CINEFORUM
ISSN: 0009-7039
Vol. 66. No. S9, 2026 (Special Issue S9)

Global Research Productivity on Machine Learning in Healthcare, 2021–2025: A Scientometric Analysis

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ABSTRACT
The application of machine learning (ML) to healthcare has expanded rapidly, generating a large and fragmented body of scholarly literature. A quantitative, structured overview, of this literature can help researchers, funders, and policymakers identify leading contributors, thematic clusters, and emerging research fronts. Objective: This study presents a scientometric analysis of global scholarly publications on machine learning in healthcare indexed in the Web of Science (WoS) Core Collection over five consecutive publication years, 2021–2025. Methods: A structured topic search combining machine-learning/artificial-intelligence terms with healthcare-related terms was applied to the WoS Core Collection. The exported bibliographic records (15,221 records: 1,709 in 2021, 2,089 in 2022, 2,541 in 2023, 3,904 in 2024 and 4,978 in 2025) were parsed field by field from the native WoS tagged format for annual growth, document types, country and institutional productivity, source and citation analysis, author productivity, and author-keyword co-occurrence.
Keywords: Machine learning; artificial intelligence; Healthcare; scientometrics; bibliometric analysis; Web of Science; keyword co-occurrence; research trends

1. INTRODUCTION

Machine learning (ML) — encompassing supervised, unsupervised, deep learning, and reinforcement learning methods — has become one of the most consequential technological forces in contemporary healthcare research. Applications now span diagnostic image interpretation, early-warning risk scoring, drug discovery, clinical natural language processing, remote patient monitoring, and health-system operations.

Scientometric (bibliometric) analysis offers a quantitative lens for understanding how a research field evolves: which countries and institutions lead output, where the work is published, which papers and authors are most influential, and which conceptual themes dominate the discourse. This report analyses five consecutive publication years, 2021–2025, of the Web of Science Core Collection (15,221 records). All years were processed with a single parsing and analysis pipeline, so that countries, institutions, sources and themes can be compared year by year rather than described only as a single snapshot.

2. RELATED BIBLIOMETRIC WORK

Several prior studies have mapped adjacent territory using different databases, time windows, or disease-specific scopes. Broad bibliometric analyses of artificial intelligence in healthcare using WoS have tracked longitudinal publication growth and highly cited work. Other studies have examined ML applications across three decades of medical and healthcare analytics research using Scopus and PubMed data, finding that funding support was a stronger predictor of productivity than co-authorship collaboration at the country level. Condition-specific bibliometric studies — covering domains such as glaucoma, rehabilitation robotics, hypertension in primary care, cancer in primary care, and cardiomyopathy/heart failure — have applied Bibliometrix/Biblioshiny, VOSviewer, CiteSpace, and topic-modeling techniques to WoS-derived corpora, consistently reporting rapid growth in ML-related output within their respective clinical subfields. This report follows the same broad methodological tradition — structured WoS search, systematic field parsing, and keyword co-occurrence mapping for theme detection — applied here to the general ML-in-healthcare domain. Unlike single-snapshot or single-condition studies, the present report adds a year-by-year view across five consecutive publication years.

3. MATERIALS AND METHODS

3.1 Data Source

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Bibliographic records were exported from the Web of Science Core Collection in the native tagged (plain-text) format. A structured topic search combining machine-learning in healthcare-related terms was run for each of the five publication years, and each year's result set was exported in sequential batches of up to 500 records: 4 files for 2021 (records 1–1,709), 5 for 2022 (records 1–2,089), 6 for 2023 (records 1–2,541), 8 for 2024 (records 1–3,904) and 10 for 2025 (records 1–4,978). In total, 15,221 records were analyzed. All exports carry the same extraction date (15 September 2026), so citation counts for every year refer to that date. No record appears in more than one year's export: the WoS accession number (UT) is unique across the combined corpus. Records carry a document type of Article, Review, Proceedings Paper, or a small residual category (Editorial Material, Letter, Correction, Meeting Abstract, Data Paper, and similar).

Records are assigned to analysis years by export batch, that is, by the WoS publication-year filter, which also captures early-access items. The volume year in the PY field therefore differs from the batch year for 1,080 records (7.1% of the corpus; 154 in 2021, 152 in 2022, 206 in 2023, 245 in 2024 and 323 in 2025), mainly articles published online in one year and assigned to the following year's volume (for example, 321 of the 4,978 records in the 2025 batch carry a 2026 or 2027 volume year).

4. DATA ANALYSIS

Year wise Analysis (2021–2025)

4.1 Growth of Output and Corpus Overview

The corpus comprises 15,221 records drawn from 4,418 distinct source titles and affiliations in 157 countries, authored across 67,458 unique author-name instances. Table 1 shows the annual profile. Output rose from 1,709 records in 2021 to 4,978 in 2025, an increase of 191% (CAGR 30.6%). Year-over-year growth was steady at 22.2% in 2022 and 21.6% in 2023, accelerated to 53.6% in 2024, and remained high at 27.5% in 2025 (Figure 1). Participation broadened alongside volume: the number of distinct source titles rose from 823 to 1,918, the number of countries from 103 to 137, and the number of distinct author names from 8,411 to 24,384.

Table 1. Annual profile of the ML-in-healthcare corpus in WoS, 2021–2025.

Year	Records (n)	YoY growth	Source titles	Countries	Total citations	Mean cit./record	Uncited (%)	Intl. co-auth. (%)
2021	1,709	—	823	103	61,426	35.94	6.4	36.5
2022	2,089	+22.2%	962	108	56,883	27.23	7.8	37.3
2023	2,541	+21.6%	1,086	119	54,870	21.59	7.9	37.0
2024	3,904	+53.6%	1,613	126	49,217	12.61	16.1	33.1
2025	4,978	+27.5%	1,918	137	27,570	5.54	29.0	33.3
2021–2025	**15,221**	**CAGR 30.6%**	**4,418**	**157**	**249,966**	**16.42**	**16.7**	**34.8**

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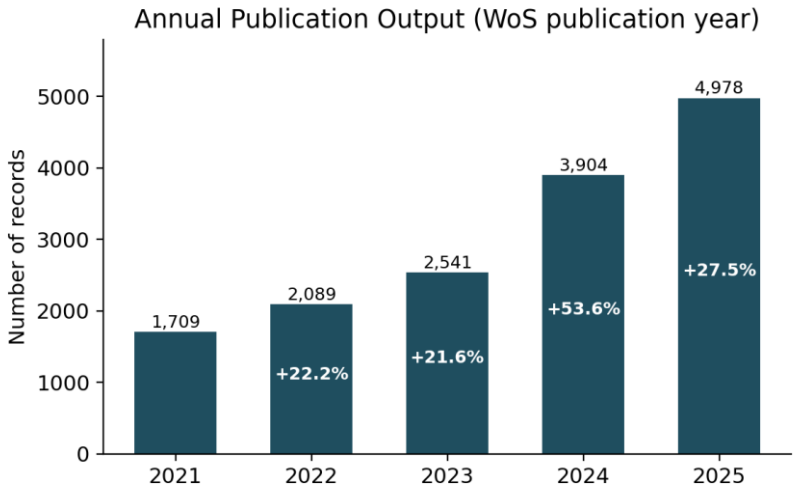


Figure 1. Annual publication output of ML-in-healthcare records in WoS, 2021–2025 (n = 15,221); inset labels show year-over-year growth.

Table 2 summarizes the document-type composition. Articles dominate the corpus (63.0%), followed by conference proceedings papers (18.7%) and reviews (16.6%). The share of reviews rose from 14.2% in 2021 to 18.3% in 2025, whereas the share of proceedings papers fluctuated between 14.0% and 24.1% with no monotonic trend.

Table 2. Document-type composition by year, n (% of year).

Year	Article (incl. early access)	Review (incl. early access)	Proceedings paper	Other*	Total
2021	1,026 (60.0%)	243 (14.2%)	412 (24.1%)	28 (1.6%)	1,709
2022	1,351 (64.7%)	310 (14.8%)	377 (18.0%)	51 (2.4%)	2,089
2023	1,682 (66.2%)	449 (17.7%)	356 (14.0%)	54 (2.1%)	2,541
2024	2,353 (60.3%)	613 (15.7%)	869 (22.3%)	69 (1.8%)	3,904
2025	3,175 (63.8%)	911 (18.3%)	831 (16.7%)	61 (1.2%)	4,978
2021–2025	**9,587 (63.0%)**	**2,526 (16.6%)**	**2,845 (18.7%)**	**263 (1.7%)**	**15,221**

*Other = editorial material, letter, correction, meeting abstract, data paper, and similar.
Citation metrics: total citations accrued across the corpus were 249,966 (mean 16.42 citations/record; corpus h-index = 170); 16.7% of records had zero citations at the extraction date. Citation profiles differ strongly by batch year because of citation age: mean citations per record fall from 35.9 for 2021 records to 5.5 for 2025 records, and the uncited share rises from 6.4% to 29.0%. The h-index likewise falls from 107 (2021) to 54 (2025).

4.2 Leading Countries

Table 3 ranks the ten most productive countries by author affiliation (a paper is counted once per country if it has at least one co-author affiliated there). The United States, India, and China are the three leading contributors, together accounting for 33.7% of all country-attributed record counts. By corresponding-author country the order is the same for the leading three (United States 2,688, India 2,240, China 1,515), but the relation between affiliation and corresponding-author counts differs: a corresponding author is based in India for 83% and in China for 83% of the papers with an author affiliated there, compared with 74% for the United States and 60% for the United Kingdom, suggesting that Indian and Chinese teams more often lead their own projects, while Pakistani

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authorship (657 papers; 43% with a corresponding author in Pakistan) more often appears within projects led from elsewhere.

Table 3. Top 10 countries by publication output, 2021–2025.

Rank	Country	Records (n)	Corresp.-author records	Total citations	Avg. citations/record
1	United States	3,644	2,688	73,885	20.28
2	India	2,709	2,240	41,791	15.43
3	China	1,833	1,515	34,224	18.67
4	United Kingdom	1,468	881	36,570	24.91
5	Saudi Arabia	1,258	687	21,282	16.92
6	Italy	827	613	15,767	19.07
7	Canada	800	514	19,071	23.84
8	Australia	659	420	21,045	31.93
9	Pakistan	657	283	14,884	22.65
10	South Korea	605	501	13,375	22.11

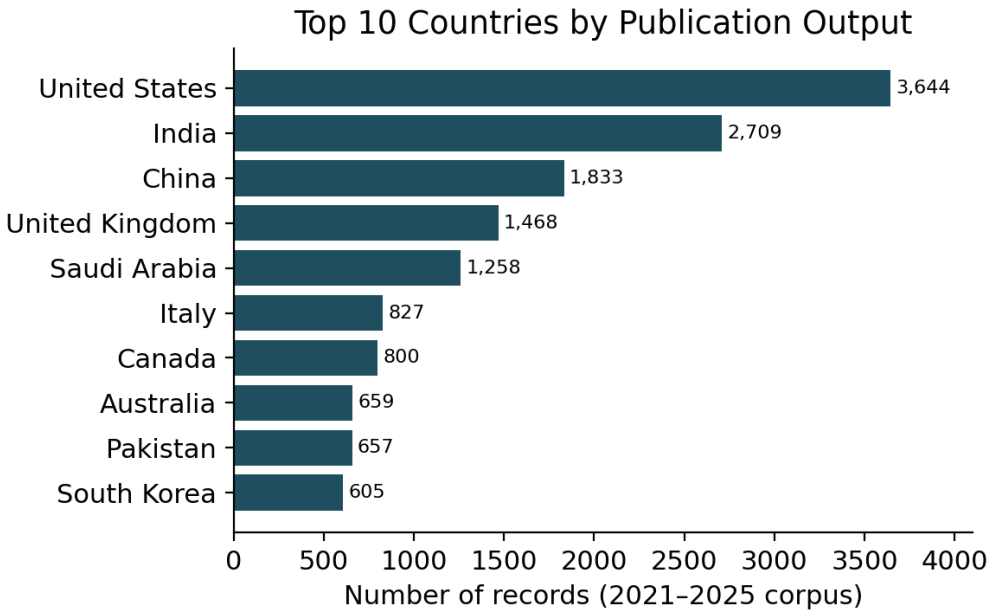


Figure 2. Top 10 countries by publication output, 2021–2025 (n = 15,221).

The composition of the leading group changed markedly over the five years (Table 4, Figure 3). The United States' share of records with country data fell steadily from 29.5% in 2021 to 21.1% in 2025, even though its absolute output doubled (504 to 1,047 records). China's share rose from 8.5% to 15.6%, and its output grew more than five-fold (145 to 776), moving ahead of the United Kingdom in 2023. India's share fluctuated between 15.8% and 19.6% without a clear trend, Saudi Arabia's rose from 7.0% to a high of 9.6%, while the shares of Canada (6.7% to 4.4%) and Australia (6.0% to 3.4%) declined gradually.

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Table 4. Output of the eight leading countries by year, n (% of records with country data).

Country	2021	2022	2023	2024	2025
United States	504 (29.5%)	575 (27.6%)	626 (24.7%)	892 (22.9%)	1,047 (21.1%)
India	269 (15.8%)	409 (19.6%)	441 (17.4%)	746 (19.2%)	844 (17.0%)
China	145 (8.5%)	172 (8.3%)	267 (10.5%)	473 (12.1%)	776 (15.6%)
United Kingdom	189 (11.1%)	223 (10.7%)	249 (9.8%)	361 (9.3%)	446 (9.0%)
Saudi Arabia	119 (7.0%)	194 (9.3%)	243 (9.6%)	293 (7.5%)	409 (8.2%)
Italy	93 (5.4%)	112 (5.4%)	139 (5.5%)	216 (5.5%)	267 (5.4%)
Canada	114 (6.7%)	130 (6.2%)	141 (5.6%)	195 (5.0%)	220 (4.4%)
Australia	102 (6.0%)	113 (5.4%)	123 (4.8%)	151 (3.9%)	170 (3.4%)

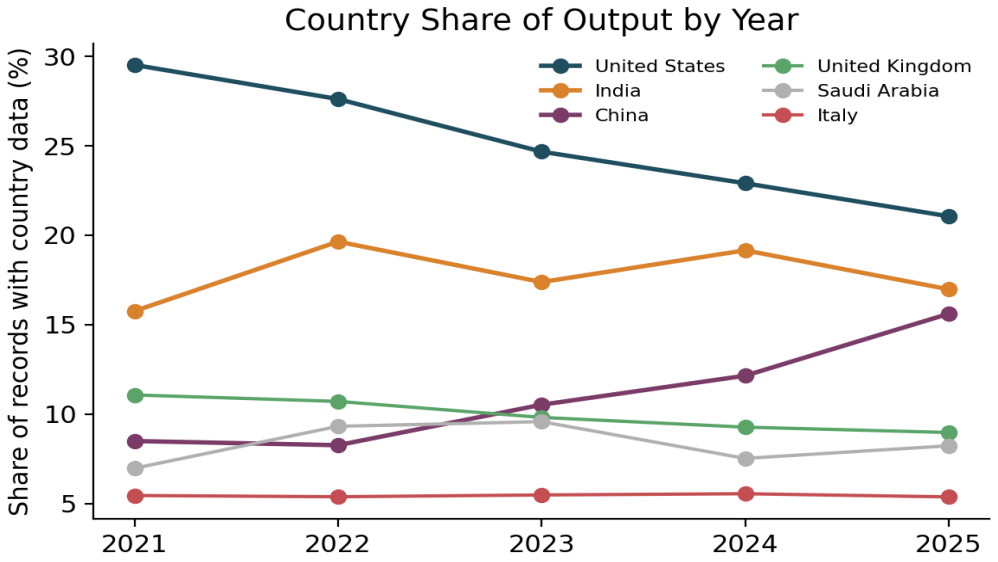


Figure 3. Share of records by country and year for the six leading countries, 2021–2025.

International co-affiliation (papers with authors based in two or more countries) accounted for 34.8% of records with identifiable country data (5,281 of 15,191); the remaining 65.2% were single-country efforts. The rate was 36.5% in 2021, peaked at 37.3% in 2022, and was 33.1% and 33.3% in 2024 and 2025, so the strong growth in volume has not been accompanied by a rise in the share of cross-border collaboration.

4.3 Leading Institutions

Table 5 lists the ten most productive institutions by raw affiliation-name matching. Saudi Arabian universities (King Saud University, Princess Nourah Bint Abdulrahman University, Prince Sattam Bin Abdulaziz University and King Abdulaziz University) occupy four of the ten positions, alongside leading Indian, US, Canadian and UK institutions. Among the fifteen most productive institutions, University College London shows the highest average citation impact (40.1 citations/record), followed by Stanford University (37.5) and Harvard Medical School (35.6); the lowest averages among the fifteen are those of King Khalid University (11.4) and SRM Institute of Science and Technology (12.1). Averages depend on each institution's mix of publication years and document types and should be read with the caution given in Section 3.3.

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Table 5. Top 10 institutions by publication output, 2021–2025.

Rank	Institution	Records (n)	Total citations	Avg. citations/record
1	King Saud University	191	3,824	20.02
2	Princess Nourah Bint Abdulrahman University	188	2,406	12.80
3	Harvard Medical School	186	6,620	35.59
4	Vellore Institute of Technology	170	3,131	18.42
5	Stanford University	144	5,402	37.51
6	Prince Sattam Bin Abdulaziz University	141	2,165	15.35
7	University of Toronto	141	4,101	29.09
8	University of Oxford	134	4,192	31.28
9	King Abdulaziz University	133	2,494	18.75
10	Imperial College London	126	4,074	32.33

4.4 Leading Journals and Source Analysis

Table 6 presents the twelve most productive source titles by record count. Output is widely dispersed: the ten leading sources together publish only 13.8% of all records, spread over 4,418 source titles. Consistent with adjacent bibliometric studies of AI in healthcare, output concentrates in multidisciplinary, engineering and informatics venues (IEEE Access, Scientific Reports, Sensors) rather than traditional single-specialty clinical journals. The leading sources have followed different trajectories: Scientific Reports grew from 22 records in 2021 to 217 in 2025, IEEE Access from 59 to 150, whereas Sensors peaked at 77 records in 2023 and published 50 in 2025. Among the twelve sources, Healthcare has the highest average citation count (39.1), and IEEE Access the highest h-index (50).

Table 6. Top 12 source titles by publication output, 2021–2025.

Rank	Source title	Records (n)	Total citations	Avg. cites/record	h-index
1	IEEE Access	488	10,063	20.62	50
2	Scientific Reports	381	5,479	14.38	35
3	Sensors	277	8,318	30.03	44
4	Applied Sciences (Basel)	182	2,220	12.20	23
5	Diagnostics	143	3,534	24.71	31
6	PLOS ONE	142	1,273	8.96	19
7	BMC Medical Informatics and Decision Making	129	1,937	15.02	23
8	Int. J. of Advanced Computer Science & Applications	127	276	2.17	7
9	Cureus Journal of Medical Science	118	2,900	24.58	29
10	Healthcare	111	4,344	39.14	28
11	Electronics	108	2,539	23.51	27
12	CMC-Computers, Materials	104	973	9.36	15

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Web of Science subject-category tagging (Table 7) confirms the field's dual identity as both a computer-science and a health-sciences discipline. 41.5% of records carry at least one Computer Science category, while 19.3% carry at least one of the principal health categories (Medical Informatics; Health Care Sciences & Services; Public, Environmental & Occupational Health; Medicine, General & Internal).

Table 7. Top 10 WoS categories, 2021–2025.

Rank	WoS Category	Records (n)	%
1	Computer Science, Information Systems	2,769	18.2%
2	Computer Science, Artificial Intelligence	2,688	17.7%
3	Computer Science, Interdisciplinary Applications	2,142	14.1%
4	Engineering, Electrical & Electronic	2,119	13.9%
5	Computer Science, Theory & Methods	1,745	11.5%
6	Medical Informatics	1,499	9.8%
7	Telecommunications	1,326	8.7%
8	Health Care Sciences & Services	1,181	7.8%
9	Engineering, Biomedical	931	6.1%
10	Multidisciplinary Sciences	821	5.4%

4.5 Author Productivity

Author productivity follows the expected long-tail (Lotka-like) distribution typical of large, fast-growing fields: of the 67,458 unique author-name instances, 86.7% appear on a single record and only 700 appear on five or more. The most prolific author name in the corpus (U. Rajendra Acharya) appears on 25 records, followed by Qammer H. Abbasi (23) and Sudeep Tanwar (22) (Table 9). Records have 5.4 authors on average, and 4.1% are single-authored. This pattern is consistent with a field driven substantially by first-time or occasional contributors rather than a small entrenched core of repeat authors. Counts are based on author-name strings without disambiguation, so very common names may combine several individuals.

Table 9. Ten most productive author names, 2021–2025 (ties broken by citations).

Rank	Author	Records (n)	Total citations
1	U. Rajendra Acharya	25	2,012
2	Qammer H. Abbasi	23	352
3	Sudeep Tanwar	22	553
4	Mohsen Guizani	21	1,485
5	Imran Ashraf	21	319
6	Vinay Chamola	19	2,337
7	Muhammad Adnan Khan	19	524
8	Leo Anthony Celi	18	1,036
9	David A. Clifton	18	708
10	Nan Liu	16	1,041

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4.6 Keyword Co-occurrence and Thematic Structure

Author-keyword frequency analysis (Table 10) confirms machine learning and artificial intelligence as the dominant umbrella terms: 'machine learning' appears among the author keywords of about half of all records in every year (47–52%), with deep learning, healthcare, and the internet of things completing the top five. The next tier comprises COVID-19, federated learning, explainable AI, neural networks, and natural language processing.

Table 10. Top 15 author keywords, 2021–2025, with annual occurrences.

Rank	Keyword	Total	2021	2022	2023	2024	2025
1	machine learning	7,499	856	1,042	1,200	2,033	2,368
2	artificial intelligence	2,983	275	357	476	842	1,033
3	deep learning	1,809	203	250	344	477	535
4	healthcare	1,280	200	199	239	316	326
5	internet of things	735	105	127	153	160	190
6	COVID-19	535	158	122	114	82	59
7	federated learning	518	30	50	92	126	220
8	explainable AI	498	27	42	67	112	250
9	neural networks	437	75	77	80	109	96
10	natural language processing	407	42	58	73	98	136
11	convolutional neural network	383	30	47	65	112	129
12	classification	362	45	64	70	90	93
13	electronic health records	347	42	58	65	90	92
14	prediction	302	43	59	40	86	74
15	medical services	284	41	35	30	72	106

Figure 4 shows the fifteen most frequent author keywords. The five-year trends in the share of records using selected keywords (Figure 5, Table 11) reveal where the field is moving. Between the 2021–2022 and 2024–2025 batches, the keywords with the largest gains in occurrence per 1,000 records were large language models, generative AI and ChatGPT, none of which appears in the 2021–2022 batches, followed by SHAP, quantum machine learning, data privacy, explainable AI and personalized medicine. Terms linked to the pandemic and to earlier-generation data technologies declined: 'COVID-19' fell from 92.5 to 11.9 occurrences per 1,000 records between 2021 and 2025, and 'internet of things' from 61.4 to 38.2. Federated learning (17.6 to 44.2) and explainable AI (15.8 to 50.2) rose steadily, and 'natural language processing' stayed broadly stable (24.6–28.7). The keyword 'ChatGPT' peaked in 2024 (32 records) and fell to 18 in 2025, while 'large language models' continued to rise (53 to 108 records), suggesting a shift from product names to generic terminology.

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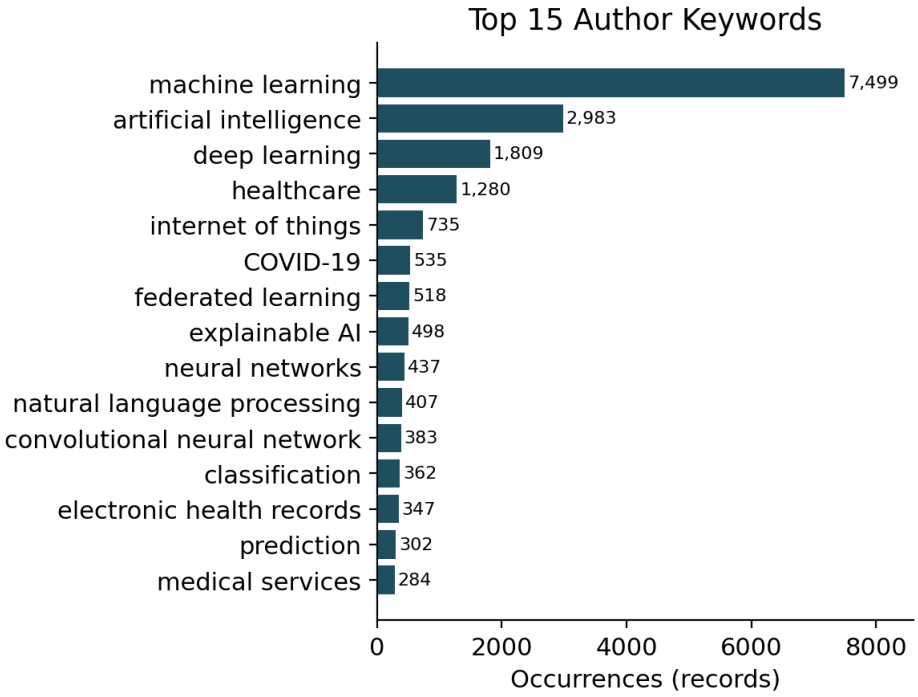


Figure 4. Top 15 author keywords by frequency, 2021–2025 (n = 15,221 records).

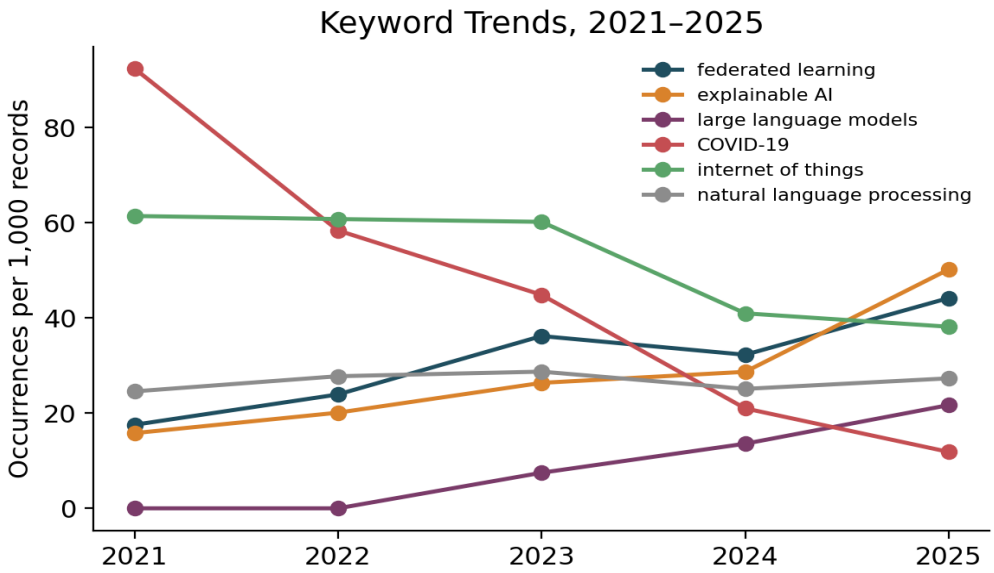


Figure 5. Occurrences per 1,000 records of selected author keywords by year, 2021–2025.

Figure 6 presents the author-keyword co-occurrence network of the 30 most frequent keywords, with node size proportional to keyword frequency and edges shown where the association strength is at least 0.10. The most frequent keyword pairs are 'machine learning' with 'artificial intelligence' (2,047 co-occurrences), 'deep learning' (1,143) and 'healthcare' (765). Community detection resolves three groups. The first, the largest (19 keywords), is a core of machine-learning methods and clinical applications: machine learning, artificial intelligence, deep learning, healthcare, COVID-19, explainable AI, neural networks, natural language processing, convolutional neural networks, classification, electronic health records, prediction, feature selection, random forest, big data, large language models, diagnosis, digital health and precision medicine. The second (6 keywords) links the

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internet of things, federated learning, blockchain, security, privacy and smart healthcare, a privacy-preserving and connected-health theme. The third (5 keywords: medical services, feature extraction, data models, predictive models and accuracy) consists of index-style technical terms that occur almost exclusively in IEEE-published records (99% of records with 'medical services' or 'data models' appear in IEEE-branded sources) and therefore reflects publisher keyword conventions as much as topical content.

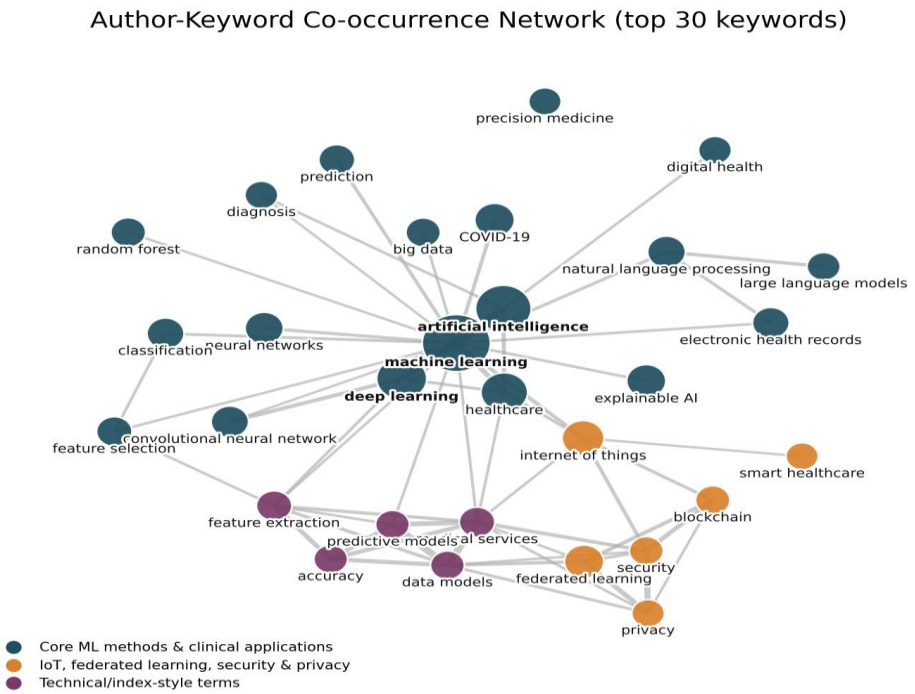


Figure 6. Author-keyword co-occurrence network, top 30 keywords, 2021–2025 (node size ∝ keyword frequency; colors indicate communities).

5. FINDINGS & DISCUSSION

Between 2021 and 2025, ML-in-healthcare research in WoS grew from 1,709 to 4,978 records a year (CAGR 30.6%), with the strongest acceleration in 2024 (53.6%). Growth was broad rather than concentrated: the number of source titles more than doubled (823 to 1,918), the number of author names almost tripled (8,411 to 24,384), the number of countries rose by about a third (103 to 137), and the ten most productive sources publish only 13.8% of records. The literature sits at the intersection of computer science and health sciences and is published predominantly in multidisciplinary, engineering and informatics journals rather than traditional single-specialty clinical outlets.

First, the geography of output is shifting: the United States, India and China remain the three leading producers, but the US share fell from 29.5% to 21.1% while China's rose from 8.5% to 15.6%, and four Saudi Arabian universities are among the ten most productive institutions. Second, international collaboration did not intensify as the field grew: the share of internationally co-authored records was 37.3% in 2022 and 33.3% in 2025, so most of the added output is single-country in origin. Third, the thematic center of gravity has moved. A stable core of machine learning, artificial intelligence and deep learning is accompanied by growing attention to interpretability (explainable AI, SHAP), privacy-preserving computation (federated learning, data privacy) and, from 2023, large language models and generative AI, whose appearance follows the public release of ChatGPT in late 2022, while pandemic-related terms have receded. Fourth, the most-cited work consists mainly of reviews, with explainability reviews prominent, and of methodological and reporting-standard papers such as PROBAST+AI, which suggests that appraisal, interpretability and trustworthiness are central concerns of the field.

6. CONCLUSIONS AND FUTURE DIRECTIONS

Machine learning in healthcare is a fast-growing, internationally distributed but geographically shifting research domain whose thematic center of gravity is moving from pandemic-era and IoT-oriented work toward

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interpretable, privacy-preserving and generative approaches. The 2021–2025 Web of Science corpus shows machine learning in healthcare to be a large, fast-growing and internationally distributed research domain: 15,221 records, annual output nearly tripling, and authorship from 157 countries. Annual output grew 191% over the period from 1,709 to 4,978 records. The corpus spans 4,418 source titles and 157 countries. The United States (3,644 records), India (2,709) and China (1,833) lead output, but the United States' share of country-attributed records fell from 29.5% in 2021 to 21.1% in 2025 while China's rose from 8.5% to 15.6%. 34.8% of records were internationally co-authored, with no upward trend. The United States, India and China lead production, but China is gaining and the United States is losing share, Saudi Arabian institutions are prominent among the leading producers, and the share of internationally co-authored work has remained near one third. Future work can extend the same to later publication years as they become available, add co-citation and bibliographic-coupling analyses, disambiguate authors and institutions with identifier fields (ORCID, ROR), apply topic modelling to titles and abstracts to complement author keywords, and compare WoS with Scopus or PubMed coverage

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