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Bibliometric Analysis of Microwave Antenna-Based Hyperthermia Research: Insights for Physics and Biomedical Education

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ABSTRACT

Breast cancer remains a major global health challenge, requiring more precise and minimally invasive therapeutic approaches. Microwave-based hyperthermia, which utilizes antennas to generate controlled heat distribution in tumor tissue, has emerged as a promising solution. However, research developments in this field remain fragmented and lack systematic mapping. Therefore, this study aims to analyze research trends and the knowledge structure of microwave antenna-based hyperthermia using a bibliometric approach, and to explore its potential contributions to physics and biomedical education. Data were collected from the Scopus database for the period 2000–2026, yielding 100 relevant publications. The analysis includes annual scientific production, contributions by countries, authors, and institutions, as well as citation impact and collaboration patterns. The results show a significant increase in publications after 2010, with a peak in 2019–2021, and a dominance of contributions from the United States, China, and Turkey. Despite this growth, disparities between productivity and citation impact persist, and collaboration networks remain relatively fragmented. Beyond mapping scientific developments, this study highlights the relevance of key concepts such as electromagnetic wave propagation, Specific Absorption Rate (SAR), and thermal energy transfer as valuable resources for interdisciplinary learning. These findings demonstrate the potential of this field to support scientific literacy, critical thinking, and curriculum development in physics and biomedical education.

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INTRODUCTION

Breast cancer is one of the leading causes of cancer-related deaths among women worldwide and has shown a rising trend in incidence over the past few decades (Jazrawi et al., 2021; Sung et al., 2021). A report from the World Health Organization (2021–2024) notes approximately 2.3 million new cases of breast cancer each year, with approximately 685,000 deaths globally, underscoring the significant burden this disease places on the global healthcare system (Habtegiorgis et al., 2022; Zheng et al., 2023). These high incidence and mortality rates not only reflect the biological complexity of breast cancer but also indicate that existing therapeutic approaches have not yet been fully capable of delivering optimal and sustainable outcomes. Although significant progress has been made through early detection and the application of conventional therapies such as surgery, chemotherapy, and radiation therapy, these approaches still face fundamental challenges, namely low selectivity for target tissues and a high risk of systemic side effects (Dulińska-Litewka et al., 2022; Pinto et al., 2024). In clinical practice, damage to healthy tissue surrounding the tumor is often unavoidable, directly impacting patients' quality of life post-treatment (Brower et al., 2021). Furthermore, tumor heterogeneity and variations in biological responses among individuals further complicate treatment efficacy (Blanco-Fernandez et al., 2023). This situation underscores that cancer therapy approaches focused solely on eliminating tumor cells without considering precision, control, and biological safety are becoming increasingly inadequate. This complexity also

highlights the importance of integrating interdisciplinary knowledge, particularly in connecting physics and biomedical sciences within educational contexts.

In addressing these challenges, hyperthermia therapy has emerged as a promising complementary approach in cancer management, including breast cancer (Yue et al., 2022). This therapy uses controlled elevation of tumor tissue temperature to induce damage to cancer cells through various biological mechanisms, including protein denaturation, disruption of cell membrane structure, and activation of the apoptosis pathway (Ibrahim et al., 2023; Lopresti et al., 2022). Additionally, hyperthermia is known to enhance cancer cells' sensitivity to radiotherapy and chemotherapy, thereby producing more optimal therapeutic effects through synergistic mechanisms (Hansen et al., 2021). However, the effectiveness of hyperthermia heavily depends on the system's ability to precisely control temperature distribution, both spatially and temporally. Inaccuracies in temperature regulation can cause uneven heating, thereby reducing therapeutic effectiveness or even damaging healthy tissue (B. Yang et al., 2022). Therefore, understanding the therapeutic temperature range is crucial to the implementation of hyperthermia. The temperature range and the resulting biological effects in hyperthermia therapy are presented in Table 1 (Juel Mortensen et al., 2021).

Table 1. Temperature Ranges and Biological Effects in Hyperthermia Therapy (B. Yang et al., 2022)

Temperature Range	Biological Effects
~37°C	Normal physiological conditions
40–43°C	Mild hyperthermia (increased tumor sensitivity, induction of apoptosis)
43–45°C	Moderate hyperthermia (significant increase in tumor cell death)
>45°C	Thermal ablation (permanent tissue damage and necrosis)

To achieve effective, localized heat distribution in hyperthermia therapy, an energy delivery system capable of precisely targeting tumor tissue is required (Besse et al., 2019; Gu & Zhu, 2024). Electromagnetic waves in the microwave spectrum are widely used because they can penetrate biological tissue and generate volumetric heating via interactions between the electromagnetic field and tissue molecules. Microwave antennas play a key role in this system, as they determine the radiation pattern, energy distribution, and the rate of energy absorption within the tissue, typically represented by the Specific Absorption Rate (SAR) parameter (Ware et al., 2017). However, antenna design for medical applications cannot focus solely on conventional electromagnetic parameters such as gain and bandwidth; it must also consider biomedical aspects such as penetration depth, heating homogeneity, and tissue safety (Kim et al., 2021). Operating frequency is a critical parameter that governs these interaction characteristics, with lower frequencies providing deeper penetration, whilst higher frequencies result in shallower but more localized heating. Therefore, frequency selection must be tailored to the tumor's characteristics, particularly the lesion's depth and size. The relationship between microwave frequencies and their applications in hyperthermia therapy is shown in Table 2 (Sayed et al., 2024). Understanding these interactions is essential not only for engineering applications but also for strengthening conceptual learning in electromagnetism, wave propagation, and biomedical physics education.

Table 2. Microwave Frequencies and Their Applications in Hyperthermia Therapy (Sayed Et Al., 2024)

Frequency	Application
~433 MHz	Deep-seated tumours
~915 MHz	Medium penetration (breast cancer)
~2.45 GHz	Superficial tumours
>5 GHz	Very shallow and localised heating

However, previous studies have predominantly emphasized technical antenna optimization, such as gain, bandwidth, radiation efficiency, and SAR reduction, while paying limited attention to the alignment among antenna performance, clinical hyperthermia requirements, and educational relevance. In addition, existing bibliometric studies have not comprehensively mapped microwave antenna-based hyperthermia research within an interdisciplinary framework that connects biomedical engineering, applied physics, and physics education (Lyon et al., 2021). To date, there has been no comprehensive bibliometric study mapping the development of microwave antenna-based hyperthermia research within an integrated interdisciplinary framework that also considers its relevance to educational domains (Altintas et al., 2021; Kavya & Ramana, 2024; Sharma et al., 2025; Singh et al., 2025; Wang et al., 2024). Moreover, limited attention has been given to how this rapidly evolving research field contributes to physics and biomedical education, particularly in supporting interdisciplinary learning, scientific literacy, and curriculum development (Chan et al., 2025; Hernandez et al., 2025; King & Salvo, 2024; Menard et al., 2024; Prestigiacomo et al., 2024; Suhail et al., 2024; Wells et al., 2025).

Recent bibliometric studies in physics education have shown that bibliometric mapping is useful for identifying publication trends, collaboration patterns, dominant themes, and research gaps in technology-enhanced and inquiry-oriented physics learning (Rusmaya & Utami, 2026). Therefore, applying a bibliometric approach to microwave antenna-based hyperthermia research can extend the use of scientific mapping from physics education studies to an interdisciplinary biomedical physics context. The integration of microwave antenna technology and hyperthermia therapy represents a rich interdisciplinary domain that connects fundamental physics concepts, such as electromagnetic waves and energy transfer, with real-world biomedical applications (Geyikoğlu & Çavuşoğlu, 2022; Xiong et al., 2025). In the context of education, this field offers significant potential to enhance students' scientific literacy, problem-solving skills, and ability to apply physics concepts in authentic contexts (de Oliveira Cafiero et al., 2024; Gao & Wang, 2024; Pramod, 2023; Sirajudin et al., 2021).

Therefore, mapping the development of this research area is not only important for technological advancement but also for informing physics and biomedical education practices. Based on the identified research gaps, this study addresses the following research questions: (1) How has research on microwave antennas for hyperthermia developed from 2000 to 2026? (2) Who are the key authors, institutions, countries, and sources contributing to microwave antenna-based hyperthermia research? (3) What are the dominant themes, keyword patterns, and knowledge structures in this research field? (4) What research gaps and future research directions can be identified from the bibliometric mapping? (5) How can the development of microwave antenna-based hyperthermia research contribute to interdisciplinary learning in physics and biomedical education?

Accordingly, this study aims to conduct a comprehensive bibliometric analysis of the development of microwave antennas for hyperthermia research over the period 2000–2026. The early 2000s marked the emergence of modern computational and antenna-based hyperthermia studies, while 2026 represents the most recent year available at the time of data retrieval (May 2026). This analysis aims to identify publication trends, key contributors, influential institutions, and patterns of scientific collaboration in this field. Furthermore, this study aims to uncover the knowledge structure through co-occurrence and co-citation analysis, thereby providing an overview from 2000 to the present of dominant research themes and the direction of future research development. In addition, this study seeks to generate educational insights by exploring how the evolution of this research domain can support interdisciplinary learning, enhance scientific literacy, and advance physics and biomedical education. Consequently, the results of this study are expected to contribute to the development of a structured scientific map, whilst bridging the gap between antenna technology development and clinical needs in hyperthermia-based cancer therapy, as well as serving as a reference for educators, researchers, and curriculum developers in integrating emerging biomedical technologies into physics education.

RESEARCH METHOD

This study adopts a multidisciplinary approach that integrates electromagnetic analysis, biological thermal modeling, and bibliometric methods to map the development of research on microwave antennas in hyperthermia therapy, while offering a broader perspective on hyperthermia research and its interdisciplinary relevance to physics and biomedical education. Conceptually, the hyperthermia system under study comprises several main components: an electromagnetic energy source, an antenna as the energy emitter, biological tissue as the propagation medium, and the resulting heat distribution in response to microwave exposure (Yao et al., 2021; Zhang & Zhou, 2023). The antenna functions not only as a

radiating device but also as a controller of energy distribution, thereby determining the effectiveness of targeted, localized heating of tumor tissue. This system design approach emphasizes the integration of electromagnetic, thermal, and biomedical aspects, given that the interaction between electromagnetic fields and biological tissue not only produces radiation phenomena but also the conversion of energy into heat, which must be precisely controlled to achieve optimal therapeutic effects without causing damage to healthy tissue (Sui et al., 2024; M. Y. Yang et al., 2022). From an educational perspective, this integrated system also serves as a representative model for connecting fundamental physics concepts, such as electromagnetic wave propagation and energy transfer, with real-world biomedical applications. A conceptual framework of a microwave antenna-based hyperthermia system is presented in Figure 1 (Gunduz et al., 2021; Prelević et al., 2023).

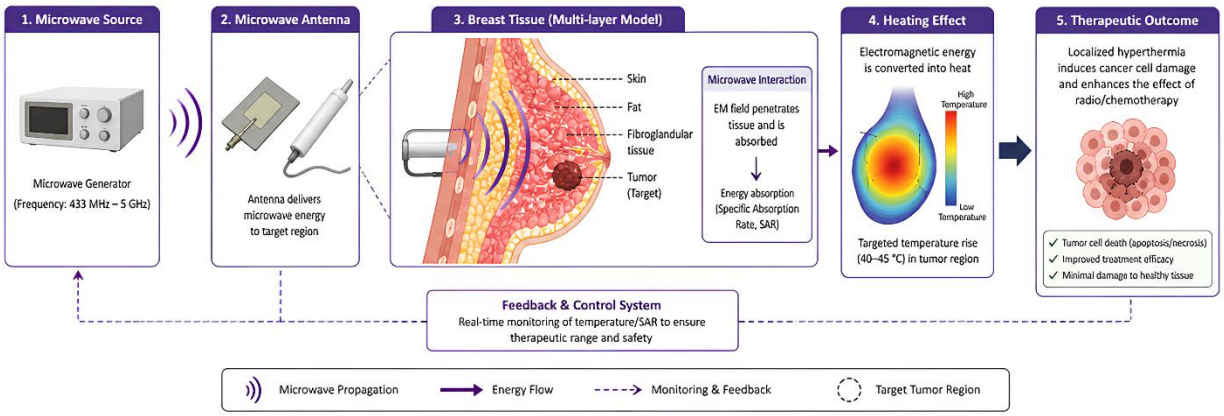


Figure 1. Conceptual Framework of A Microwave Antenna-Based Hyperthermia System Illustrating the Interaction Between Electromagnetic Energy, Antenna Design, Biological Tissue, and Resulting Heat Distribution (Acar et al., 2025; Bevacqua et al., 2023; Crezee et al., 2020; Rajput et al., 2023)

Heat distribution in hyperthermia therapy is determined by the complex interaction between the electromagnetic field emitted by the antenna and the electrical properties of biological tissue (Gavazzi et al., 2020; Kok & Crezee, 2021). The primary parameter used to evaluate this interaction is the Specific Absorption Rate (SAR), which represents the rate of electromagnetic energy absorption per unit mass of tissue. The SAR value is significantly influenced by the operating frequency, the tissue's dielectric properties, and the antenna's configuration and position relative to the tumor target. Additionally, the temperature distribution within the tissue arises from the conversion of electromagnetic energy into thermal energy and is influenced by thermal conductivity, blood perfusion, and heat diffusion (Andreozzi et al., 2019; Pandey, 2024). Therefore, antenna design for hyperthermia applications must produce a localized, homogeneous SAR distribution that aligns with the characteristics of the target tumor (Singla et al., 2021). These physical and biological interactions provide essential conceptual foundations for teaching topics such as electromagnetic energy absorption, thermal diffusion, and biomedical system modeling in physics education.

To gain a more comprehensive understanding of the electromagnetic field distribution and thermal effects, this study employs numerical simulation methods commonly used in hyperthermia research. The biological tissue model is represented using a breast tissue phantom consisting of multiple layers, such as skin, fat, and tumor tissue, each with distinct dielectric parameters. Simulations are performed using electromagnetic software such as CST Studio Suite or HFSS to analyze the distribution of electric fields, antenna radiation patterns, and SAR values in the tissue (Lak & Oraizi, 2013). The simulation approach enables non-invasive evaluation of antenna performance and provides insights into energy distribution that cannot be directly measured in the human body. In addition, this simulation-based approach offers opportunities to integrate computational modeling into physics and biomedical learning environments, particularly to develop students' analytical and problem-solving skills.

Furthermore, a bibliometric analysis was conducted to identify trends and developments in research in this field. Data collection was performed using the Scopus database with searches in the Title, Abstract, and Keywords fields using relevant keyword combinations, such as "microwave antenna," "hyperthermia," and related biomedical and engineering terms. The publication timeframe was limited to the years 2000–2026 to capture the dynamics of research development over the past two decades. The search process

utilized Boolean operators (AND, OR) to ensure a broad yet relevant data scope, followed by filtering based on topic relevance, document type, and the removal of duplicate data to obtain a representative final dataset. This bibliometric approach is particularly useful not only for mapping scientific development but also for identifying knowledge domains that can be integrated into interdisciplinary education.

The collected data was then analyzed using bibliometric software to identify patterns and knowledge structures within this research field (Donthu et al., 2021; Kok & Crezee, 2021; Nguyen et al., 2015). The analysis included annual publication trends, contributions by authors and institutions, patterns of scientific collaboration (co-authorship), citation and co-citation analysis, as well as co-occurrence analysis of keywords. Network visualizations were used to illustrate relationships among research elements, such as topic interconnections, researcher collaborations, and the evolution of research themes over time. Additionally, thematic mapping was used to identify emerging and dominant topics that have potential relevance for curriculum development in physics and biomedical education. The bibliometric analysis workflow, which includes data collection, filtering, data export, analysis, and visualization and interpretation of results, is shown in Figure 2.

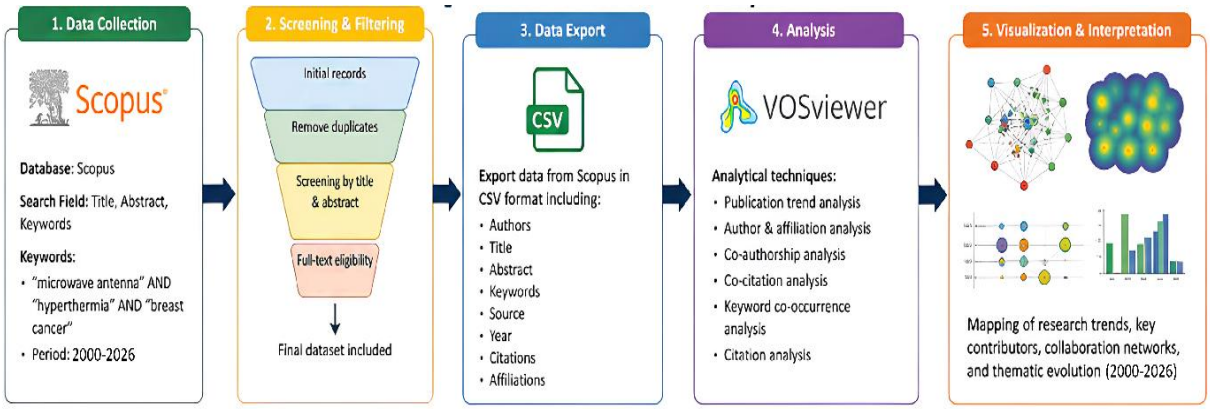


Figure 2. Bibliometric Analysis Workflow, Including Data Collection, Screening, Analysis, Visualization, and Interpretation of Research Trends and Educational Insights

RESULTS AND DISCUSSION

Result

Search Strategies

The literature identification process yielded a significant variation in the number of documents for each search strategy used (Table 3). The search was conducted in the Scopus database using the Title, Abstract, and Keywords fields, with an access date of May 1, 2026. The most specific query, namely ("microwave antenna") AND ("hyperthermia") AND ("breast cancer"), yielded 100 documents, which constitutes the most relevant dataset for the focus of this study. Meanwhile, the broader query, namely ("microwave antenna") AND ("hyperthermia"), yielded 991 documents, indicating a much larger scope of literature.

Additionally, the query ("antenna") AND ("hyperthermia") AND ("cancer") yields 580 documents, representing research within a broader scope related to hyperthermia-based cancer therapy. On the other hand, a highly specific query, namely ("microstrip antenna") AND ("microwave hyperthermia") AND ("breast cancer"), yields only 15 documents, indicating a relatively limited number of publications for this highly focused combination of topics. Based on these results, the primary dataset used in the subsequent bibliometric analysis is the result of the query ("microwave antenna") AND ("hyperthermia") AND ("breast cancer"), comprising 100 documents. This dataset not only represents a focused body of knowledge but also provides a meaningful basis for identifying concepts that can be integrated into physics and biomedical education.

Table 3. Dataset Specifics

Database	Search Field	Search Strategies	Count
Scopus	Title, Abstract, Keywords	("microwave antenna") AND ("hyperthermia") AND ("breast cancer")	100
Scopus	Title, Abstract, Keywords	("microwave antenna") AND ("hyperthermia")	991
Scopus	Title, Abstract, Keywords	("antenna") AND ("hyperthermia") AND ("cancer")	580
Scopus	Title, Abstract, Keywords	("microstrip antenna") AND ("microwave hyperthermia") AND ("breast cancer")	15

*The date the data was viewed is 01.05.2026

Annual Scientific Production

The annual trend in scientific publications on microwave antennas for breast cancer hyperthermia therapy is shown in Figure 3. In general, the number of publications exhibits a fluctuating pattern with a long-term upward trend. In the early period (around 2000–2010), the number of publications was relatively low, with few articles each year. Entering the 2011–2016 period, the number of publications increased more steadily, although fluctuations between years still occurred.

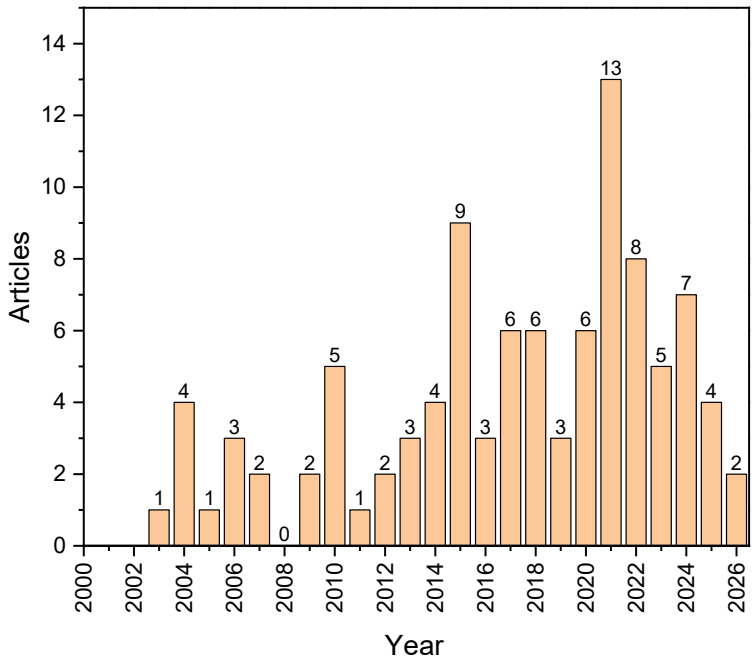


Figure 3. Annual Scientific Production

A more significant increase was observed during 2019–2021, when the number of publications reached its highest level. After reaching this peak, the publication trend declined in subsequent years, although it remained higher than in the early period. This increasing trend reflects not only growing scientific interest but also the expanding relevance of interdisciplinary topics that can be integrated into physics and biomedical education, particularly for introducing students to emerging medical technologies.

The Country's Scientific Production

The distribution of scientific output by country, shown in Figure 4, reveals a global imbalance in research contributions. The visualization indicates that only a few countries dominate the publication count, while others make relatively smaller contributions. The United States is recorded as the country with the highest contribution, followed by China and Turkey, which also demonstrate significant research productivity. Additionally, India and Egypt are moderate contributors, whereas several European countries, such as Sweden, Italy, Malta, and the Netherlands, have lower contributions. Australia is also among the

countries with relatively small contributions in this global distribution. Overall, the total number of contributing countries reaches 321, representing the cumulative involvement of these nations in the analyzed publications. From an educational perspective, this global distribution highlights the importance of international collaboration in shaping research-informed learning environments and globally relevant curricula.

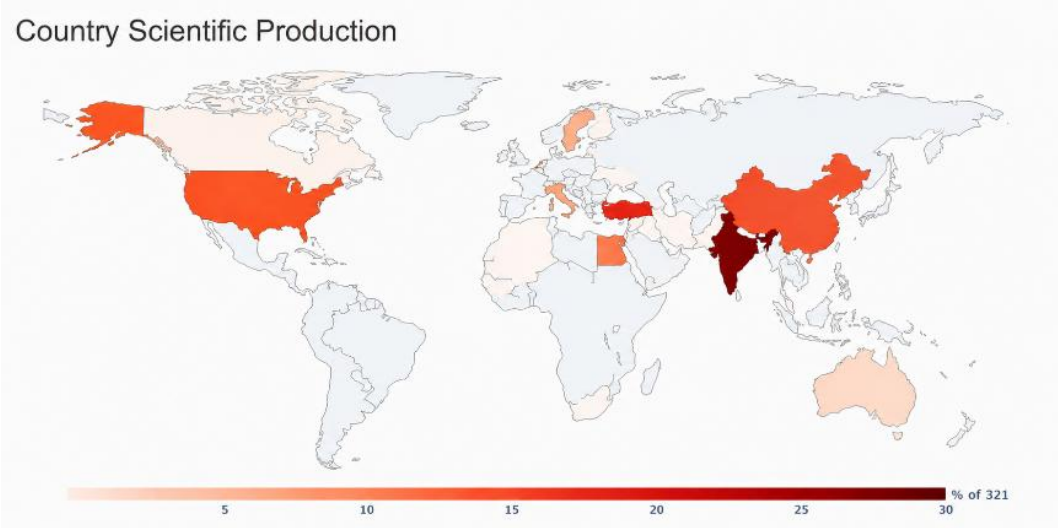


Figure 4. Country's Scientific Production

Most Relevant Authors

The distribution of the most relevant authors in the field of microwave antennas for breast cancer hyperthermia therapy is shown in Figure 5. The analysis results indicate that publication output is dominated by a small number of authors, who produce a relatively large number of documents compared to other authors. The author with the highest number of publications is Yilmaz T, with 9 documents, followed by Maccarini PF, Stauffer PR, and Wang X, each with 7 documents. Next, Akduman I and Yildiz G each contributed 6 documents, while Curto S, Prakash P, and Suh M each produced 5 documents. The author with the lowest contribution on this list is Crozier S, with 4 documents. The distribution of publication counts indicates that most authors contributed between 4 and 7 documents, with only one author reaching a significantly higher number. This suggests a concentration of contributions among a few key researchers in this field. The presence of these core researchers also provides important reference points for developing research-based teaching materials and academic resources in physics and biomedical education.

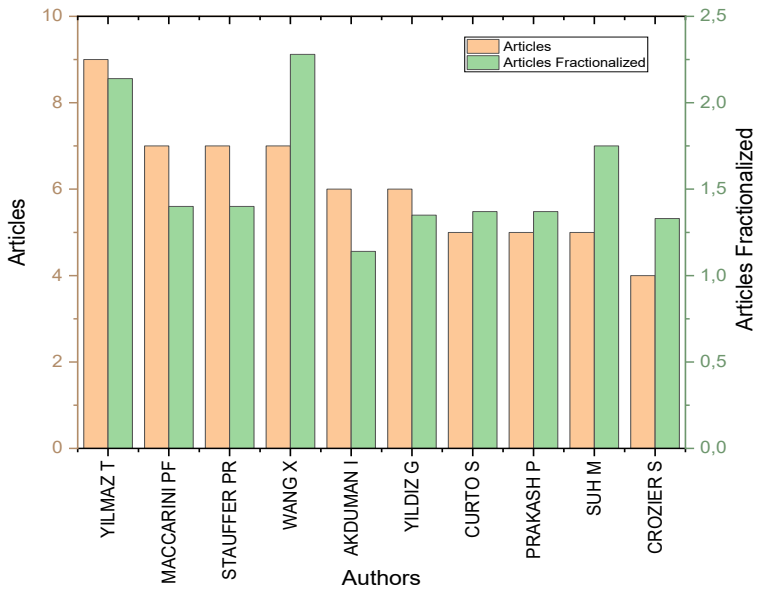


Figure 5. Country's Scientific Production

Co-Author Network

The structure of collaboration among researchers in the field of microwave antennas for breast cancer hyperthermia therapy is shown in Figure 6. The co-authorship network reveals that collaborative relationships are organized into several distinct clusters, with each cluster representing a group of researchers who share strong ties through joint publications. One of the most dominant clusters is led by Yilmaz T, whose node has the largest size and a broader network of connections compared to other researchers. This cluster also includes several authors such as Yildiz G and other collaborators, indicating a high level of collaboration within the group. In addition, there are several other relatively smaller clusters, such as the group involving Maccarini PF and Stauffer PR, as well as the cluster centered on Wang X. These clusters indicate collaboration on a more limited scale. Several other groups also appear isolated with fewer members, suggesting limited collaboration or collaboration specific to certain topics. This collaborative structure can serve as a model for project-based and collaborative learning approaches in higher education, where students engage in interdisciplinary problem-solving.

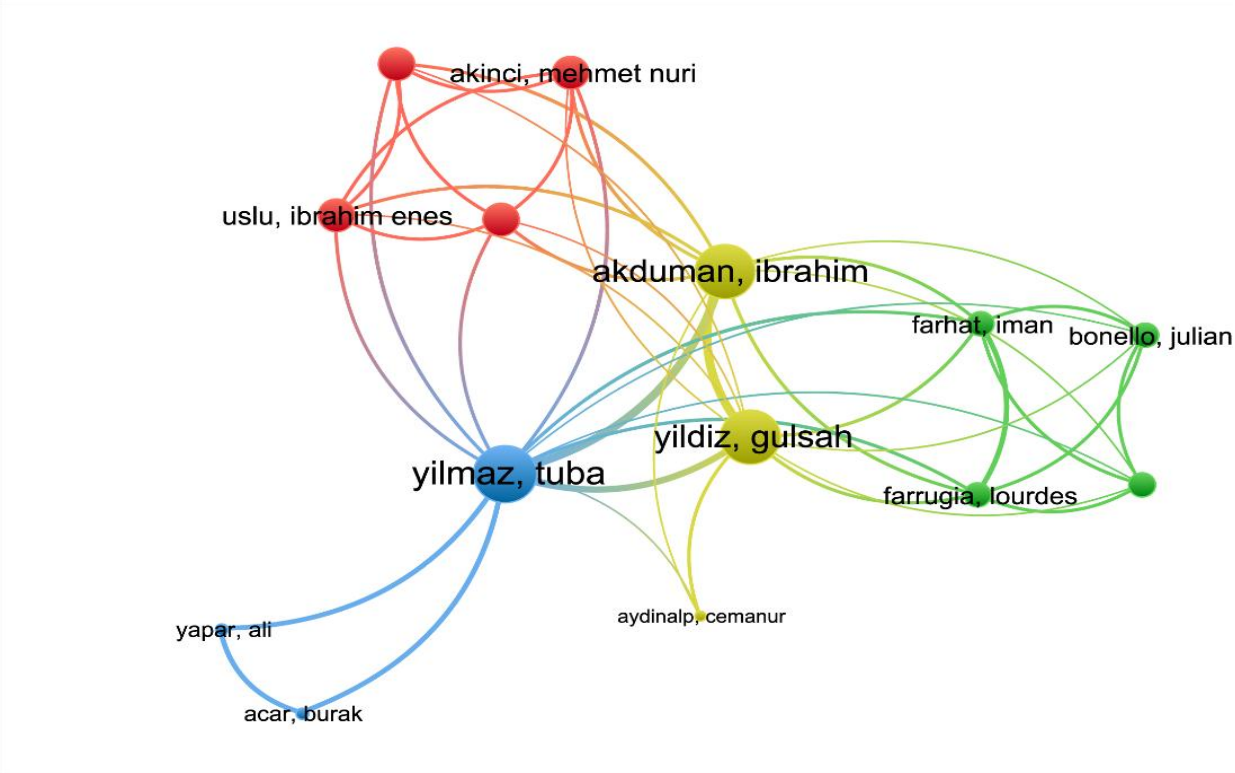


Figure 6. Co-Author Network

Institution analysis

The contributions of institutions to research on microwave antennas for breast cancer hyperthermia therapy are presented in Table 4. The analysis results show that Istanbul Technical University (Turkey) ranks first with 10 publications (10.2%), making it the institution with the largest contribution in this dataset. Several institutions from the United States also made significant contributions, including Kansas State University, with 6 publications (6.1%), and the University of California and the University of Wisconsin–Madison, each with 5 publications (5.1%). Additionally, the Egypt-Japan University of Science and Technology and Mitos Medical Technologies each produced 4 publications (4.1%).

In terms of citation impact, there is considerable variation among institutions. The University of Wisconsin–Madison recorded the highest total citations (TC = 692) with a CPP of 138.40, far surpassing other institutions. Conversely, Istanbul Technical University, despite having the highest number of publications, recorded a relatively lower CPP (5.20). These findings can support the development of partnerships between academic institutions and educational programs in physics and biomedical fields.

Table 4. Top Institutions with Publications and Country

Rank	Institution	Country	TP	P (%)	TC	CPP
1	Istanbul Technical University	Turkey	10	10.2	52	5.20
2	Kansas State University	USA	6	6.1	95	15.83
3	University of California	USA	5	5.1	74	14.80
4	University of Wisconsin–Madison	USA	5	5.1	692	138.40
5	Egypt-Japan University of Science and Technology	Egypt	4	4.1	29	7.25
6	Mitos Medical Technologies	Turkey	4	4.1	47	11.75

Literature co-citation analysis

The results of the co-citation analysis in Table 5 show that several publications have made a highly significant contribution to the development of research on microwave antennas for breast cancer hyperthermia therapy. The article with the highest number of citations is Converse et al. (2006), with 179 citations, followed by Stang et al. (2012) with 143 citations and Converse et al. (2004) with 128 citations. Most of the highly cited publications originate from reputable journals, particularly IEEE Transactions on Microwave Theory and Techniques, IEEE Transactions on Biomedical Engineering, and IEEE Transactions on Antennas and Propagation. Additionally, there are contributions from interdisciplinary journals such as Physics in Medicine and Biology and Biocybernetics and Biomedical Engineering. In terms of publication dates, the most-cited articles are predominantly from 2002–2017, indicating that publications during this period have had a significant influence on the development of this field. Furthermore, several authors, such as Converse M. and Nguyen P.T., appear more than once on the list, demonstrating their sustained contributions to this research. Highly cited works can also be utilized as core references in teaching materials and curriculum design.

Table 5. Top Institutions with publications and country

Rank	Author	Title	Journal	Year	Citations	Reference
1	Converse M.	A computational study of ultra-wideband versus narrowband microwave hyperthermia	IEEE Transactions on Microwave Theory and Techniques	2006	179	(Converse et al., 2006)
2	Stang J.	A preclinical system prototype for focused microwave thermal therapy of the breast	IEEE Transactions on Biomedical Engineering	2012	143	(Stang et al., 2012)
3	Converse M.	Ultrawide-band microwave space-time beamforming for hyperthermia treatment	IEEE Transactions on Microwave Theory and Techniques	2004	128	(Converse et al., 2004)
4	Vargas H.I.	Focused microwave phased array thermotherapy for breast cancer	Annals of Surgical Oncology	2002	103	(Gardner et al., 2002)
5	Nguyen P.T.	Microwave hyperthermia for breast cancer treatment	IEEE Transactions on Antennas and Propagation	2015	88	(Nguyen et al., 2015)
6	Nguyen P.T.	3-D focused microwave hyperthermia for breast cancer	IEEE Transactions on Antennas and Propagation	2017	87	(Nguyen et al., 2017b)
7	Nguyen P.T.	Three-Dimensional Microwave Hyperthermia for Breast Cancer Treatment in a Realistic Environment Using Particle Swarm Optimization	IEEE Transactions on Biomedical Engineering	2017	86	(Nguyen et al., 2017a)

8	Zastrow E.	3D computational study of non-invasive patient-specific hyperthermia	Physics in Medicine and Biology	2010	83	(Zastrow et al., 2010)
9	Iero D.A.M.	Thermal and Microwave Constrained Focusing for Patient-Specific Breast Cancer Hyperthermia: A Robustness Assessment	IEEE Transactions on Antennas and Propagation	2014	77	(Iero et al., 2014)
10	Gas P.	Optimization of multi-slot coaxial antennas for microwave thermotherapy based on the S 11 -parameter analysis	Biocybernetics and Biomedical Engineering	2017	61	(Gas, 2017)

Discussion

Search Strategies

The variation in the number of documents retrieved from each search strategy indicates a clear distinction between data coverage (*recall*) and relevance (*precision*). Broader queries yield a large number of documents but may include many publications not directly related to the research focus, particularly those not specifically about breast cancer. Conversely, highly specific queries yield a limited number of documents; while these are highly relevant, they are not sufficiently representative to comprehensively describe research developments. This situation underscores the trade-off between data completeness and topic relevance in the literature search process. The selection of the primary dataset of 100 documents from the query ("microwave antenna") AND ("hyperthermia") AND ("breast cancer") was based on a balance between coverage and relevance. This dataset is considered broad enough to represent research trends, yet remains focused on integrating microwave antenna design with hyperthermia therapy applications for breast cancer.

Annual Scientific Production

The observed trend in the number of publications reflects growing scientific interest in the use of microwave antennas in hyperthermia therapy for breast cancer. The low number of publications in the early period indicates that research was still in the exploratory phase, during which the integration of antenna technology and medical applications had not yet been extensively developed. The increase observed in subsequent periods, particularly after 2010, can be attributed to advancements in electromagnetic simulation technology and the growing need for more precise, minimally invasive cancer therapies. These developments have enabled researchers to explore more complex and practical antenna designs in a biomedical context. The surge in publications during the 2019–2021 period indicates an acceleration in research, likely driven by the integration of modern communication technologies, such as microwave-based systems and Multiple-Input, Multiple-Output (MIMO) antennas, into medical applications. This reflects the growing strength of multidisciplinary approaches in this field. The decline in the number of publications in the most recent period does not necessarily indicate a decline in research interest; rather, it suggests a phase of consolidation or maturation of the field. At this stage, research tends to focus on optimization, experimental validation, and integrating technology into more specific applications.

The Country's scientific production

The observed trend in the number of publications reflects growing scientific interest in the use of microwave antennas in hyperthermia therapy for breast cancer. The low number of publications in the early period indicates that research was still in the exploratory phase, during which the integration of antenna technology and medical applications had not yet been extensively developed. The increase observed in subsequent periods, particularly after 2010, can be attributed to advancements in electromagnetic simulation technology and the growing need for more precise, minimally invasive cancer therapies. These developments have enabled researchers to explore more complex and practical antenna designs in a biomedical context. The surge in publications during the 2019–2021 period indicates an acceleration in research, likely driven by the integration of modern communication technologies—such as microwave-

based systems and MIMO into medical applications. This reflects the growing strength of multidisciplinary approaches in this field. The decline in the number of publications in the most recent period does not necessarily indicate a decline in research interest; rather, it suggests a phase of consolidation or maturation of the field. At this stage, research tends to focus on optimization, experimental validation, and integrating technology into more specific applications. This trend suggests that the field of microwave antennas for breast cancer hyperthermia therapy has evolved from an exploratory phase to one of growth and maturation. This opens opportunities for further research, particularly in developing systems that more closely integrate antenna design with clinical needs.

Most Relevant Authors

The dominance of a small number of authors by publication count reflects the presence of a core group of researchers who play a key role in the development of microwave antennas for breast cancer hyperthermia therapy. Authors with the highest number of publications, such as Yilmaz T, likely make consistent contributions to the development of antenna design, electromagnetic simulation, and microwave-based hyperthermia applications. The presence of several authors with relatively balanced publication counts (5–7 papers) indicates that this field is not entirely centered on a single dominant researcher but rather evolves through the collective contributions of several research groups. This reflects the field's multidisciplinary nature, integrating electrical engineering, applied physics, and biomedicine. However, the relatively small distribution of publications among individual authors also indicates that this field is still developing and has not yet been dominated by one or two major figures globally. This situation can be interpreted as an opportunity for new researchers to contribute and establish a position within this field. Furthermore, variations in contributions among authors may also reflect differences in research focus, such as microstrip antenna design, Specific Absorption Rate (SAR) analysis, or the development of simulation-based hyperthermia systems. Therefore, further analysis of the co-authorship network is necessary to understand the relationships among researchers and the structure of collaboration within this field.

Co-Author Network

The fragmented pattern of collaborative networks indicates that research on microwave antennas for breast cancer hyperthermia therapy is still dominated by research groups working relatively independently. This indicates that although this field is multidisciplinary, global collaboration among researchers remains suboptimal. The dominance of clusters led by researchers such as Yilmaz T indicates the presence of core research groups that have made significant contributions to this field. Clusters with high connectivity indicate intensive and sustained collaboration, which typically contributes to greater research productivity and impact. Conversely, the presence of small clusters and relatively isolated groups indicates that some research is still conducted within limited scopes, both institutionally and geographically. This may be due to differences in research focus, limitations in interdisciplinary collaboration, or a lack of integration between engineering and medical communities. This situation highlights opportunities to enhance collaboration among researchers, particularly through cross-institutional and cross-national cooperation. Such enhanced collaboration has the potential to accelerate innovation, broaden the scope of research, and improve the scientific quality and impact of microwave antenna-based hyperthermia therapy. Overall, this co-authorship analysis reveals that while there is an active core group of researchers, the collaborative structure in this field remains fragmented, thereby presenting significant opportunities to strengthen research networks in the future.

Institution Analysis

Istanbul Technical University's dominance in the number of publications indicates a strong concentration of research activity at that institution, particularly in the development of microwave antennas for hyperthermia applications. This suggests that the institution serves as one of the primary research hubs in this field. However, when viewed from the perspective of quality or scientific impact, the University of Wisconsin–Madison demonstrates significantly higher performance with a very high CPP value. This indicates that although its publication count is not dominant, the research produced has a significant influence within the scientific community. This finding confirms that the number of publications does not always correlate directly with the quality or impact of research. The inclusion of several U.S. institutions in the top rankings demonstrates that the country plays a crucial role in the development of this field, likely supported by strong research infrastructure and integration between engineering and medicine. Meanwhile, contributions from Turkey and Egypt demonstrate that research in this field is not confined to developed

nations but is also flourishing across various regions. Additionally, the presence of institutions such as Mitos Medical Technologies highlights contributions from the industrial sector, signaling that research in this field is beginning to shift toward practical applications and technology translation. This is crucial in the context of developing hyperthermia therapies that are not merely conceptual but also implementable.

Literature Co-Citation Analysis

The prevalence of highly cited articles during the early period, particularly between 2004 and 2012, indicates that these studies served as the primary foundation for the development of microwave-based hyperthermia technology. These articles generally focused on fundamental aspects such as antenna design, electromagnetic modeling, and thermal energy distribution within biological tissues, which formed the basis for subsequent research. The presence of several highly cited articles in IEEE journals indicates that this field is heavily dominated by engineering approaches, particularly in antenna system development and electromagnetic performance analysis. However, the emergence of journals such as Physics in Medicine and Biology and the International Journal of Hyperthermia suggests a strong integration between engineering and medical disciplines. Furthermore, the recurring contributions of authors such as Converse M. and Nguyen P.T. suggest that key researchers are playing a significant role in shaping the direction of research in this field. This aligns with findings from the authors' previous analysis, which identified a core research group. Interestingly, although recent publications have fewer citations than older ones, the upward trend in citations for recent articles suggests a shift in research focus toward more applied and integrated approaches, such as phased-array-based therapy systems, 3D modeling, and clinical applications.

Educational Implications of Bibliometric Findings

The results of the bibliometric analysis provide important insights not only into the development of microwave antenna-based hyperthermia research but also into its potential contribution to physics and biomedical education. The dominance of topics such as electromagnetic wave propagation, Specific Absorption Rate (SAR), and thermal energy distribution indicates that this field is highly relevant for teaching fundamental physics concepts in real-world contexts. Furthermore, the multidisciplinary nature of this research highlights its potential for interdisciplinary learning, where students can integrate knowledge from physics, engineering, and biomedical sciences. This supports the development of scientific literacy, critical thinking, and problem-solving skills. The collaboration patterns observed in the co-authorship network also suggest opportunities for implementing research-based learning approaches, allowing students to engage with authentic scientific practices such as collaboration and data analysis. Additionally, the identification of dominant and emerging research themes can inform curriculum development, particularly in courses related to electromagnetism, biomedical instrumentation, and computational modeling.

CONCLUSION

This study reveals that research on microwave antenna-based hyperthermia has grown significantly over the past two decades, reflecting a shift toward more precise and minimally invasive therapeutic approaches. Although contributions are dominated by certain countries and institutions, a disparity exists between productivity and scientific impact, and collaboration remains relatively fragmented despite the presence of core research groups. The research trend has evolved from fundamental studies toward more clinically integrated applications. Beyond these findings, this study highlights the strong potential of this field as a valuable resource for physics and biomedical education. Key topics such as electromagnetic wave propagation, Specific Absorption Rate (SAR), and thermal energy transfer demonstrate its relevance for supporting conceptual understanding through real-world applications. The interdisciplinary nature of this research also offers opportunities to enhance scientific literacy, critical thinking, and problem-solving skills. Therefore, future research should emphasize not only technological advancement but also the integration of these developments into educational practices, while strengthening interdisciplinary collaboration to support both clinical innovation and education.

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