Original Article

MEDICINE PALLIATIVE CARE

DOI: 10.47582/jompac.1668510

J Med Palliat Care. 2025;6(3):224-231

Exploring the evolution of artificial intelligence in pathology: a bibliometric and network analysis

Burcu Sanal Yılmaz

Department of Medical Pathology, Faculty of Medicine, Karamanoğlu Mehmetbey University, Karaman, Turkiye

Cite this article as: Sanal Yılmaz B. Exploring the evolution of artificial intelligence in pathology: a bibliometric and network analysis. *J Med Palliat Care*. 2025;6(3):224-231.

Received: 31.03.2025 • **Accepted**: 06.05.2025 • **Published**: 18.06.2025

ABSTRACT

Aims: Artificial intelligence (AI) has emerged as a transformative force in pathology, significantly influencing diagnostic accuracy, workflow efficiency, and digital pathology integration. Despite the rapid growth in AI-related pathology research, a comprehensive analysis of publication trends, key contributors, and scientific impact remains limited. This study aims to provide a bibliometric and network analysis of AI applications in pathology, mapping research trends, citation networks, institutional collaborations, and emerging thematic clusters.

Methods: A bibliometric analysis was conducted using data from the Web of Science Core Collection, covering studies published between 2007 and 2024. Research trends, citation distributions, keyword co-occurrences, and collaboration networks were analyzed using VOSviewer. Descriptive statistics and network visualization techniques were applied to assess publication growth, author collaborations, and journal impact.

Results: The findings are consistent with other studies showing a more than proportionate increase in AI-based research in pathology since 2018, especially AI related pathology research is on a significant rise focusing on laboratory investigation, modern pathology and journal of pathology as the primary high impact journals. Important research centers like the University of Pittsburgh, Radboud Universiteit, and the Cleveland Clinic have made significant advancements in AI based pathology which have and will continue to make a significant impact within this area. The key words used most frequently were "AI", "digital pathology", "deep learning", and "machine learning" which corroborate the centrality of AI in pathology.

Conclusion: AI does have a major contribution towards transforming pathology by aiding in providing quick and efficient diagnosis. Nonetheless, issues around the standardization of data, the black box nature of algorithms, and the regulation of data raise serious challenges towards achieving successful clinical incorporation of AI. The focus of future work should center around standardization of validation protocols, inter-disciplinarity, and ethical issues in order to ensure the dependable implementation of AI enabled solutions in pathology.

Keywords: Artificial intelligence, digital pathology, deep learning, machine learning, bibliometric analysis

INTRODUCTION

Artificial intelligence (AI) is transforming virtually every facet of medicine, including pathology. The integration of AI in pathology stems from its ability to improve diagnostic accuracy, enable workflow efficiency, and increase the adoption of digital pathology systems.[1,2] These innovations have transformed clinical medicine and fundamentally altered the academic research landscape of the discipline. Even with the growing body of literature around AI and pathology, little is known regarding the research landscape, major works, and their scholarly influence.[3]

Tracing the articulation of AI in pathology is important as it allows the stakeholders to identify gaps in work as well as evaluate potential high-impact interventions for collaborative efforts. Today, deep learning and machine learning based approaches have led to significant automation of feature extraction, disease classification, and predictive modeling within histopathological image analysis.[4,5] As a result, there has been improved diagnostic accuracy, decreased interobserver variability, and more sophisticated decision support systems. On the other hand, the concepts of standardization of data, obscurity of algorithms, and embodying ethics still shape the issues on the adoption of AI in clinical practice.[6]

While AI is transforming technology in medicine and healthcare, its application areas seem to deepen by the minute. The application of computer vision in pathology has witnessed tremendous growth due to its capability of improving accuracy in diagnosis, improving workflow productivity, and smooth integration with digital pathology systems. These developments have equally transformed health care practice as much as they have influenced academic pursuit in the area.

Corresponding Author: Burcu Sanal Yılmaz, burcusanalyilmaz@gmail.com

However, there does not appear to be an extensive analysis of the fusion of AI and pathology, and its research trends, major stakeholders, or academic contributions. The development of such analysis is fundamental in helping close pertinent research gaps, understanding the scope of high-impact publications, and enable cross-border collaborations.

This paper takes on the systematic investigation of the scientific landscape concerning AI applications in pathology with the use of bibliometric analysis. In doing so, the research tackles the mapping of publication activity, citation and indexing of articles, the collaborations of various authors, and the thematic clusters of research which in turn helps towards providing an evidence based analysis on the growth and academic impact of AI in pathology. The analysis further investigates the concentration of research productivity in the top journals, the leading institutions and countries in the field that help in identifying important contributions and new areas of research. Using bibliometric data extracted from Web of Science, this study applies quantitative methods to assess publication patterns and scholarly impact, facilitating a deeper understanding of how AI-driven innovations are shaping the field of pathology. The findings aim to serve as a valuable reference for researchers, clinicians, and policymakers, guiding future investigations and strategic decision-making in AI-based pathology research.

METHODS

Ethics

Since this research is a bibliometric study, it did not require ethics committee approval.

Data Collection

Data for this bibliometric analysis were obtained from the Web of Science (WoS) Core Collection, a comprehensive database containing high-quality, peer-reviewed scientific publications. The study focused on the topic of "AI" within the field of "pathology" and examined studies published between January 1, 2007, and December 31, 2024. The search query applied the keyword "AI" with the "topic" filter and restricted the results to the "pathology" category in WoS categories (Table 1).

Table 1. Data set creation and analysis process

Step	Description
1. Data collection	Data was retrieved from the Web of Science platform using the keyword 'artificial intelligence' with the 'topic' filter applied.
2. Category selection	The 'pathology' category was selected from the Web of Science Categories section.
3. Data analysis	A bibliometric analysis method was used to evaluate 959 articles.
4. Presentation of results	The analysis findings were reported with tables and graphics.

As a result of the initial search, 959 articles were identified. The titles, abstracts, and keywords of the articles were carefully examined, and duplicate records were removed. Only peer-reviewed articles that met the inclusion criteria were selected for analysis. The first 10 articles were independently reviewed by two researchers, and disagreements regarding selection were resolved through discussion and consensus.

Data collection was conducted between January and March 2024. For each article, the following bibliometric information was extracted:

- Article title
- Author names
- Publication year
- Journal name
- Journal impact factor
- Citation counts
- Country of affiliation of authors
- Institution names
- Frequently used keywords

The extracted data were verified by two independent observers, and inconsistencies were resolved through consensus.

Bibliometric Analysis

Bibliometric analysis was performed using VOSviewer (version 1.6.11, Leiden University, The Netherlands) to visualize research trends, keyword relationships, and collaboration networks. The primary areas of focus in the analysis included:

- **Annual publication trends:** Examination of publication growth over time.
- **Journal-specific publication trends:** Identification of the most frequently publishing journals in the field.
- **Citation analysis:** Assessment of highly cited authors, articles, journals, and publication years.
- **Keyword co-occurrence analysis:** Identification of commonly used terms and thematic clusters.
- **Institutional affiliations and inter-institutional collaborations:** Mapping research contributions by different institutions.
- **Country-level collaboration networks:** Visualization of international research collaborations.
- **Author collaboration networks:** Analysis of research partnerships among authors.

Statistical Analysis

Descriptive statistics (frequencies and percentages) were used to summarize publication numbers, citation distributions, and journal impact measures. Temporal trends in article output were analyzed using SPSS software to assess changes in research activity over time. Keyword co-occurrence networks were generated to reveal thematic clusters and conceptual relationships in the field.

Inter-institutional and international collaboration patterns were visualized using bibliometric mapping techniques. The density of collaborations was represented by the thickness

of the connection lines, revealing common research focuses across institutions and countries. Cluster coefficients and connection densities were calculated to measure the integrity and integration of research themes within the bibliometric landscape.

RESULTS

Analysis of the Distribution of Articles by Year

Figure 1 presents the distribution of studies over the years in the dataset compiled using Web of Science data.

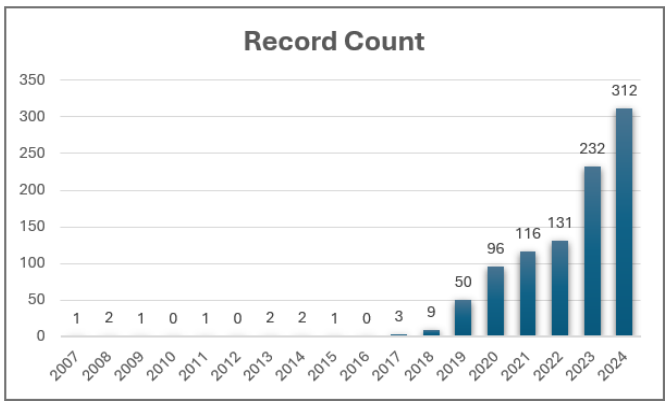

Figure 1. Distribution of articles by year

An analysis based on Web of Science data illustrates the distribution of studies published between 2007 and 2024 in the "AI" field within the "pathology" category.

In 2007, only one study was published. In the following years, a limited increase was observed. By 2018, the number of studies had reached 9, followed by a substantial increase in 2019, with 50 publications. A more pronounced growth trend began in 2020, with the number of studies reaching 232 in 2023 and peaking at 312 in 2024.

Overall, these findings indicate a notable rise in scientific research on AI in pathology, particularly in recent years. This trend highlights the increasing significance of AI applications in pathology and demonstrates the growing interest in the field, driven by technological advancements and innovative approaches.

Journals with the Highest Number of Publications on the Topic

The distribution of journals publishing the highest number of articles related to "AI" in the field of "pathology" in the Web of Science database is presented in Table 2.

The majority of 959 analyzed publications are concentrated in a few key journals. Laboratory Investigation leads with 168 articles (17.52%), followed by modern pathology (106, 11.05%), and Virchows Archiv (75, 7.82%).

While a significant portion of studies is published in a select group of journals, 364 articles (37.96%) are spread across various other journals, indicating both specialization and diversity in publication venues.

Table 2. Distribution of journals by number of publications and proportional shares

Publication titles	Record count	% of 959
Laboratory Investigation	168	17.52%
Modern Pathology	106	11.05%
Virchows Archiv	75	7.82%
Journal of Pathology	63	6.57%
American Journal of Clinical Pathology	36	3.75%
Histopathology	36	3.75%
American Journal of Pathology	32	3.34%
Toxicologic Pathology	28	2.92%
Expert Review of Molecular Diagnostics	27	2.82%
Cancer Cytopathology	24	2.50%
Others	364	37.96%

Comprehensive Analysis of the Most Cited Studies: Authors, Article Titles, Published Journals, Publication Years, and Citation Counts

Table 3 provides detailed information on the authors, article titles, publication journals, years, and citation counts of these highly cited studies.

The data in Table 3 highlights the most cited studies on AI in pathology. The most cited study, van Leenders et al. (2020), published in the American Journal of Surgical Pathology, received 366 citations, discussing the ISUP consensus on grading prostatic carcinoma.

Steiner et al. (2018) followed with 283 citations, examining deep learning-assisted diagnosis of metastatic breast cancer. Abels et al. (2019), with 238 citations, focused on best practices and regulations for digital pathology. Cui and Zhang (2021) explored AI's role in pathology (230 citations), while Baxi et al. (2022) assessed AI in clinical digital pathology (224 citations).

These highly cited studies underscore AI's growing impact on pathology, highlighting its critical role in diagnostics and academic research.

Statistical Evaluation of Publications from the Most Cited Institutions

The database Web of Science was examined to find the institutions with the largest citation impact within the scope of "AI" in "pathology." The Table 4 contains the records of each institution in regard to publication numbers and total citations received.

Table 4 indicates that the University of Pittsburgh have the largest number of publications (33) and citations (588), followed by Radboud Universiteit (20 publications, 539 citations), and Cleveland Clinic (21 publications, 524 citations).

However, after only 7 published articles, the private sector company PathAI has already made a tremendous academic impact with a staggering 485 citations. This shows the increasing penetration of Ai in the pathology scope of even the private sector driven research.

Table 3. Most cited studies on "artificial intelligence" in pathology

No	Author(s)	Article title	Journal name	Year of publication	Citation count
1	van Leenders Geert JLH et al.	The 2019 international society of urological pathology (ISUP) consensus conference on grading of prostatic carcinoma	American Journal of Surgical Pathology	2020	366
2	Steiner DF. et al.	Impact of deep learning assistance on the histopathologic review of lymph nodes for metastatic breast cancer	Merican Journal of Surgical Pathology	2018	283
3	Abels E. et al.	Computational pathology definitions, best practices, and recommendations for regulatory guidance: a white paper from the Digital Pathology Association	Journal of Pathology	2019	238
4	Cui M and Zhang DY	Artificial intelligence and computational pathology	Laboratory Investigation	2021	230
5	Baxi V et al.	Digital pathology and artificial intelligence in translational medicine and clinical practice	Modern Pathology	2022	224

Table 4. Most cited institutions and their publications (Web of Science Data)

Organization	Documents	Citations
University of Pittsburgh	33	588
Radboud Universiteit	20	539
Cleveland Clinic	21	524
Pathai	7	485
Ohio State University	31	475

In sum, these results imply that noted medical faculties and research institutions head the activities of AI in pathology, but at the same time, increasing industrial participation is also noted. These results reinforce the notion to a wide variety of research from academic and industry interest of focus in pathology in which AI is applicable.

Trends in Keyword Usage

The most frequently used keywords related to " AI " in the field of pathology, along with their associations, are illustrated in Figure 2.

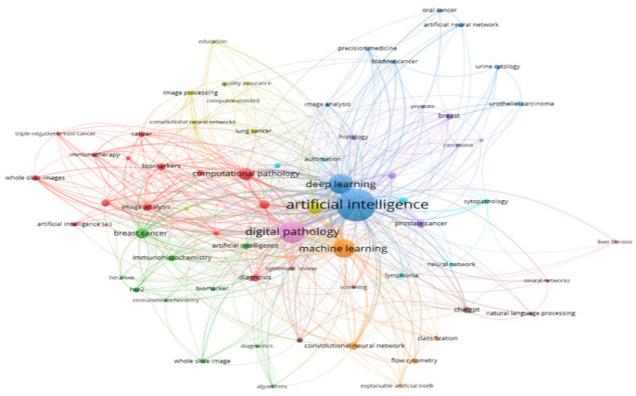

Figure 2. Keyword co-occurrence and frequency of use

VOSviewer software was used for the bimetrical analysis along with a set minimum of five occurrences for inclusion during keyword selection. This measure allowed for occurrence over five times without going to over-focusing on relevant and often used terms.

Despite the discovery of 1.639 varied keywords, only 68 were chosen to be significant and analyzed further. This type of analysis makes it clear how the study prioritized the chosen keywords and their assigned relations.

The analysis captured the previously mentioned keywords that were most frequently used in conjunction to the research field and their strongest overlaps. 8 other groups showed the presence of 533 linked keywords, creating a total of 9 clusters. These figures are illustrative of the presence of conglomerates for certain terms that aid in constructing boundaries for various evolving concepts that need to be investigated in the future. In figure 1, the link between AI and academic publications in pathology is represented through the arising prominent phrases and their relationships.

From the presented data sets, "AI" is the most common keyword used, recorded 355 times. This figure is accurate as “AI” plays an important role in pathology research. The second most common keyword “digital pathology” was found recorded 166 times which underlines the importance of digital activities in pathology. “deep learning” is recorded for the 128 times, while “machine learning” came to second at 114 times showing focus of sub AI fields in Pathology studies.

The notable keywords that were recorded less frequently but still captured the eye were “computational pathology”, flagged at 49 times & “pathology” at 48. Both indicate a growing interest of academic literature towards computational approaches and core pathology concepts.

These examples confirm that AI has impacted pathology research. The number of times keywords appear is one of the most important sign of ongoing research, whereas the repetition of certain words improves the comprehension of pathology aided by AI.

Analysis of Institutional Collaborations in Publications

Academic studies focusing on "AI" in the field of "pathology" were analyzed in terms of the institutions affiliated with researchers and their collaboration networks. The findings reveal the structure and intensity of institutional collaborations, with the results visually presented in Figure 3.

Collaboration analysis was performed using VOSviewer software, which uses colors to differentiate thematic or regional groups, while the links represent collaborative activities (or relations) of the institutions. The thickness of the connections

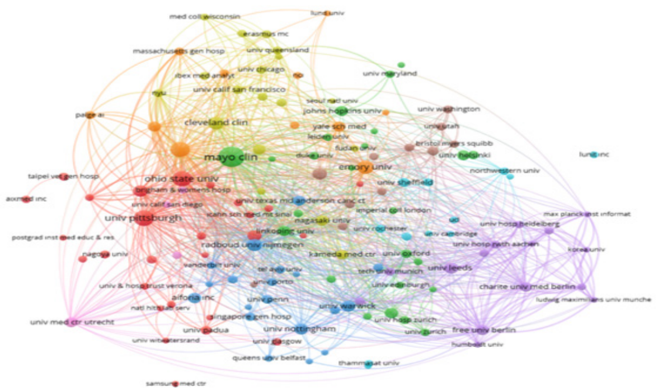

Figure 3. Visualization of institutional bibliometric networks

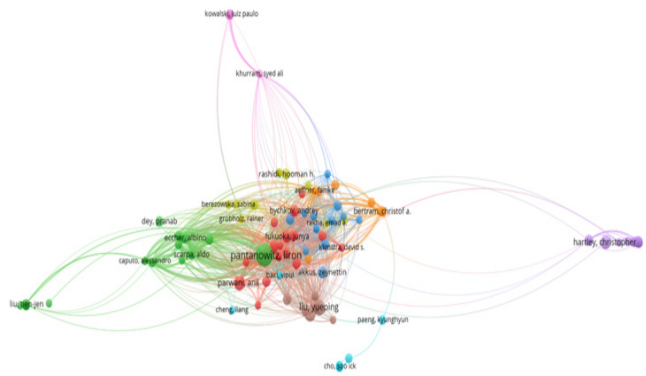

Figure 4. Academic collaboration network (larger circles represent prominent authors, and connecting lines indicate scientific collaborations.)

shows the less and more interactions among the institutions. This type of analysis protects against large intercontinental differences as it reveals important interactions and possible future collaboration covers in AI in pathology research.

The analysis reveals that academic collaboration in this area is limited to few institutions. For instance, the University of Michigan and Mayo Clinic have formed over 139 connections. These are some of the most central institutions, which capture their strong academic network and leadership in AI pathology research.

In the same manner, the University of Pittsburgh, and Ohio State University also has formed connections with 138 other institutions. Both are considered as another primary institutions that maintain active collaboration with a large number of scientists from multiple research centers and academic institutions. There have been other centers such as Radboud Universiteit and Emory University with 137 and 135 connections respectively, which are considered lesser but are also significant academic contributors to the research landscape.

Generally, the results show that the studies about AI and pathology are concentrated in certain universities and research centers. These analyses help in understanding academic interactions, assessing collaboration potential, and identifying new partnership opportunities in a strategic research framework.

Analysis of Author Collaborations

A comprehensive analysis of academic publications on AI in pathology within the Web of Science database was conducted, focusing on the collaboration networks among researchers. The results of this analysis reveal the structure of academic interactions and the dynamics of scientific collaborations, visually represented in **Figure 4**.

Figure 4 analyzes bibliometric connections among researchers who have published at least five articles in the field of AI in pathology. Out of 5.198 authors, only 106 researchers met the threshold for inclusion in the analysis. This selection criterion ensures that the study focuses on influential researchers with substantial contributions, enhancing the reliability and scientific value of the findings.

The visualization illustrates the collaborative networks and bibliometric connections among researchers in the field. Every author is represented as circles, where the size of their circle indicates their significance in terms of their contributions to the literature. The lines between circles show the intensity of collaborations as well as the strength of bibliometric relationships. Clusters distinguished by colors indicate groups of researchers working in themes or methodologically related areas.

• **Green cluster:** Pantanowitz Liron is a recognized central figure of the group, as he is one of the top scientists within this network. Scarpa Aldo and Eloy Catarina are also prominent figures in this network. This green cluser proves to have a higher interfiliatory interaction which is thematic in nature, forming a wide net of collaboration, as well as contributing greatly to the literature.

• **Orange cluster:** In this cluster, the strongest net is built up by Bertram Christof A. together with Klopfleisch Robert and Westerling-Bui Thomas, who are also active contributors. The theme of this cluster is single but well defined and it is one of the key themes in the realm.

• **Blue cluster:** In this group, Rajpoot Nasir is the key researcher, who works closely with Kather Jakob Nikolas and Snead David. In this literature cluster, there is a dense network of these researchers focusing on specific sub disciplines and making significant contributions to the field.

• **Purple cluster:** This group is led by Khurram Syed Ali and Kowalski Luiz Paulo. This cluster is less connected than others, which makes it focus on subtopics of great importance. Because of this, it contributes significantly to niche areas.

This sheds light on the particular movements of author collaborations and scientific social networks. The color coded clusters show the diversity of themes studied and their contribution to the body of literature. The analysis of these author relationships aids in forming one of the academic collaboration strategies to focus research efforts and improve innovation and collaborative efforts in AI in pathology as a branch of science.

Citation Distribution by Country

Using the Web of Science (WoS) database, the citation distribution for AI in pathology was examined comprehensively

at the national level. Results are shown below in Figure 5 for the citation distribution by country, as well as for the geographical distribution of citations, regional concentration, and the international scientific community partnership. This study shows an important consideration on the dynamics of research and scholarly activity across different countries.

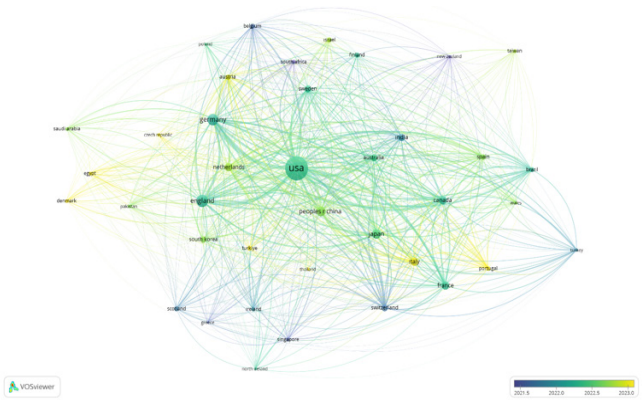

Figure 5. Analysis of citation distribution by country

In Figure 5, I depicted the concentration of citation counts from international studies conducted in Web of Science (WoS) and also charted the collaborative academic networks worldwide. This analysis covered 74 countries, but in the end only 39 countries qualified for the evaluation, as they published a minimum of five papers each. It clustered the participants into five distinct categories, each reflecting their primary area of interest or the collaboration network they belong to. This work is crucial for understanding not only the interactions between various countries, but also the overarching tendencies of AI-pathology research.

The circles which appear in figure 4 portray citation concentration regions in addition to international scientific collaboration networks. The mini-maps exhibit the interconnectedness between different countries depicting the degree of research collaboration, while the basic citation regions of IP and literature contribution bya are signified by size of the circles.

As such, the United States (US) is the first and the key node and therefore the most important country within the network which suggests that AI-related pathology research is most advanced there. The US is also collaborating with China, the United Kingdom, Canada, Germany, France and Japan, which points to the cooperation power of the USA.

Among European countries, Germany, the United Kingdom, France, Italy, and the Netherlands stand out, demonstrating both high citation impact and strong collaborative ties with each other.

In Asia, China and Japan are among the most prominent contributors. China shows strong connections with the US, while Japan has established a robust research network with both the US and European countries. India, Taiwan, and South Korea also contribute significantly, maintaining both regional and international collaborations.

Canada and Australia play key roles in their respective regions, forming strong research ties with the US. Brazil is noteworthy in South America, while Turkiye appears as a bridge between Europe and Asia, highlighting its regional research impact.

Countries with less dense collaboration networks include Sweden, Switzerland, Spain, Israel, and Portugal. These nations contribute to regional and thematic research collaborations, enriching the diversity of the literature.

DISCUSSION

The results of the research highlight the growing pace and reach of AI in pathology, which can be observed from the drastic increase in the number of research publications in the last twenty years. Based on previous studies, bibliometric evaluations reported that novel technologies powered by AI have significantly improved digital pathology by enhancing diagnostic accuracy, increasing efficiency of workflows, and improving decision-support systems. In addition to these general trends, it is important to highlight the key studies that have significantly contributed to the advancement of AI in pathology. For instance, van Leenders et al. (2020) discussed the ISUP consensus on grading prostatic carcinoma, contributing to standardized diagnostic criteria and receiving 366 citations. Steiner et al. (2018) demonstrated the role of deep learning-assisted diagnosis in metastatic breast cancer detection, showcasing AI's potential to enhance diagnostic sensitivity, with 283 citations. Abels et al. (2019) focused on establishing best practices and regulatory frameworks for digital pathology, a foundational step in clinical translation, cited 238 times. Cui and Zhang (2021) provided an extensive overview of AI applications in pathology, offering critical insights into emerging methods, cited 230 times. Finally, Baxi et al. (2022) examined the integration of AI into clinical digital pathology workflows, reflecting the shift from theoretical research to clinical utility, with 224 citations. Together, these influential studies highlight how AI has progressed from experimental innovations to practical applications in diagnostic pathology, improving accuracy, standardization, and operational efficiency.

This trajectory of growth is consistent with other scholarly studies such as those done by Shen et al.[7] and Zhao et al.,[8] which noted as well the increased and expanded thematic focus of AI-driven research in pathology. This work answers and builds on these studies by providing a comprehensive overview of the key research players, new development directions, and international collaboration networks.

Great attention must be paid to the exponential increase in AI-pathology publications, that began in 2018, predicting a peak in 2024, which is very noticeable. This surge can be attributed to the advancements in the deep learning architecture, increased adoption of whole-slide imaging, and the increased computational power available to perform large scale data analysis. Such phenomenon was also noted by Xiong et al.[9] in their examination of AI-based digital pathology research in relation to lung cancer where it was noted AI played a vital role in the Automated Image Analysis and AI-based high through put diagnostics and triaging bulk samples. These technologies and the collaboration among different

specialties have propelled the use of AI in pathology to active practice. However, despite the surge in publications, a review of previous literature suggests that there is publication bias towards primary subfoelds such as leepology and predictive deep learning, rather than the cross-branch applications of molecular pathology or predictive modeling, which are at best labeled as minimalistic in scope.[4,5] These unbalanced windows should be the center of focus for upcoming studies.

The citation and journal analysis reports indicate that the AI pathology works seem to be concentrated within high impact journals like Laboratory Investigation, Modern Pathology, and Journal of Pathology. This looks like AI is one of the main features within the scope of pathology research which correlates with the work of Moran-Sanchez et al.,[10] who said that "in diagnostic pathology, especially in the field of lymphoid neoplasms, innovative AI-based technologies are greatly changing the scope of the specialty. Furthermore, the institutional analysis indicates that other major medical and research institutions such as University of Pittsburgh, Radboud Universiteit, and Cleveland Clinic are leaders on the AI pathology research. This suggests a concentration of resources in technologically sophisticated and well funded research centers, supporting the work done by Zhang et al.,[11] who claimed that a disproportionate concentration of resources is needed so that instititons can be considered AI innovation leaders in pathology.

Co-occurrence of keywords and thematic analysis shows that the most used phrases are "AI," "digital pathology," "deep learning," and "machine learning," which highlights the primary focus of pathology research: AI. These results are consistent with previous bibliometric studies which noted an increasing dependence on deep learning and computational approaches to automated histopathological analysis.[4,5] A significant gap of this study was that few papers had been published focusing on the explainability of AI models. Although many strides have been made, the reality remains that AI is a "black-box" system that threatens any semblance of transparency and confidence in the clinical setting.[6] Subsequent researches should utilize AI technologies in pathology for better regulation and acceptance of the algorithms.

The analysis of institutional and authors' collaborations indicates that AI-pathology research is largely conducted by some leading research groups that have well-established collaborative networks between the US, Europe, and Asia. This corroborates the work of Xiong et al.,[9] who pointed out the disparity of AI lung cancer pathology research and the need for international collaboration. However, our work shows that these networks are unevenly distributed and concentrated among high and upper middle-income regions that have advanced research activity, while less developed countries remain underrepresented in AI based pathology research. This indicates that more efforts are needed to promote international pathology research programs and equity in funding for AI applications in diverse health care systems.

There is, however, a range of persistent challenges that remain prevalent regarding the integration of AI within the domain of pathology. As some literature suggests, these issues include, but are not limited to, data standardization, algorithmic opacity, and ethical issues that are recurrent in this field.[6,10] The diminishing of interobserver variability using AI models is one of the critical contentious issues. Research has shown that while some areas benefit from enhanced consistency AI provides, human and AI collaboration is crucial for sustaining trust in the diagnosis.[1] Furthermore, the proliferation of commercial AI models into pathology such as those provided by PathAI, for example, brings to light the question of data confidentiality and training bias regarding the proprietary data. The fair use of AI to solve problems in pathology requires greater responsiveness than this approach offers. There is a stronger case for using open-source AI and greater collaboration between institutions to achieve an ethical and fair use of AI in pathology.[12]

In addition, the citation impact of PathAI's work shows that there are significant contributions from the private sector, hinting the industry's impact on AI development is growing. This marks a shift towards transnational work on AI, where commercial AI systems are put to use as Baxi et al.[12] put it - integrated into the workflows. The combination of academic and industry sponsored AI Development requires continuous scrutiny to avoid unethical practices, biasing and clinically unverified applications.

Moreover, the thematic evolution of research over time provides additional insights into the development trajectory of AI in pathology. When evaluating the evolution of AI in pathology, a clear thematic shift over time becomes evident. In the early years (2007–2015), studies predominantly focused on developing image analysis algorithms for histopathological slides, using traditional machine learning methods such as support vector machines and random forests. These systems primarily aimed at automating simple tasks like nuclei detection and mitosis counting. However, with the advent of deep learning technologies post-2016, the research focus expanded towards more complex tasks, including whole-slide imaging analysis, automated cancer grading, and prediction of molecular alterations directly from pathology images. Systems such as convolutional neural networks (CNNs) and deep convolutional generative adversarial networks (DCGANs) became the most intensively studied technologies. In recent years (2020 onwards), attention has shifted towards explainable AI (XAI) models, multimodal data integration (combining pathology with genomics and clinical data), and regulatory frameworks for clinical implementation. This developmental trajectory illustrates the maturation of AI in pathology from isolated image analysis tools to sophisticated, clinically oriented diagnostic support systems.

Finally, the absence of common standardized evaluation criteria for various studies poses a significant barrier for AI research in pathology. As many AI studies apply different validation methods, comparison across studies becomes difficult.[13] There is a call for development of benchmarking criteria for designing AI systems in pathology to promote reliability and reproducibility of results, which is the focus of future studies.

Ultimately, this study sheds light on AI's pivotal role in transforming the pathology field. Despite the remarkable AI-facilitated progress in histopathological analysis, standardization, transparency, and clinical implementation still require essential attention. Achieving wider clinical utilization of AI applications in pathology will require intensified cross-border collaborations as well as legislative changes. In order to leverage AI's full potential in pathology, subsequent studies need to enhance AI model interpretability, resolve concerns regarding the unity of global research, and create universally validated benchmark standards. By focusing on these areas, AI pathology research will begin to tackle the gaps that can maximize patient benefits through ethical and valid clinical practices.

Limitations

One limitation of this study is its reliance on the Web of Science database, which, while comprehensive, may not include all relevant publications indexed in other databases such as PubMed or Scopus. Additionally, citation-based metrics may not fully capture the qualitative impact of studies, as citation practices can vary across disciplines. Furthermore, the study primarily focuses on English-language publications, potentially overlooking significant contributions in other languages. Despite these limitations, the bibliometric and network analysis provides valuable insights into the evolution of AI in pathology, offering a robust foundation for future research and interdisciplinary collaboration.

CONCLUSION

As a result, this research assesses the evolution of AI in pathology, especially in diagnostics, workflow management, and decision-support system enhancement. While AI-based research in pathology is booming, the field still faces considerable challenges such as a lack of standardization, opaque algorithms, and insufficient regulation. The study also underlines that interrelations between science and business must be considered as factors that foster development in the area and that future studies need to concern themselves with how to construct ethical and dependable universal validation frameworks for clinical AI. Through multidisciplinary cooperation, data standardization, and the establishment of regulatory structures, AI in pathology can become more effective and reliable.

ETHICAL DECLARATIONS

Ethics Committee Approval

Since this research is a bibliometric study, it did not require ethics committee approval.

Informed Consent

Since this research is a bibliometric study, it did not require informed consent.

Referee Evaluation Process

Externally peer-reviewed.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

Financial Disclosure

The authors declared that this study has received no financial support.

Author Contributions

All of the authors declare that they have all participated in the design, execution, and analysis of the paper, and that they have approved the final version.

REFERENCES

1. Försch S, Klauschen F, Hufnagl P, Roth W. Artificial intelligence in pathology. *Dtsch Arztebl Int*. 2021;118(12):199. doi:10.3238/arztebl.m2021.0011
2. Chang HY, Jung CK, Woo JI, et al. Artificial intelligence in pathology. *J Pathol Transl Med*. 2019;53(1):1-12. doi:10.4132/jptm.2018.12.16
3. Moxley-Wyles B, Colling R, Verrill C. Artificial intelligence in pathology: an overview. *Diagn Histopathol*. 2020;26(11):513-520. doi:10.1016/j.mpdhp.2020.08.004
4. Acs B, Rantalainen M, Hartman J. Artificial intelligence as the next step towards precision pathology. *J Intern Med*. 2020;288(1):62-81. doi:10.1111/joim.13030
5. Rakha EA, Toss M, Shiino S, et al. Current and future applications of artificial intelligence in pathology: a clinical perspective. *J Clin Pathol*. 2021;74(7):409-414. doi:10.1136/jclinpath-2020-206908
6. Harrison Jr JH, Gilbertson JR, Hanna MG, et al. Introduction to artificial intelligence and machine learning for pathology. *Arch Pathol Lab Med*. 2021;145(10):1228-1254. doi:10.5858/arpa.2020-0541-CP
7. Shen Z, Hu J, Wu H, et al. Global research trends and foci of artificial intelligence-based tumor pathology: a scientometric study. *J Transl Med*. 2022;20(1):409. doi:10.1186/s12967-022-03615-0
8. Zhao J, Han Z, Ma Y, Liu H, Yang T. Research progress in digital pathology: a bibliometric and visual analysis based on Web of Science. *Pathol Res Pract*. 2022;240:154171. doi:10.1016/j.prp.2022.154171
9. Xiong DD, He RQ, Huang ZG, et al. Global bibliometric mapping of the research trends in artificial intelligence-based digital pathology for lung cancer over the past two decades. *Digit Health*. 2024;10:20552076241277735. doi:10.1177/20552076241277735
10. Moran-Sanchez J, Santisteban-Espejo A, Martin-Piedra MA, Perez-Requena J, Garcia-Rojo M. Translational applications of artificial intelligence and machine learning for diagnostic pathology in lymphoid neoplasms: a comprehensive and evolutive analysis. *Biomolecules*. 2021;11(6):793. doi:10.3390/biom11060793
11. Zhang T, Chen J, Lu Y, Yang X, Ouyang Z. Identification of technology frontiers of artificial intelligence-assisted pathology based on patent citation network. *PLoS One*. 2022;17(8):e0273355. doi:10.1371/journal.pone.0273355
12. Baxi V, Edwards R, Montalto M, Saha S. Digital pathology and artificial intelligence in translational medicine and clinical practice. *Mod Pathol*. 2022;35(1):23-32. doi:10.1038/s41379-021-00919-2
13. Abels E, Pantanowitz L, Aeffner F, et al. Computational pathology definitions, best practices, and recommendations for regulatory guidance: a white paper from the Digital Pathology Association. *J Pathol*. 2019;249(3):286-294. doi:10.1002/path.5331