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Research

A global bibliometric and visualized analysis of the status and trends of lung metastasis in breast cancer research from 2000 to 2024

Baoyi Huang[1] · Shengchao Huang[1] · Zeming Yan[1] · Jialun Li[1] · Yuanqi Zhang[1]

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Abstract
Breast cancer remains a significant global health challenge, with lung metastasis presenting critical barriers to effective treatment and patient survival. This study conducts the first comprehensive bibliometric and visualized analysis of lung metastasis research in breast cancer from 2000 to 2024, illustrating evolving research trends and collaboration patterns in this critical area. Utilizing data from the Web of Science Core Collection, we employed bibliometric tools such as VOSviewer and CiteSpace to assess publication trends, international collaborations, influential institutions, authors, and keyword dynamics. Our findings reveal a steady increase in annual publications, peaking in 2021, with a significant concentration of research emerging from the USA and China, alongside key insights into molecular mechanisms such as epithelial-mesenchymal transition and immunotherapy. Notably, genes like ERBB2 and ESR1 were identified as pivotal in the metastatic process, highlighting potential therapeutic targets. This study not only illuminates the current landscape of breast cancer lung metastasis research but also underscores the necessity for interdisciplinary collaboration to enhance understanding and treatment strategies for this lethal condition.

1 Introduction

Breast cancer remains the most prevalent malignancy among women worldwide, accounting for approximately 30% of all female cancer diagnoses and serving as a leading cause of cancer-related mortality [1]. Despite advancements in early detection and multimodal therapies, metastatic disease continues to drive poor clinical outcomes, with more than 30% of patients eventually developing distant metastases [2, 3]. Among metastatic sites, bone, liver, brain, and lungs are frequently involved, each presenting distinct challenges in management and prognosis [4]. While bone metastasis is the most common and extensively studied, lung metastasis—occurring in 21–32% of metastatic breast cancer cases [5]—is associated with particularly aggressive disease biology, limited therapeutic options, and a median survival of 11–31 months [6]. Overall, the 5-year survival rate for breast cancer with lung metastasis is approximately 10.94% [4]. However, with advancements in treatment methods, the survival period for some patients has been extended. For example, patients who undergo complete resection of lung metastases can achieve a 5-year survival rate of up to 38% [7]. The molecular mechanisms underlying pulmonary metastasis, including interactions between

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✉ Baoyi Huang, hbyonly@163.com; ✉ Yuanqi Zhang, 31428319@qq.com | [1]Department of Breast Surgery, Affiliated Hospital of Guangdong Medical University, Zhanjiang, Guangdong Province, People's Republic of China.

circulating tumor cells, the lung microenvironment, and immune evasion [8], remain incompletely understood, necessitating further research to improve targeted therapies and patient outcomes.

Bibliometric analyses have emerged as powerful tools to map research landscapes, identify trends, and highlight knowledge gaps in biomedical fields [9]. Recent studies have systematically evaluated global research outputs on bone [10, 11], liver [12], and brain [13] metastases in breast cancer, revealing evolving priorities such as skeletal-related events, hepatic resection, and blood–brain barrier penetration. However, a comprehensive bibliometric assessment of lung metastasis in breast cancer remains absent, despite its clinical significance and unique pathophysiological features. Existing literature on pulmonary metastasis is fragmented, with limited synthesis of collaborative networks, emerging hotspots, or temporal shifts in research focus.

This study aims to fill this gap by conducting the first global bibliometric and visualized analysis of breast cancer lung metastasis research from 2000 to 2024. Using data extracted from the Web of Science Core Collection, we employ VOSviewer and CiteSpace to analyze publication trends, international collaborations, influential journals, and keyword dynamics. By identifying core research themes—such as metastatic microenvironments, epithelial-mesenchymal transition and immunotherapy—this work seeks to illuminate current research trajectories and untapped opportunities. The findings will provide clinicians, researchers, and policymakers with a structured framework to prioritize resources, foster interdisciplinary collaboration, and accelerate translational breakthroughs in managing this lethal complication of breast cancer.

2 Materials and methods

2.1 Data source and search strategy

Relevant papers on lung metastasis from breast cancer were sourced from the Science Citation Index Expanded (SCIE) within the Web of Science Core Collection, covering publications from January 1, 2000, to December 31, 2024. The search strategies were as follows: TS = ("neoplasm of the breast" OR "breast neoplasm" OR "breast carcinoma" OR "carcinoma of the breast" OR "breast cancer" OR "cancer of the breast") AND TS = ("lung metastasis" OR "metastatic carcinoma of lung" OR "metastatic tumor of lung" OR "metastatic cancer of lung"). The inclusion criteria were English-language papers relevant to the search topic, excluding letters, conference abstracts, and retracted articles, resulting in a total of 2241 articles (Fig. 1). The full records and cited references were extracted from the SCIE database, including publication year, title, authors, affiliations, countries/regions, abstracts, keywords, citations, references, and journal names. The data was downloaded in plain text and tab-delimited formats for further analysis and visualization.

2.2 Bibliometric analysis and visualization

Bibliometric analysis was conducted using a combination of tools to leverage their unique strengths in data visualization and analysis. Specifically, we employed VOSviewer 1.6.18 (Centre for Science and Technology Studies, Leiden University, The Netherlands) for its capability to handle large datasets and generate high-quality network visualizations, enabling the identification of research hotspots. CiteSpace 6.3.R1 (Chaomei Chen, China) was utilized to analyze temporal changes in literature, revealing trends and patterns in the evolution of research on lung metastasis in breast cancer. Pajek 64 5.16 (University of Ljubljana, Slovenia) was chosen for its efficiency in processing large network data, making it particularly useful for studying collaborative relationships among authors and institutions. Additionally, Scimago Graphica 1.0.35 (https://www.graphica.app/, USA) provided an intuitive interface for quickly creating visual representations of the data, while Microsoft Excel (Microsoft Office 2021, Microsoft, Redmond, WA) facilitated data organization and preliminary analysis before further exploration in the other tools. Data on gene involvement were sourced from the citexs platform (https://www.citexs.com), and relevant visual maps were generated to analyze the overall research landscape, hotspots, and trends. Finally, gene enrichment analysis was performed using the R package clusterProfiler [14] to explore and visualize the key pathways associated with lung metastasis in breast cancer.

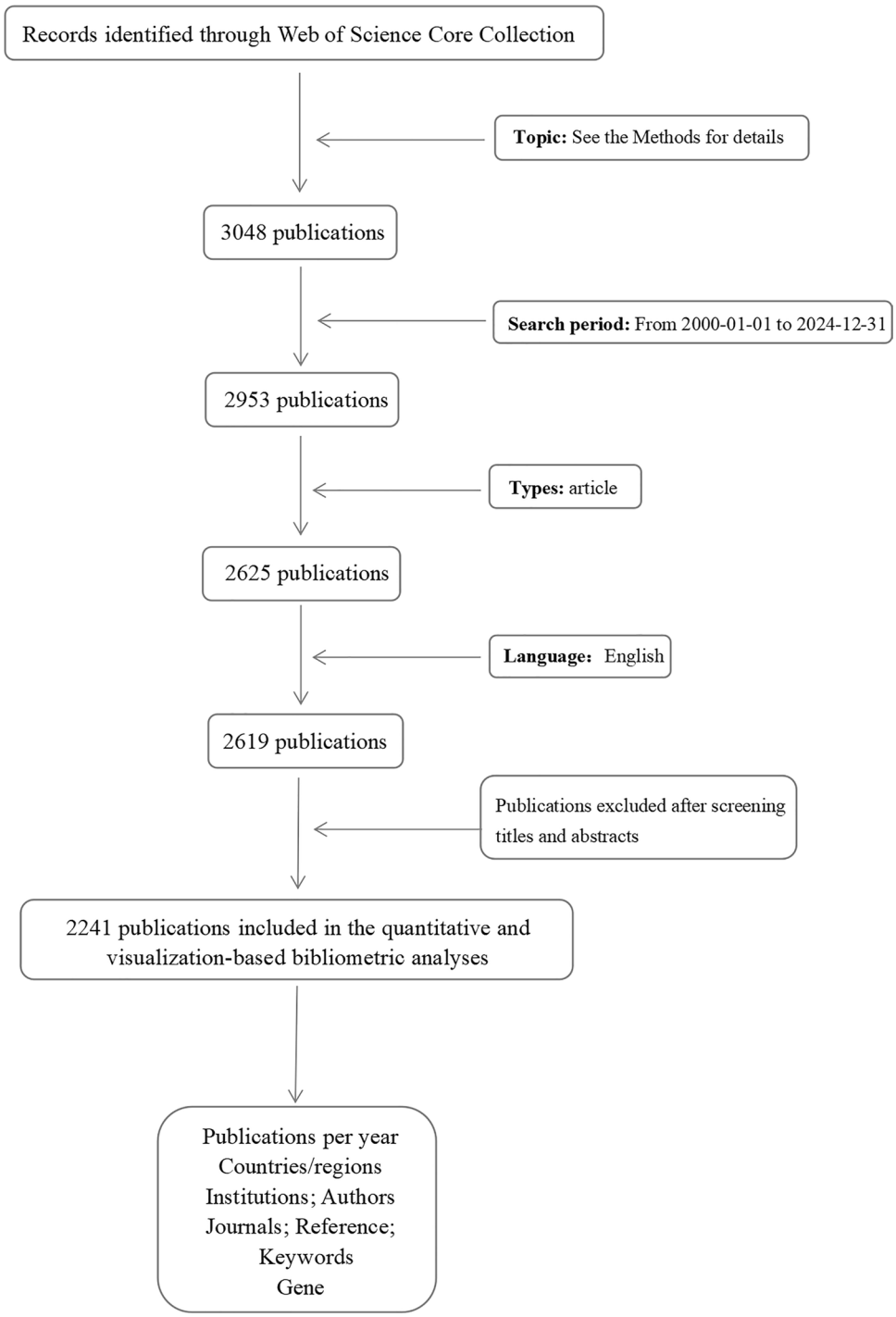


Fig. 1 Flowchart illustrating the publication selection process

3 Results

3.1 Annual publication trend analysis

Figure 2 presents the publication trend analysis on lung metastasis of breast cancer from January 1, 2000, to December 31, 2024. The data reveals a steady increase in the annual publication volume, rising from 7 articles in 2000 to 222 articles in 2024, which highlights the growing interest and research activity in this area. By 2024, the cumulative number of publications reached 2241, reflecting the long-term accumulation and continuous development of research. The year 2006 saw the highest growth rate, with an increase of 84.62%, nearly doubling the publication volume from the

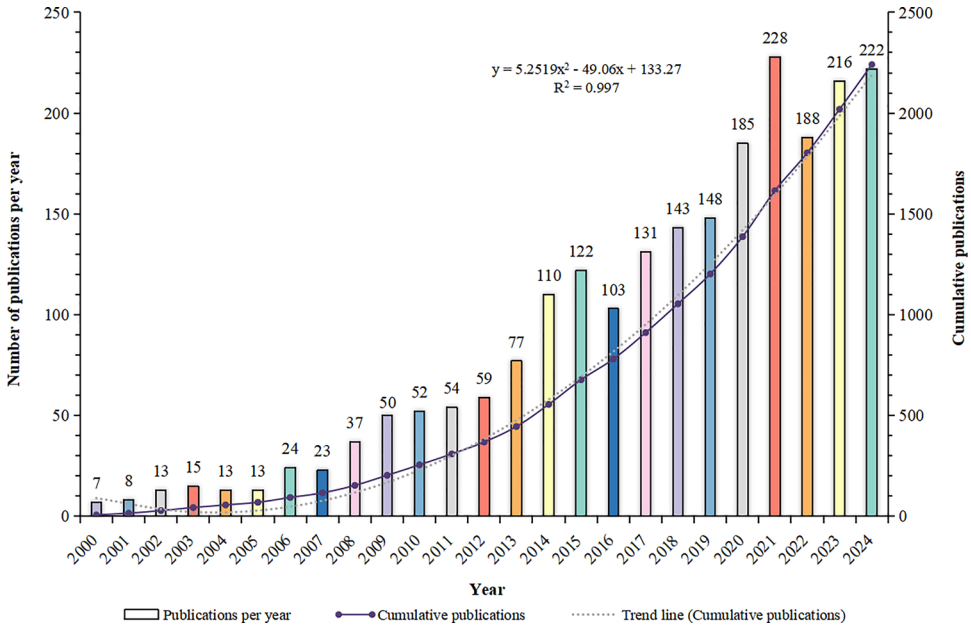


Fig. 2 The annual publication count for breast cancer lung metastasis from January 1, 2000, to December 31, 2024

previous year. The peak number of publications occurred in 2021, with 228 articles published. To better understand the overall trend, a polynomial function ($y = 5.2519x^2 - 49.06x + 133.27$, $R^2 = 0.997$) was fitted to the cumulative publication data from 2000 to 2024. This function provides a strong fit, effectively characterizing the growth pattern of publications on lung metastasis of breast cancer.

3.2 Analysis of research regions/countries relationships

A visual analysis of publication regions was conducted using VOSviewer, revealing that a total of 66 countries published 2,241 articles on breast cancer lung metastasis. With a minimum publication threshold of 5 articles per country, a co-authorship network of countries involved in this research area was generated (Supplementary Table 1).

As shown in Fig. 3A, the USA exhibits the highest total link strength, indicating the strongest collaborative ties with other countries and regions. Among all collaborations, the USA and China have the strongest partnership, followed by the USA and Japan, and the USA and Canada. China leads in publication volume with 1,079 articles, more than 12 times the number of publications from Canada (ranked 5th with 87 articles). The USA and Japan follow, with 754 and 139 articles, respectively. Of the top 10 publishing countries, Spain has the highest average citation per paper, at 113.84, followed by Canada with 99.92, suggesting that research from these countries is highly regarded (Supplementary Table 1).

Figure 3B presents a CiteSpace analysis of the top 10 countries with the strongest citation bursts in breast cancer lung metastasis research from January 1, 2000, to December 31, 2024. The red areas in the graph highlight periods of citation surges for each country. Japan experienced a citation burst from 2000 to 2008, with the highest burst strength of 7.04. Japan and Denmark had early citation bursts, with Denmark's lasting the longest from 2001 to 2010, spanning 10 years. Among the top 10 countries, Mexico showed a later citation burst, indicating a rising interest in breast cancer lung metastasis research in recent years.

3.3 Analysis of research institution collaboration

A visual analysis of research institutions was conducted using VOSviewer, revealing that a total of 2436 institutions published 2241 articles on breast cancer lung metastasis. With a minimum publication threshold of 16 articles per institution, a collaboration network of institutions involved in this research area was generated (Fig. 4A). The analysis shows that the Chinese Academy of Sciences has the highest total link strength, indicating the strongest collaboration with other institutions. Among all pairwise collaborations, the Chinese Academy of Sciences and the University of Chinese Academy of Sciences exhibit the most intense collaboration, highlighting their frequent and close cooperation. The next strongest collaborations are between Shanghai Jiao Tong University and Fudan University, as well as between the Chinese Academy of Sciences and Shenyang Pharmaceutical University (Supplementary Table 2).

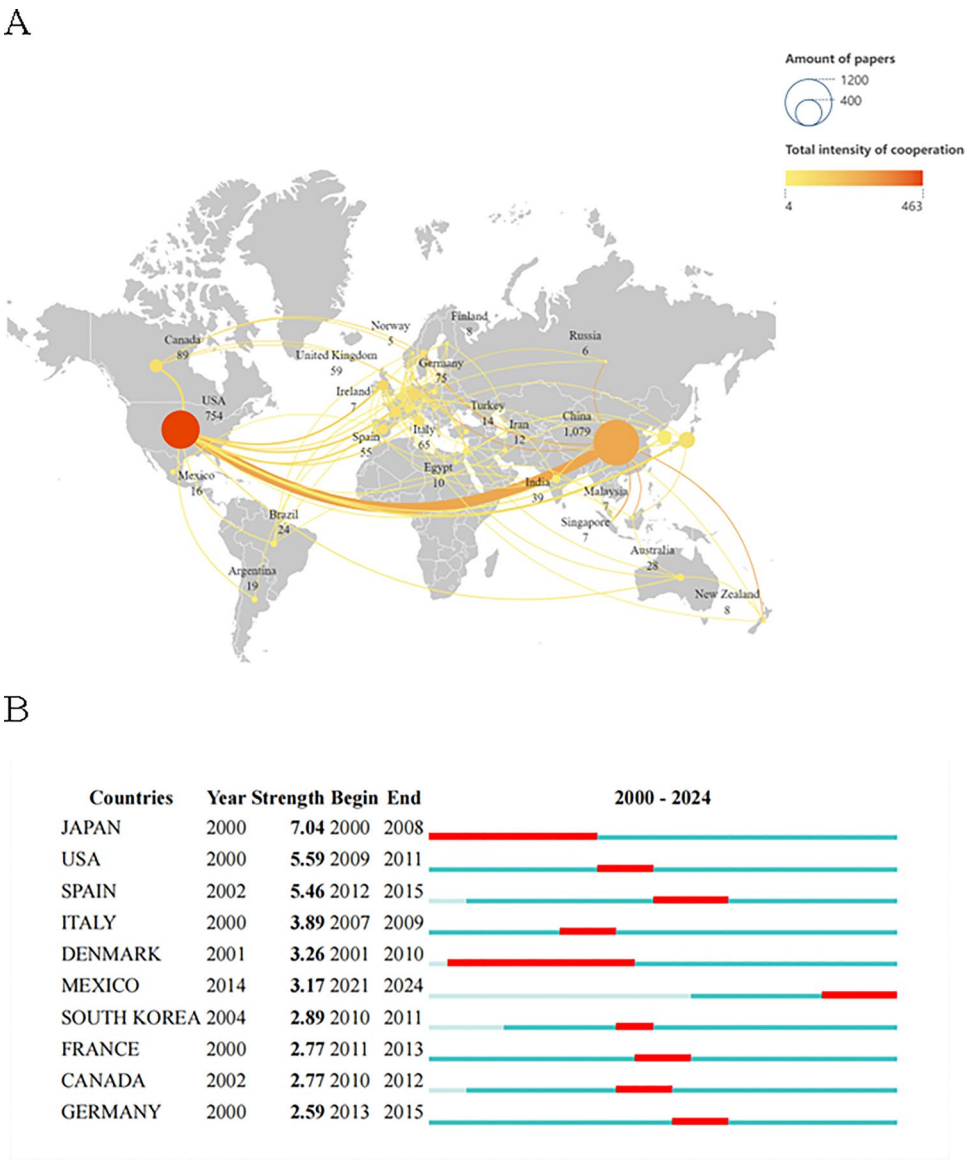


Fig. 3 Mapping of regions/countries associated with lung metastasis of breast cancer. **A** Regional/country collaboration analysis based on Vosviewer. Each node represents a country or region, with line thickness indicating collaboration strength and node size reflecting publication volume. **B** Top 10 regions/countries with the strongest citation bursts of breast cancer lung metastasis. Lines in red indicate the periods of citation bursts for each country

A CiteSpace analysis of institutional citation bursts from January 1, 2000, to December 31, 2024, identified the top 10 institutions with the strongest citation bursts in breast cancer lung metastasis research. The graph highlights periods of citation surges for each institution (Fig. 4B). The Chinese Academy of Sciences experienced a citation surge between 2016 and 2018, with the highest burst strength of 9.85. Among the top 10 institutions, the University of Texas had the earliest citation burst, occurring from 2001 to 2006, with the second-highest burst strength of 9.94. Albert Einstein College of Medicine had the longest citation burst, lasting 11 years from 2006 to 2016, indicating its sustained academic influence in the field of breast cancer lung metastasis. Notably, the Chinese Academy of Medical Sciences and Peking Union Medical College experienced recent citation surges, suggesting a growing recognition of their research in this area in recent years.

3.4 Analysis of author relationships

A visual analysis of author publications was conducted using VOSviewer, revealing that 15,446 authors published 2241 articles on breast cancer lung metastasis. A minimum publication threshold of 6 articles per author was set, resulting in a co-authorship network of researchers involved in this area. As shown in Fig. 5A, each circle and label represent an author, with different colors indicating distinct collaboration networks. Li Yaping has the highest total link strength, indicating the strongest collaboration with other authors. The line thickness between circles represents collaboration intensity, with the highest collaboration strength observed between Li Yaping and Zhang

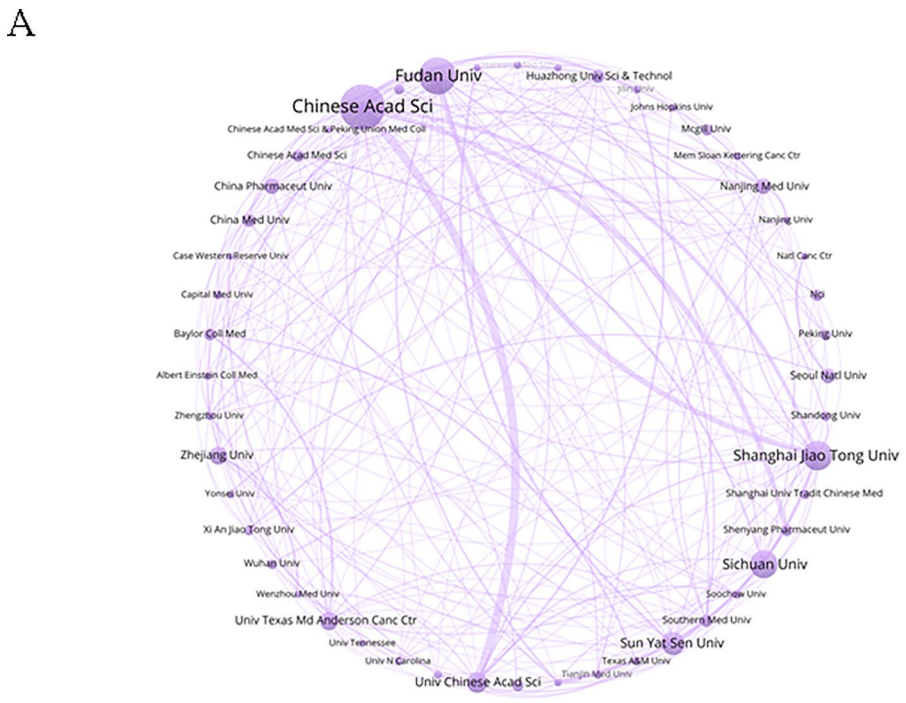
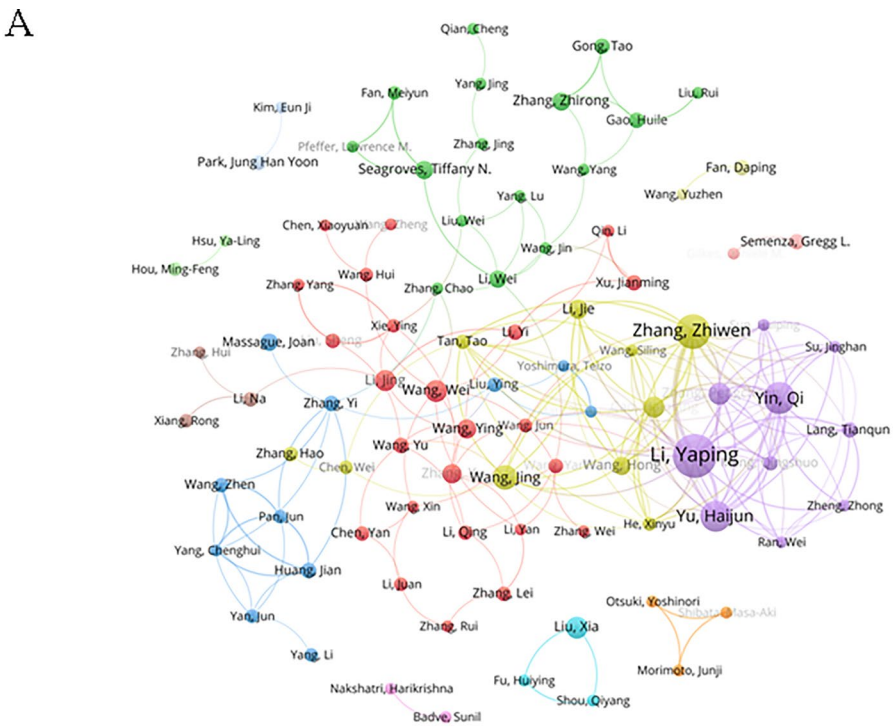


Fig. 4 Mapping of institution associated with lung metastasis of breast cancer. **A** Institution collaboration analysis based on Vosviewer. The nodes and text represent an institution; the gradient shows collaboration intensity; line thickness indicates collaboration strength; and node size correlates with publication volume. **B** Top 10 institutions with the strongest citation bursts of breast cancer lung metastasis. Lines in red indicate the periods of citation bursts for each institution

Zhiwen, reflecting their most frequent and close cooperation. The collaboration strength between Li Yaping and Yin Qi is also notable, with both authors belonging to the purple cluster. The top three authors by publication count are Li Yaping (39 articles), Zhang Zhiwen (28 articles), and Yin Qi (25 articles), underscoring their significant contributions and high output in the field of breast cancer lung metastasis (Supplementary Table 3).

From January 1, 2000, to December 31, 2024, a CiteSpace analysis of author citation bursts identified the top 10 authors with the strongest citation bursts. These are the authors who experienced the most significant citation surges within specific time periods (Fig. 5B). The analysis shows that Yu Hajun experienced a citation burst between 2014 and 2017, with the highest burst strength of 9.68. Citation bursts for the top 10 authors began in 2014 or later, indicating that these researchers have been primarily active in the field of breast cancer lung metastasis research since 2014. Recent citation bursts were observed for Liu Xia and Li Jing, with burst periods covering 2021 to 2024, suggesting that their research has gained significant attention in the past three years.



Authors	Year	Strength	Begin	End	2000 - 2024
Yu, Haijun	2014	**9.68**	2014	2017	
Li, Yaping	2014	**9.12**	2014	2018	
Zhang, Zhiwen	2014	**8.92**	2014	2018	
Yin, Qi	2014	**7.55**	2014	2019	
Liu, Xia	2021	**5.43**	2021	2024	
Zhang, Pengcheng	2016	**5.29**	2016	2018	
Li, Jing	2018	**3.81**	2018	2024	
Cao, Haiqiang	2016	**3.78**	2016	2020	
Li, Jie	2018	**3.65**	2018	2020	
Zhang, Yu	2019	**3.62**	2019	2021	

Fig. 5 Visualization of author analysis regarding lung metastasis of breast cancer. **A** Author collaboration network analysis diagram by Vosviewer. The circles and text labels form a node, with different colors representing different collaboration networks. **B** Top 10 authors with the strongest citation bursts of breast cancer lung metastasis. The lines in red indicate the periods of citation bursts for each author

3.5 Analysis of journals

In general, the study revealed that 539 journals published 2241 articles on breast cancer lung metastasis. A minimum publication threshold of 9 articles per journal was set, resulting in a heatmap of journal publication activity in this research area (Fig. 6A). The most prolific journal was Cancer Research, with 95 articles published, peaking between 2013 and 2014. Following this, Oncogene and Oncotarget published 68 and 52 articles, respectively, with their peak publication periods between 2015 and 2016. These journals' early focus on breast cancer lung metastasis and their high volume of related publications highlight their significant contributions to the field (Supplementary Table 4).

A CiteSpace analysis of citation bursts in the top 20 journals on breast cancer lung metastasis from January 1, 2000, to December 31, 2024, identified the journals with the most significant citation surges. The analysis highlights the periods of citation spikes for each journal, with red areas in the graph indicating surge periods (Fig. 6B). Cancers had the highest citation burst strength, reaching 52.17, with the burst period from 2021 to 2024. Among the top 20 journals with citation bursts, nearly half experienced bursts lasting over 10 years, suggesting that articles published

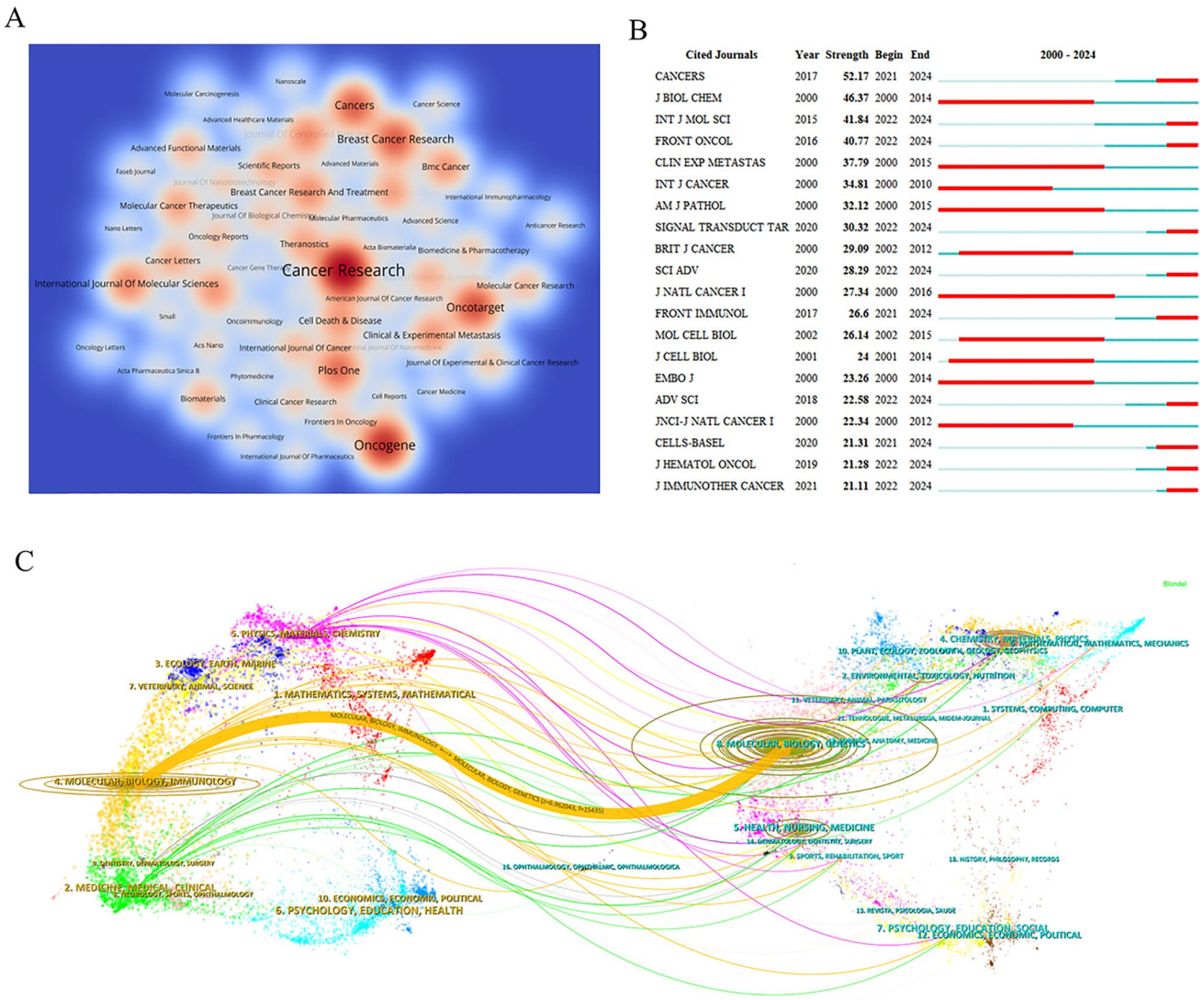


Fig. 6 Visualization of journal publications about lung metastasis of breast cancer. **A** Journal publication activity heatmap by Vosviewer. The word size and orange-red opacity indicate the number of journal publications. **B** Top 20 cited journals with the strongest citation bursts of breast cancer lung metastasis. The lines in red indicate the periods of citation bursts for each journal. **C** The dual-map overlay of journals related to lung metastasis of breast cancer. Each point on the graph represents a journal, and the curves show citation connections, illustrating interdisciplinary relationships. The vertical axis of the ellipse is longer for journals with more papers, while the horizontal axis is longer for journals with more authors

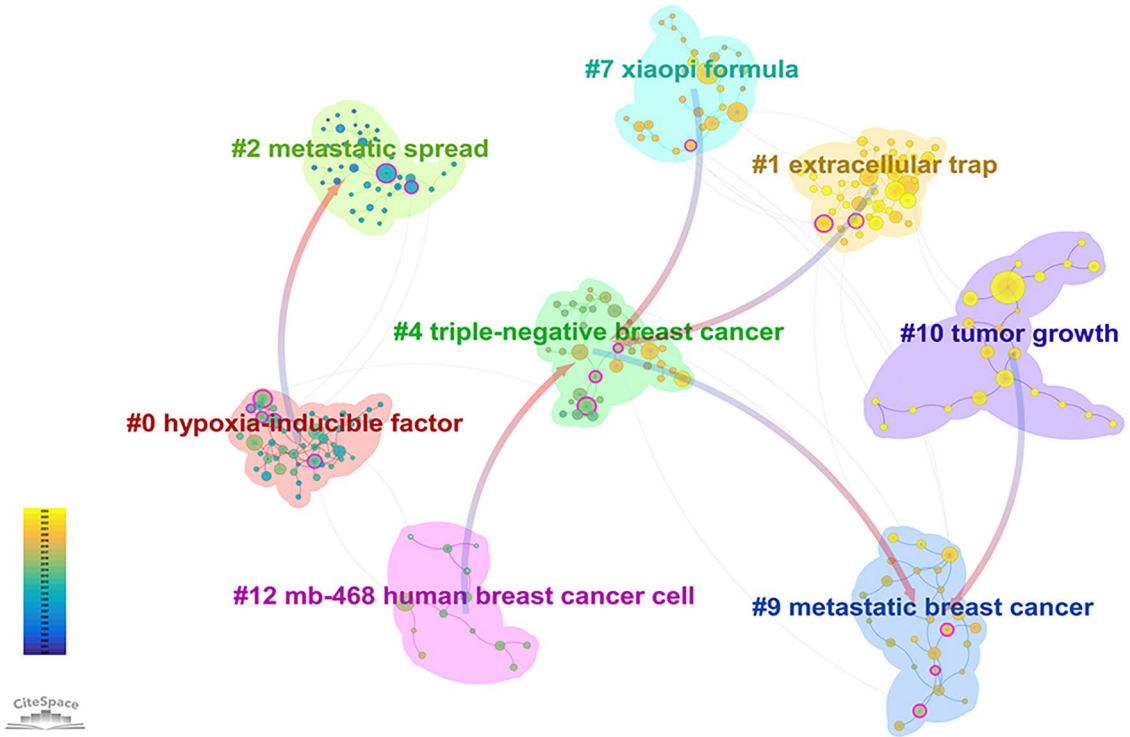
in these journals between 2000 and 2016 had a sustained academic impact and remained highly visible in the field of breast cancer lung metastasis. This reflects both the academic reputation and influence of these journals. The other half of the journals experienced citation bursts within the past three years, indicating the dynamic and evolving research activity in this area, which is important for researchers when choosing journals for publication and tracking research trends.

Figure 6C presents the dual-map overlay analysis of journals, where each point represents a journal. The curved citation links between the left and right sections illustrate citation relationships, providing insights into interdisciplinary connections and citation flow within the field. The vertical axis length of each ellipse corresponds to the number of papers published in the journal, while the horizontal axis length reflects the number of authors.

This dual-map overlay analysis highlights the positioning of breast cancer lung metastasis research within broader academic disciplines. The diagram is divided into two sections: the left side represents citing journals, while the right side represents cited journals. The analysis reveals that publications on breast cancer lung metastasis are

predominantly concentrated in journals within the fields of Molecular Biology and Immunology, while the cited literature is mainly found in journals within Molecular Biology and Genetics.

A



B

References	Year	Strength	Begin	End	2000 - 2024
Sung H, 2021, CA-CANCER J CLIN, V71, P209, DOI 10.3322/caac.21660, DOI	2021	40.47	2022	2024	
Lambert AW, 2017, CELL, V168, P670, DOI 10.1016/j.cell.2016.11.037, DOI	2017	18.56	2019	2022	
Minn AJ, 2005, NATURE, V436, P518, DOI 10.1038/nature03799, DOI	2005	17.98	2006	2010	
Unknown -, 2020, CA CANCER J CLIN, V70, P313, DOI 10.3322/caac.21492, DOI	2020	15.59	2020	2022	
Quail DF, 2013, NAT MED, V19, P1423, DOI 10.1038/nm.3394, DOI	2013	14.38	2015	2018	
Koboldt DC, 2012, NATURE, V490, P61, DOI 10.1038/nature11412, DOI	2012	14.22	2013	2017	
Bianchini G, 2016, NAT REV CLIN ONCOL, V13, P674, DOI 10.1038/nrclinonc.2016.66, DOI	2016	13.66	2017	2021	
Nguyen DX, 2009, NAT REV CANCER, V9, P274, DOI 10.1038/nrc2622, DOI	2009	13.23	2010	2014	
Hanahan D, 2011, CELL, V144, P646, DOI 10.1016/j.cell.2011.02.013, DOI	2011	12.88	2012	2016	
Medeiros B, 2019, INT J MOL SCI, V20, P0, DOI 10.3390/ijms20092272, DOI	2019	12.64	2021	2024	
Peinado H, 2017, NAT REV CANCER, V17, P302, DOI 10.1038/nrc.2017.6, DOI	2017	12.42	2018	2022	
Gupta GP, 2007, NATURE, V446, P765, DOI 10.1038/nature05760, DOI	2007	12.27	2007	2012	
Yin L, 2020, BREAST CANCER RES, V22, P0, DOI 10.1186/s13058-020-01296-5, DOI	2020	12.27	2022	2024	
Qian BZ, 2011, NATURE, V475, P222, DOI 10.1038/nature10138, DOI	2011	11.63	2013	2016	
Steeg PS, 2016, NAT REV CANCER, V16, P201, DOI 10.1038/nrc.2016.25, DOI	2016	11.3	2017	2021	
Padua D, 2008, CELL, V133, P66, DOI 10.1016/j.cell.2008.01.046, DOI	2008	11.08	2009	2013	
Chaffer CL, 2011, SCIENCE, V331, P1559, DOI 10.1126/science.1203543, DOI	2011	10.96	2012	2016	
Liang YR, 2020, SEMIN CANCER BIOL, V60, P14, DOI 10.1016/j.semcancer.2019.08.012, DOI	2020	10.06	2022	2024	
Gupta GP, 2006, CELL, V127, P679, DOI 10.1016/j.cell.2006.11.001, DOI	2006	10.03	2007	2010	
Bos PD, 2009, NATURE, V459, P1005, DOI 10.1038/nature08021, DOI	2009	9.65	2010	2014	

Fig. 7 Mapping of references in studies on lung metastasis of breast cancer. **A** Co-citation cluster analysis map of references based on CiteSpace. The size of the overlapping spheres on the timeline reflects total co-citations, with blue for earlier citations and yellow for later ones. Overlapping colors indicate citations in those years. Lines between circles show co-citation relationships, and magenta nodes highlight key points. **B** Top 20 references with the strongest citation bursts of publications related to lung metastasis of breast cancer. The red areas indicate periods of citation surges for each article

Fig. 8 Mapping of keywords in studies on lung metastasis of breast cancer. **A** Keywords clustering analysis map based on Vosviewer. Circles and labels form nodes, with circle size related to keyword frequency and line thickness indicating relationship strength. Different colors represent distinct clusters and research areas. **B** Keywords distribution based on their average frequency of occurrence; keywords in yellow emerged later than those in blue. Node size correlates with keyword frequency, while color gradient indicates the average year of occurrence. **C** Top 10 keywords with the strongest citation bursts of publications regarding lung metastasis of breast cancer. The red lines indicate periods of citation surges. **D** Keyword clustering timeline analysis map by CiteSpace. Circle sizes reflect keyword frequency; lines show co-occurrences. Purple indicates early appearances, yellow denotes later ones, and overlapping colors represent concurrent occurrences. Magenta nodes are central hubs. Keywords in the same cluster align horizontally, with first appearances at the top and time progressing to the right

3.6 Analysis of references

CiteSpace was used to analyze the co-citation network of references on breast cancer lung metastasis from January 1, 2000, to December 31, 2024 (Fig. 7A). The network consists of 8 co-citation clusters, labeled as follows: hypoxia-inducible factor, extracellular trap, metastatic spread, triple-negative breast cancer, Xiaopi formula, metastatic breast cancer, triple-negative breast cancer, and MB-468 human breast cancer cell. The top three most co-cited papers are by Sung H (2021), Lambert AW (2017), and Bray F (2020), with co-citation frequencies of 95, 45, and 42, respectively. Among all the key nodes, Qian BZ (2011) has the highest centrality, indicating that this node may serve as a bridging or pivotal point in the entire co-citation network (Supplementary Table 5).

A CiteSpace analysis of citation bursts for the top 20 articles on breast cancer lung metastasis from January 1, 2000, to December 31, 2024, was also conducted (Fig. 7B). Citation bursts refer to a sharp increase in the number of citations for a paper within a specific period, with red areas in the graph highlighting these bursts. According to the graph, the paper by Sung H (2021) has the highest citation burst intensity, reaching 40.47, with a burst period from 2022 to 2024. Following this, Lambert AW (2017) ranks second with a burst intensity of 18.56, with a burst period from 2019 to 2022. Minn AJ (2005) ranks third in burst intensity, reflecting the significant impact these papers have had on the field of breast cancer lung metastasis. Among the top 20 papers, those by Sung H (2021), Medeiros B (2019), Yin L (2020), and Liang YR (2020) experienced citation bursts in the past three years, suggesting these articles have gained substantial attention and recognition in recent years within the research field of breast cancer lung metastasis.

3.7 Analysis of keywords

As shown in Fig. 8A, the keywords are categorized into three distinct clusters. The top three most prominent keywords are grouped in the red cluster, which includes breast cancer, metastasis, and lung metastasis. The green cluster primarily focuses on the research direction of breast cancer lung metastasis, with triple-negative breast cancer being the most prominent keyword. The blue cluster primarily covers research related to epithelial-mesenchymal transition, with this keyword being the most notable in the cluster.

Additionally, the analysis reveals that among the top ten most frequent keywords, terms such as tumor angiogenesis and metastasis had an earlier average appearance time, between 2015 and 2018. Keywords like tumor microenvironment and triple-negative breast cancer had an average appearance time around 2020, while immunotherapy had its average appearance time between 2021 and 2022. This suggests a recent shift in research focus and direction (Fig. 8B, Supplementary Table 6).

CiteSpace analysis of the top 10 keyword citation bursts in breast cancer lung metastasis research from January 1, 2000, to December 31, 2024, is shown in Fig. 8C. According to the graph, the keyword with the strongest citation burst is tumor metastasis, with a burst strength of 4.82, and the burst period spanning from 2018 to 2021. Matrix metalloproteinase was the first keyword to experience a citation burst, with the longest duration from 2007 to 2012, lasting six years. Among the top 10 keywords with citation bursts, half of them had relatively recent burst periods, including immunogenic cell death, photothermal therapy, tumor-associated macrophages, neutrophil extracellular traps, and breast cancer metastasis. This indicates a shift in the focus of research on breast cancer lung metastasis in recent years.

Figure 8D presents a timeline analysis after clustering keywords related to breast cancer lung metastasis. The keywords were grouped into nine clusters: breast cancer, lung metastasis, breast cancer metastasis, tumor microenvironment, drug delivery, tumor metastasis, triple-negative breast cancer, cell migration, and maspin. This suggests that these clustered fields are continuously developing within the area of breast cancer lung metastasis research.

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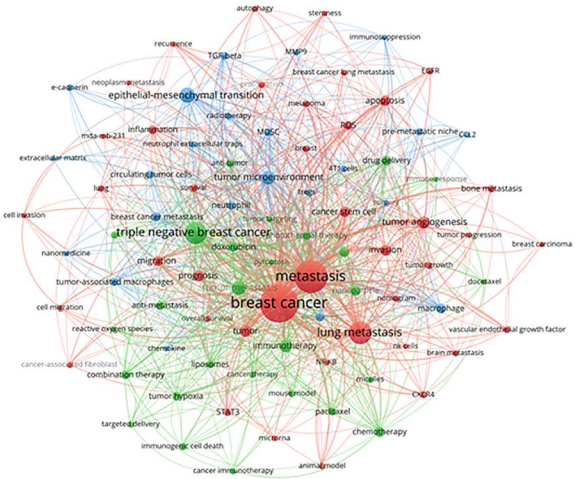

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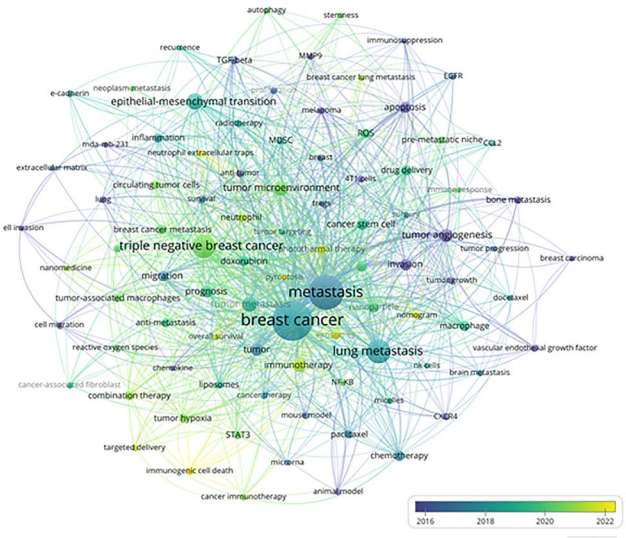

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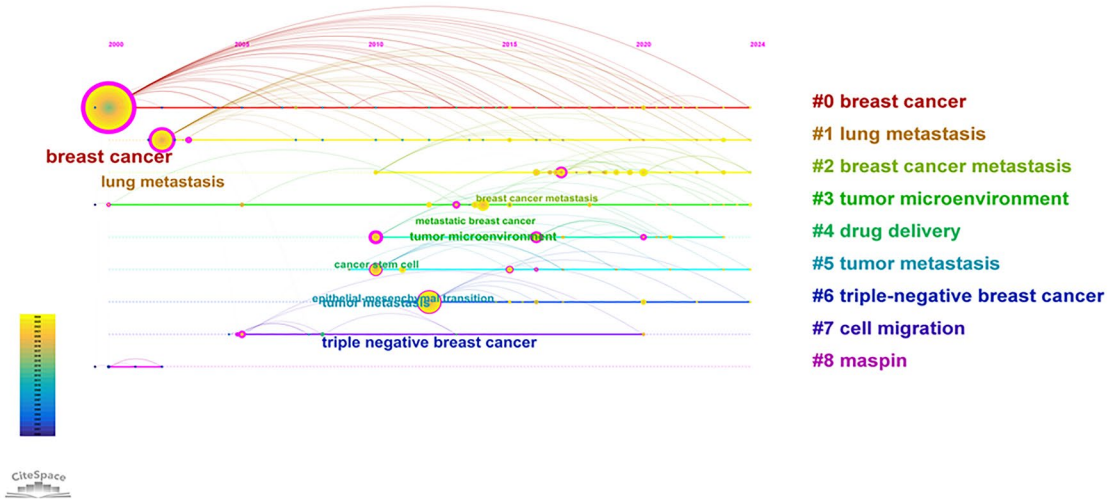
Keywords	Year	Strength	Begin	End	2000 - 2024
tumor metastasis	2010	**4.82**	2018	2021	
immunogenic cell death	2020	**4.23**	2022	2024	
cell invasion	2008	**2.93**	2013	2014	
matrix metalloproteinase	2007	**2.88**	2007	2012	
photothermal therapy	2019	**2.59**	2021	2024	
tumor-associated macrophages	2020	**2.58**	2020	2024	
neutrophil extracellular traps	2022	**2.51**	2022	2024	
cancer-associated fibroblast	2015	**2.44**	2015	2016	
cancer stem cell	2010	**2.39**	2020	2022	
breast cancer metastasis	2014	**2.35**	2022	2024	

D



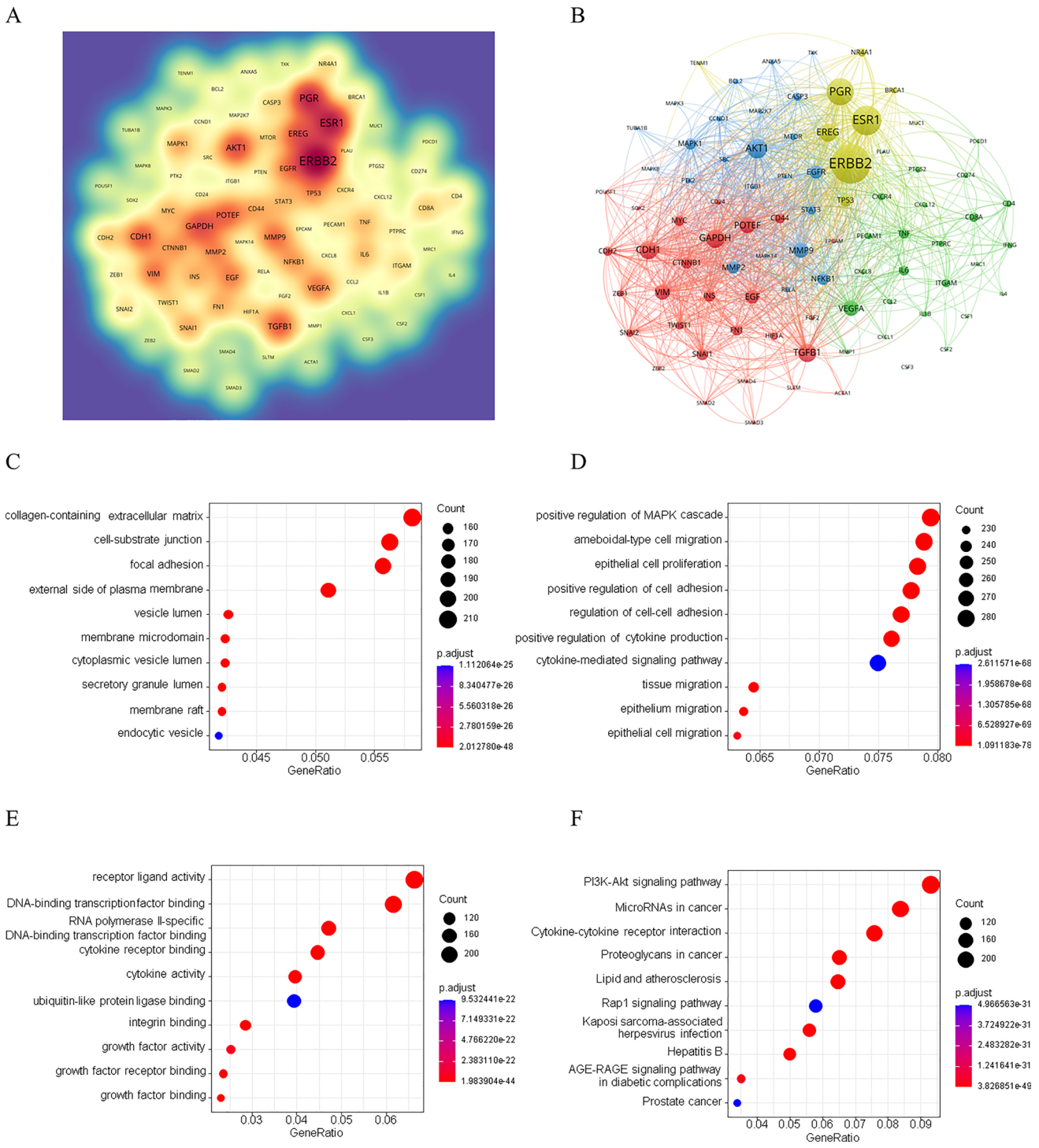


Fig. 9 Mapping of genes in studies on lung metastasis of breast cancer. **A** Related genes heatmap analysis based on Vosviewer. The word size and orange-red opacity indicate the frequency of gene. **B** Related genes clustering analysis map by Vosviewer. Nodes consist of circles and labels; circle size reflects gene frequency, while line thickness indicates relationship strength. Different colors represent clusters from various gene fields. **C** Top 10 cellular components terms of functional enrichment analysis of related genes. **D** Top 10 biological process terms of functional enrichment analysis of related genes. **E** Top 10 molecular functions terms of functional enrichment analysis of related genes. **F** Top 10 Kyoto Encyclopedia of Genes and Genomes terms of functional enrichment analysis of related genes

3.8 Analysis of related genes

The co-occurrence analysis of genes related to breast cancer lung metastasis was conducted using VOSviewer software. The Citexs big data platform extracted a total of 3847 genes from 2,241 articles. By setting the minimum occurrence frequency to 30, a heatmap of genes associated with breast cancer lung metastasis was generated (Fig. 9A). The most frequently occurring gene was ERBB2, followed by ESR1, PGR, and AKT1 (Supplementary Table 7). Additionally, a co-occurrence clustering analysis of genes was performed, resulting in four clusters being identified (Fig. 9B). The yellow cluster is primarily related to breast cancer targeted therapy receptors, with the top three most frequent genes being ERBB2, ESR1, and PGR. The red cluster is mainly associated with genes involved in epithelial-mesenchymal transition (EMT). The blue cluster primarily involves pathway genes related to cancer cell growth, with AKT1 being the most frequent gene. The green cluster is primarily associated with immune-related genes, with VEGFA being the most frequent gene.

To explore the biological functions of the associated genes, Gene Ontology (GO) and Kyoto Encyclopedia of Genes and Genomes (KEGG) enrichment analyses were conducted, presenting the top 10 enriched terms. The significantly enriched cellular component terms highlighted the crucial role of extracellular matrix organization and membrane-associated structures (Fig. 9C). In terms of biological processes, key enrichments included signaling cascades, cellular motility, and immune regulation (Fig. 9D). For molecular functions, the enriched terms emphasized interactions between signaling molecules and transcriptional regulators (Fig. 9E). Significant KEGG pathways identified gene sets related to cancer progression, metabolic disorders, and viral infection mechanisms (Fig. 9F).

4 Discussion

Bibliometric and visual analyses offer valuable insights into the current state of research in a particular field and can also help forecast future trends [15]. This study provides the first comprehensive bibliometric and visualized analysis of global research on lung metastasis in breast cancer from 2000 to 2024. The findings reveal significant trends in research activity, global collaborations, evolving hotspots, and key areas for future exploration. The rising publication trend, especially since the mid-2000s, underscores the growing recognition of lung metastasis as a critical issue in breast cancer prognosis and treatment.

4.1 Research trends and hotspots

The exponential growth in annual publications, peaking at 228 articles in 2021, reflects the urgency of addressing lung metastasis in breast cancer, a condition that significantly worsens patient prognoses. The polynomial growth model ($R^2 = 0.997$) highlights a sustained trajectory of research activity, driven by the clinical challenges posed by this aggressive metastatic site. Notably, keyword dynamics reveal a temporal shift in focus: early studies emphasized matrix metalloproteinases and tumor angiogenesis (2007–2018), while recent surges in immunotherapy (2021–2024) and tumor microenvironment (2020–2024) align with advancements in precision oncology and immune modulation, potentially leading to more effective treatments and improved patient outcomes [16–18]. The emergence of terms like neutrophil extracellular traps and photothermal therapy further underscores the diversification of therapeutic strategies, suggesting a paradigm shift from traditional cytotoxic approaches to innovative, mechanism-driven interventions. Understanding that neutrophil extracellular traps are critical in the tumor microenvironment and in the metastasis of breast cancer may guide clinical strategies to enhance patient management and therapeutic options [19]. Similarly, photothermal therapy's potential as an emerging treatment emphasizes the need for clinical trials that could directly impact treatment outcomes in breast cancer patients with lung metastasis [20].

The clustering of keywords into themes such as epithelial-mesenchymal transition EMT, triple-negative breast cancer, and drug delivery highlights the dual focus on understanding molecular mechanisms and translating findings into clinical applications. For instance, TNBC's prominence in the green cluster correlates with its propensity for visceral metastasis and poor prognosis, emphasizing the need for subtype-specific research. Similarly, the blue cluster's emphasis on EMT aligns with its role in facilitating metastatic dissemination, providing a rationale for targeting EMT-related pathways in therapeutic development, which could potentially improve survival rates for affected patients.

4.2 International collaboration and influence

The bibliometric analysis also highlights the USA's leadership in breast cancer lung metastasis research, followed closely by China and Japan. The United States has been the most influential in terms of collaborative research, reflecting its strong academic and research infrastructure. The finding that China leads in publication volume is consistent with its rapid growth in biomedical research and highlights its critical role in advancing knowledge in this field. Additionally, countries like Spain, which exhibited high citation rates, point to the global recognition of research outputs that may inform clinical practices worldwide.

In terms of institutions, the Chinese Academy of Sciences stands out as a key player, and its concentrated collaborations suggest a potential hub for advancements that could drive forward clinical applications, particularly for lung metastasis treatments. The increasing internationalization of research in lung metastasis, as evidenced by the strong collaborations between China and other countries, provides an opportunity for cross-cultural and interdisciplinary approaches that could accelerate discoveries and clinical applications.

4.3 Key authors and journals

Author networks highlight the pivotal role of prolific researchers like Li Yaping (39 articles) and Zhang Zhiwen (28 articles). Their collaborative clusters dominate the field, contributing to significant advancements in our understanding of lung metastasis, which is crucial for improving treatment strategies. The citation bursts of emerging authors (e.g., Liu Xia and Li Jing, 2021–2024) reflect the influx of new perspectives, particularly in immunotherapy and microenvironment studies. Journals such as Cancer Research and Cancers (burst strength: 52.17) serve as critical platforms for disseminating high-impact work, while dual-map overlay analysis underscores the interdisciplinary nature of the field, bridging molecular biology, immunology, and clinical oncology. This cross-disciplinary citation flow reinforces the importance of integrating basic science with clinical insights to address the complexity of metastasis.

4.4 Genetic insights

Our analysis of related genes has identified key molecular players such as ERBB2, ESR1, and PGR, which are well-known for their roles in breast cancer progression and metastasis [21–23]. These insights are essential for identifying new biomarkers that can facilitate early diagnosis and personalized treatment approaches, ultimately impacting patient prognosis. The clustering of genes associated with EMT, immune regulation, and cancer cell growth reinforces the multifaceted nature of lung metastasis [24–26]. These molecular insights are essential for identifying new biomarkers for diagnosis and prognosis, as well as potential therapeutic targets. Additionally, the enrichment of pathways related to cancer progression and metabolic disorders highlights the complexity of metastasis and suggests that future research could benefit from a more integrative approach that combines molecular biology with systems biology to unravel the intricate mechanisms involved.

4.5 Limitations and future directions

While this study provides a valuable overview of the field, it is important to acknowledge certain limitations. The analysis focused solely on publications indexed in the Web of Science, and therefore, the findings may not fully represent the entirety of global research output, particularly from regions with limited representation in this database. Moreover, while bibliometric analyses provide insights into research trends, they cannot fully capture the quality or impact of individual studies. Future research could complement this analysis with in-depth qualitative assessments of the most influential studies in the field.

Looking ahead, the field of lung metastasis in breast cancer research is poised for further growth. Given the identification of key emerging research areas such as immunotherapy, EMT, and the tumor microenvironment, future studies should explore these areas in greater detail, focusing on their molecular underpinnings and clinical implications. Furthermore, interdisciplinary collaboration spanning genetics, immunology, and pharmacology will be essential for translating basic science discoveries into clinical applications that enhance treatment efficacy and improve patient outcomes.

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Data availability Data is provided within the manuscript or supplementary information files.

Declarations

Ethics approval and consent to participate This study was based on published literature and did not involve human or animal experiments, thus ethical approval was not required.

Competing interests The authors declare no competing interests.

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