientific production, increasing international collaboration, and considerable research impact over the past decades. The observed publication trends suggest that the field has developed into a highly active and interdisciplinary research area involving photonics, laser technology, nanotechnology, biomedical imaging, and clinical applications. These findings are consistent with previous

bibliometric studies reporting the continuous expansion of PDT research in areas such as oncology, dermatology, endodontics, and photoacoustic imaging [36, 38, 41-43].

The thematic analyses suggest that nanotechnology, targeted drug delivery, biomedical imaging, and precision medicine have emerged as important research directions within the field. Consistent with the findings of Cheng et al. (2022), the integration of nanotechnology with PDT represents a prominent research pathway, particularly for improving therapeutic targeting and drug delivery strategies [36]. Similarly, the increasing relevance of biomedical imaging and precision medicine corresponds to trends reported by Li et al. (2023) [39], while recent studies have highlighted a growing transition from fundamental photochemical investigations toward more clinically oriented applications [42-44].

The co-word analysis, thematic density visualization, and strategic mapping collectively reveal that PDT represents a central and highly connected research theme within the field. In addition, nanomedicine, drug delivery, cancer therapy, biomedical imaging, and precision medicine appear as closely related thematic areas that contribute to the ongoing development of photodynamic and laser medicine. The density map suggests a dual structure of knowledge development, linking fundamental photochemical mechanisms with translational and technology-driven therapeutic applications.

Overall, the findings suggest that photodynamic and laser medicine is moving toward a more integrated multidisciplinary framework that combines optical technologies, nanomaterials, biomedical engineering, and clinical sciences. This interdisciplinary convergence may contribute to future advances in precision diagnosis, targeted therapies, and innovative light-based medical technologies.

The main contribution of this study is the development of a comprehensive science-mapping framework that combines bibliometric performance analysis, collaboration network analysis, co-word analysis, thematic evolution, density visualization, and strategic mapping. By identifying the intellectual structure, major research themes, and emerging directions in photodynamic and laser medicine, this study provides evidence-based insights that may support researchers, clinicians, funding organizations, and policymakers in planning future research strategies.

5. Declarations Conflict of Interest

The authors declare that they have no conflicts of interest.

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