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Global bibliometric mapping of the frontier of knowledge in the field of artificial intelligence for the period 1990–2019

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Abstract
Artificial Intelligence (AI) has emerged as a field of knowledge that is displacing and disrupting technologies, leading to changes in human life. Therefore, the purpose of this study is to scientifically map this topic and its ramifications, in order to analyze its growth. The study was developed under the bibliometric approach and considered the period 1990–2019. The steps followed were (i) Identification and selection of keyword terms in three methodological layers by a panel of experts. (ii) Design and application of an algorithm to identify these selected keywords in titles, abstracts, and keywords using terms in Web of Science to contrast them. (iii) Performing data processing based on the Journals of the Journal Citation Report during 2020. Knowing the evolution of a field of knowledge such as AI from a bibliometric study and subsequently establishing the ramifications of new research streams is in itself a relevant finding. Addressing a broad field of knowledge as AI from a multidisciplinary approach given the convergence it generates with other disciplines and specialties is of high strategic value for decision makers such as governments, academics, scientists, and entrepreneurs.

Keywords Artificial intelligence · Machine learning · Deep learning · Big Data · Bibliometric mapping · Knowledge networks · WoS · Radical changes

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1 Introduction

Artificial intelligence (AI) is a branch of knowledge that presents a sustained growth at a global level in terms of the number of scientific publications (De la Vega et al. 2021) and patents, mainly in the last 30 years (WIPO 2021). The relevance of this techno-scientific field in the world is increasing, not only because of the impact it is causing on more spheres but also because of the type of transformations it is generating (Vinuesa et al. 2020). This field of knowledge has been branching out into new specialties that are opening niches such as Machine Learning and Deep Learning, among others, which are evolving and acquiring specific properties (Srinivasa Rao and Vazquez 2020). One characteristic of AI is that it is directly intervening in different organizational spheres with applications in a growing number of activities (Panch et al. 2019; Cox 2021). Another particularity that highlights the value of this field of knowledge is that it is part of disruptive projects with high investments in research and development (R&D), such as the technological convergence project (NBICA) of the National Science Foundation (NSF), which also includes other fields of knowledge such as nanotechnology, biotechnology, information and communication technologies, cognitive sciences and, as already mentioned, AI (Roco 2020; Lee and Lim 2021).

The NBICA technological convergence and, within it, AI, are generating structural changes in national innovation systems, to such an extent that social, economic, political, technological, and cultural behaviors are being modified at different scales, depending on the level of development of each country and region (Sun et al. 2020). From a more macro perspective, these changes are clear and some specialists have called them the 4.0 revolution (Bongomin et al. 2020; Ramakrishna et al. 2020), and others have called it the sixth technological revolution, and the difference between both approaches lies in the explanatory models used for their analysis (De la Vega Hernández and Barcellos de Paula 2019; Marchena Sekli and De La Vega 2021; de Paula et al. 2022; De la Vega and Diaz Amorin 2020). This means that the constant evolution of knowledge that is under development implies knowing how to manage change to adapt to both incremental and radical innovations that happen more and more in less time and, here, AI is playing an increasingly central role (Jiang et al. 2020; De la Vega and Barcellos de Paula 2020; Delgosha et al. 2021). An unexpected global variable such as the SARS-CoV-2/COVID-19 Pandemic has accelerated the use of new technologies such as AI and this fact has modified knowledge absorption capacities at all levels (Panch et al. 2019; Agarwal et al. 2021).

The birth of AI can be approached in multiple ways and one of them is to analyze it from the scientific bases. This branch of knowledge began in the 1940s and was defined as Cybernetics (Russell et al. 2011; Zhejiang Da Xue et al. 2019). Some specialists divide it into large areas of application, namely, natural language processing, automatic programming, robotics, computer vision, and automatic data retrieval systems, among others (Haugeland 1985; Nilsson 1986). There are other more recent currents of thought in which both the theoretical and practical aspects of AI are discussed. The evolution of this branch of knowledge is rapidly expanding to other fields in which autonomous agents work, for example, AI in Law, Computational Logic, e-Government, Multi-Agent Systems, among others, in addition to the impact it is generating on emerging issues (Simari and Rahwan 2009). AI is shaping an increasingly wide range of sectors and is expected to affect global productivity, equity, inclusion, environmental outcomes, and several other areas, both in the short and long term (Vinuesa et al. 2020). Some experts point to the significant impact that AI is having on innovation processes. On the one hand, it has generated advances in multiple fields and with implications for the economy and for global society itself, given that it has the potential to directly influence both the production and the characteristics of a wide range of products and services, with important implications for productivity, employment, and competition. On the other hand, AI has the potential to change innovation from the process itself, with consequences that can be just as profound and that, over time, can come to dominate the direct effect (Cockburn et al. 2018; Santoro et al. 2018; Zabala-Iturriagagoitia et al. 2020).

The purpose of this global bibliometric mapping is to examine the theoretical evolution and topography of the knowledge base on a technological branch that grew exponentially in recent years, but whose origins could be traced back to the 1940s. This longitudinal study that evaluates the period 1990–2019 was developed under a macro approach, in order to introduce an overview that seeks to know the evolution of new disciplines and specialties that have been emerging in those 30 years. There are already bibliometric mappings referring to this subject but these are of a specific nature and do not include the family of indicators used in this work (Munim et al. 2020; Dhamija and Bag 2020; Guo et al. 2020; Fosso Wamba et al. 2021; Goodell et al. 2021). In recent years, AI has steadily increased the production of scientific articles and is playing a central role in the changing global technological pattern that is affecting multiple spheres (Bainbridge and Roco 2016; Roco 2020). The AI space is so dynamically and disruptively evolving from both a technology, society and a business perspective that related analyses and meta-analyses (including bibliometric methodologies) need to also be periodically repeated, conducting multi-modal, multi-nodal, multi-lateral and multi-layer studies including bibliometrics, surveys, semi-structured interviews and case studies as well as Knowledge, Information and Data Analytics (KID ANALYTICS) with a prospective retrospective orientation (Industry 4.0, Industry 5.0 and Society 5.0, Quadruple and Quintuple Innovation Helix-centered (Carayannis et al. 2021). In this context, prior studies may well have focused on less critical matters of today as well as missed other issues that have now become paramount (such as privacy, safety, human rights, artificial superintelligence for warfare, fake news as well as fake realities (4D misrepresentations via Meta-verse-like modalities). AI promises potential implications, challenges and opportunities both as an enabler as well as a transformer of government, business, society, nature and global peace, so bibliometrics can play a crucial role in helping attain and sustain a human- and nature-friendly digital transformation and evolution rather than deformation and disruption (Carayannis and Draper 2022). Therefore, this study answers the following key research questions that have been adapted from various bibliometric studies (Kumar et al. 2021a, b, c, d, 2022; Donthu et al. 2021a, 2021b, 2021c, 2022).

RQ1 What are publication and citation trends in AI research?

RQ2 Which are the top authors, journals, institution and countries in AI research?

RQ3 What are the major themes in AI research?

RQ4 Which directions should researchers pursue to advance AI research?

To answer these research questions, the authors analyzed 136,404 articles extracted from the Clarivate Analytics' WoS database. This review used bibliometric methods to synthesize the knowledge base on AI. These methods incorporate citation analysis, co-citation analysis, and co-occurrence and keyword analyses to plot the extracted cartographic map. The value of bibliometric methods lies in their ability to document the evolution of the literature over time and reveal the intellectual relationship of existing knowledge. Thus, this research enhances the growth of a technological branch that is increasingly influencing a change of the global techno-economic pattern.

There are recent studies that deal with AI using bibliometric and scientometric approaches but from different perspectives than the one presented in this research. One of them deals with the subject highlighting the impact that this branch of knowledge is having on society from a global viewpoint. It talks about the potential risks, the ethical implications, and the benefits it will bring (Fosso Wamba et al. 2021). The other study performs an exhaustive review of the conceptual evolution of wind energy from the perspective of AI impact, which indicates the level of specificity that can be reached in these methodologies (Chatterjee and Dethlefs 2021).

This study contributes to the world literature by providing a comprehensive bibliometric review of AI from the WoS database and linking it to one of the branches of knowledge coming from the NBICA technological convergence. The results offer a guide for new research on this topic and provide a valuable reference on the new specialties emerging strongly such as Machine Learning and Deep Learning.

2 Methodology

This section presents the methodological steps applied to conduct the bibliometric mapping that followed a combined approach (Bordons and Zulueta 1999; van Raan 1999; Tian et al. 2008; Liu et al. 2011). In this specific case, a pattern was applied that resulted in obtaining one family of indicators that allowed preparing 11 Tables and 11 Figures (Figs. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11). For subsections have been incorporated in the results following the logical structure of the 4 research questions and this was maintained in the discussion section.

The scientific mapping was carried out through the application of bibliometric techniques, which allow for quantitative analysis of published documents that reveal patterns and trends. This method allows the development of bibliometric research in related areas using mathematical, statistical, and visual approaches to generalize the research. Likewise, it is possible to manage and evaluate the research area in terms of scientific production, co-authorship, and co-citations, among other related indicators (Table 1).

The methodological process was done in five stages as shown in Fig. 1.

The process began with the identification and selection of keywords associated with the subject of study (Artificial Intelligence); the search terms were selected through an initial investigation of the predominant literature on the topic, the discussion among the co-authors, and the suggestions from experts in the AI field. The search equation used is shown in the Table 2. From this initial stage, eleven (11) keywords were selected, through which a search function was built.

The information for this study was collected from the database of Clarivate Analytics' Web of Science (WoS). This database was selected since it provides the possibility of downloading all the metadata related to the research topic for the period of study; for other databases such as Scopus, there are download restrictions because it only allows a maximum of 2000 articles per year, which represented a major limitation for the development of the study.

Table 1 Dimensions of the 4 research questions and number of tables and figures

RQ	Tables and figures
RQ 1	Table 3 Production (Articles, Citations Authors, and Mean Citations and authors) Figure 2 Total Number of Articles by Year Figure 3 Total Number of Citation by Year Table 4 Most Relevant Articles per Citation
RQ 2	Table 5 Most Productive Authors by article production (1990 – 2019) Figure 4 Most productive Authors by Period Table 6 Most relevant Institutions per production (1990–2019) Figure 5 Most relevant Institutions per production (1990–2019) by 5 periods Table 7 Top Ten Most Productive Countries (1990 – 2019) Figure 6 Articles by Countries Table 8 Most Productive Countries by Year Figure 7 Collaboration by Cluster of Countries
RQ 3	Table 9 Journals (Most Relevant Sources by Production) Figure 8 Total Number of Top Journals Table 10 Most Relevant Categories (Web of Science)
RQ 4	Table 11 Most Relevant Keywords Figure 9 Number of Keywords by period Figure 10 Longitudinal Cluster of Keywords Figure 11 Density Term Map of Keywords

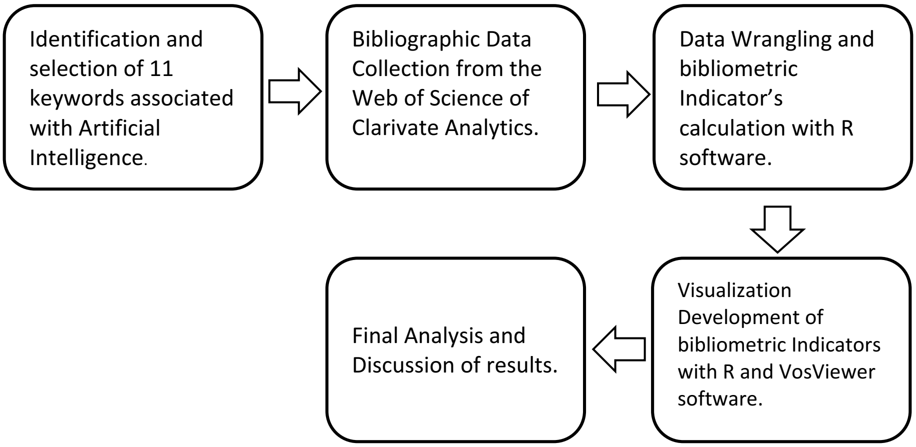

Fig. 1 Workflow for performing the bibliometric review

Table 2 Search equation for the collection of metadata

TS = ("Artificial intelligence" OR "Machine intelligence" OR "artificial neural network*" OR "Machine learning" OR "Deep learn*" OR "Natural language process*" OR "Robotic*" OR "thinking computer system" OR "fuzzy expert system*" OR "evolutionary computation" OR "hybrid intelligent system*")
AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article)

The present research is focused on articles published in the last decades (1990–2019), evaluated by double-blind peers and published in journals indexed in the main collection of the WoS database under the citation indexes Science Citation Index—SCI, Social Science Citation Index—SSCI and Arts & Humanities Citation Index—A&HCI. Consequently, the study does not include grey literature, conference proceedings, books, or book chapters. Finally, only articles published in the English language have been considered.

Following, to obtain the indicators of scientific production, analyses of co-occurrence, co-authorship and collaboration networks, a data mining algorithm developed with the R and R-Studio software was used. Through this tool, the treatment and debugging of the records downloaded from the WoS database were performed to subsequently carry out the transformation to obtain the indicators related to the present study, as well as the graphics through which the longitudinal presentation of these is made. The use of the R tool provides flexibility in terms of the possibility of developing graphical representations in the appropriate context to respond to the questions raised in this study.

The use of R + R-Studio packages allowed developing a script that contains all the processes of data wrangling (cleaning, structuring, and enriching raw data into a desired format), plotting, and table design; in this way, it is possible to have reproducible research which allows for the reproduction and update of the study in the future.

For the development of bibliometric networks, although there are several general network analysis tools available, instruments such as Pajek (Doreian 2006) and Gephi (Bastian et al. 2009) can be mentioned; these do not have the functionality to import bibliographic metadata that have been exported from the WoS database, and for this purpose, the use of other tools is required. For Pajek, there is a tool called WoS2Pajek that can be used for this purpose and in the case of Gephi, the tool is Sci2.

Among the most widely used tools that have the functionality of processing records imported from the WoS database are CiteSpace, Sci2, and VOSviewer. The latter was used for the development of this study (van Eck and Waltman 2010) because it is an easy-to-use powerful tool for network visualizing. It also allows focusing the images of bibliometric networks and provides distance-based visualizations instead of graph-based ones, which is a specific feature for the visualization of large networks.

The software VOSviewer was used to develop the maps of scientometrics networks through which the co-authorship analysis and the longitudinal analysis of the keywords were carried out. A data sample of 15,000 registers was taken from the total research records to handle the right visualization of the clusters and the limitation regarding the default memory allocation that the software can manage.

3 Results

This section presents the bibliometric results extracted from the Core Collection of the Web of Science (WoS) of Clarivate Analytics, specifically using the Journal Citation Report as a basis, for the period 1990–2019 in the branch of knowledge related to AI.

3.1 Publication and citation trends in AI research

In the first row of Table 3, the indicator referring to the behavior of the Number of Articles is observed. The data are grouped into six five-year periods that also allow the analysis of three decades, in order to know the evolution of this field of knowledge (1990–1999;

Table 3 Production (Articles, Citations Authors, and Mean Citations and authors)

	1990–1994	1995–1999	2000–2004	2005–2009	2010–2014	2015–2019	Total
P[a]	3632	5762	8595	14,588	25,386	78,441	136,404
TCS[b]	74,895	175,709	399,874	568,057	756,118	792,040	2,766,693
AU[c]	8606	14,856	27,504	53,487	108,771	401,773	614,997
MCS[d]	20.62	30.49	46.52	38.94	29.78	10.10	20.28
MA[e]	2.37	2.58	3.20	3.67	4.28	5.12	4.51

[a]Number of Publications

[b]Total Citation Score

[c]Total number of Authors

[d]Mean Citation Score

[e]Mean Authors per Publications

2000–2009 and 2010–2019). The cumulative total numbers by five-year periods and decades indicate there is a sustained growth of the number of articles published in WoS in the field of AI in the period evaluated. When examining the cumulative data between the five-year period 1990–1994 and 2015–2019, a growth of more than 21 times was observed, which allows inferring that this branch of knowledge has grown steadily. The second row shows the Total Citation Score indicator and the behavior of the data confirms the interest in publishing more articles on AI and also the existence of an exponential increase in citations. In the third row, the indicator referring to the Total number of Authors can be seen and the data once again corroborate the constant expansion of this field of knowledge, presenting a growth of more than 46 times between the first and last five-year period. The three aforementioned numerical indicators grouped by five years and decades show the sustained progression of AI over the 30 years evaluated. By correlating these three indicators, it can be inferred that it is a subject of high scientific demand. In the fourth row, the Mean Citation Score indicator is observed and the data show a significant initial increase in the first three five-year periods for the mean number of citations, and then decrease with a less pronounced curve in the following two, until the last five-year period evaluated, where the cumulative number drops even to half of the first five-year period. This decline in recent years is attributed to the closeness regarding the time it takes to write and publish a paper and the time required to receive citations, and this behavior is a logical consequence of this scientific process. In the fifth row of the table is the indicator referring to Mean Authors per Article and the data added by five-year periods show the change in the dynamics of scientific publications referring, in this case, to the average number of co-authors participating in every published paper. The evidence shows a sustained increase in the average number of researchers and this behavior is relevant in this field of AI. The inference made regarding this indicator refers to the diversification that this branch of knowledge is having in applications to other fields of knowledge as well as to different application activities.

Figure 2 shows the behavior of the total number of articles published on AI in the WoS by year and five-year period. In the first decade, the annual data allow observing that in the years 1993 and 1996, there was a slight decrease in the total number of publications, but in general, in that period the production grew around four times when examining the extreme years (1990 and 1999). When studying the second decade, it can be seen that in 2001 and 2007, there was also a slight decrease in the production of scientific articles, but when

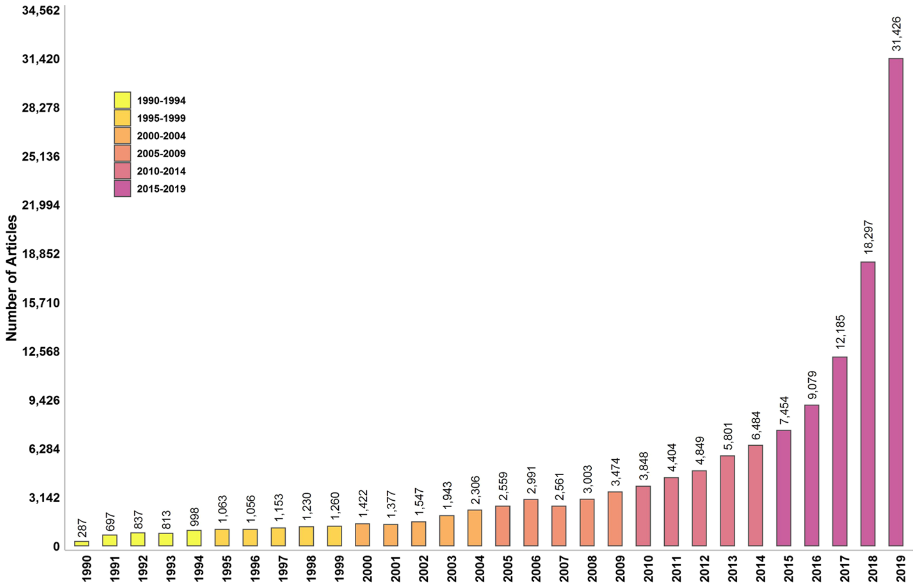

Fig. 2 Total number of articles by year

examining the extreme years (2000 and 2009), it can be seen that there was a growth close to 2.4 times. When analyzing the last decade evaluated, the behavior of the number of publications changed significantly. In all the years, there was growth and the curve increased exponentially, indicating a growth of 8.1 times between the extreme years (2010 and 2019).

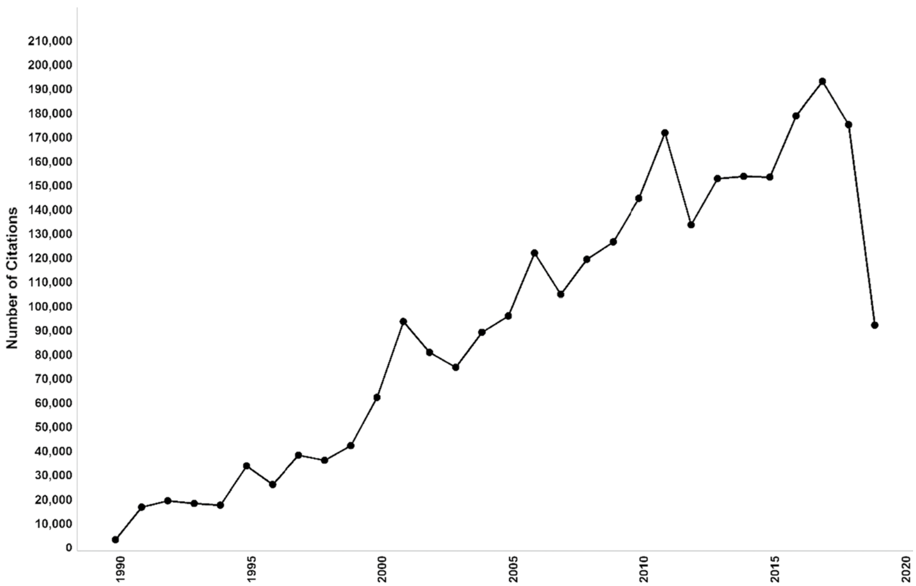

Fig. 3 Total number of citation by year

These data corroborate the sustained progression of AI, mainly in the last five years of the period evaluated.

Figure 3 shows the evolutionary line of citations per year of AI in the WoS. This type of indicator fluctuates and this behavior is considered normal since it is not directly associated with the increase in publications but with the citations made in other published works in the same database. Nevertheless, this indicator is relevant to identify patterns of behavior on a research topic. In the case of AI, a fluctuating but upward increase is observed between the years 1990 and 2017. On the contrary, in the last two years studied, the number of citations decreased significantly, especially in 2019, and this is logical due to the scientific publication process itself. When analyzing the data, it can be seen that in 1990, the total number of citations was less than 5000. By the year 2000, the total number of citations already exceeded 60,000. In 2010, they exceeded 125,000 citations and for the year 2017, the year with the highest number of citations, they exceeded 190,000 citations. This growth pattern indicates that this branch of knowledge is increasingly important in the scientific field.

Table 4 shows the 10 most cited articles in the 3 decades studied, the number of authors and the base year of each of these publications. These indicators show that there are papers with a single author and others with 2 or more of them, indicating that there is no specific behavior in terms of the number of participants in highly cited papers; In this Top 10, It is also identified that there are articles published between 1995 and 2017, which allows inferring that the oldest ones could be seminal or marker papers in a specific topic and that continue to be current. The paper with the highest citation score was written by a single author and has more than twice as many citations as the second and this in turn was written by 2 authors and has more than 5800 citations with respect to the third study; from there, the distances are closer between the other seven articles with more citations received.

3.2 Top authors, journals, institutions, and countries in AI research

Table 5 presents the ten authors with the highest scientific production related to AI in the period studied. It also shows the relationship of each one of them with their appearance as first author (corresponding author) and the total number of citations, in addition to the indicators related to the most cited articles, for which the top decile has been taken into account. In this way, the aim is to make an evaluation that is less sensitive to the biases that a high number of citations can generate in specific articles. The first two authors exceeded 500 published articles and the three that follow have more than 400 publications in the period studied, indicating an average of more than 40 papers per year, which means that they are highly productive. The relationship between published articles and being the first author is higher for the second author (WANG, Y). When examining the total number of citations received per published article, the data show that the third-largest publisher (LIU, Y) received the most references in the period evaluated, followed by the first, second, and seventh authors. This evidence shows that the position of the authors varies when examining this aspect, which indicates that the measurement of the occurrence and absolute quantity as an indicator of the level of impact on the authors are relative values. For example, it can be noted that the author with the highest proportion of articles in the top decile of the most cited is the author who, in terms of the ranking by production, is in the 10th position in absolute terms. This indicates that it is essential to select the most appropriate variable to establish the authors' positions.

Table 4 Most relevant articles per citations

Article	AU[a]	TCS[b]	YP[c]
Random forests	Breiman, L	36,256	2001
LIBSVM: A Library for Support Vector Machines	Chang, CC; Lin, CJ	17,390	2011
Scikit-learn: Machine Learning in Python	Pedregosa, F; Varoquaux, G; Gramfort, A; Michel, V; Thirion, B; Grisel, O; Blondel, M; Prettenhofer, P; Weiss, R; Dubourg, V; Vanderplas, J; Passos, A; Cournapeau, D; Brucher, M; Perrot, M; Duchesnay, E	11,810	2011
Dropout: A Simple Way to Prevent Neural Networks from Overfitting	Srivastava, N; Hinton, G; Krizhevsky, A; Sutskever, I; Salakhutdinov, R	8004	2014
An introduction to ROC analysis	Fawcett, T	7950	2006
Maximum entropy modeling of species geographic distributions	Phillips, SJ; Anderson, RP; Schapire, RE	7790	2006
Cognitive radio: Brain-empowered wireless communications	Haykin, S	7604	2005
Quantitative monitoring of gene-expression patterns with a complementary-dna microarray	Schena, M; Shalon, D; Davis, RW; Brown, PO	7087	1995
Fully Convolutional Networks for Semantic Segmentation	Shelhamer, E; Long, J; Darrell, T	6862	2017
The particle swarm—Explosion, stability, and convergence in a multidimensional complex space	Clerc, M; Kennedy, J	5551	2002

[a]Authors

[b]Total citation score

[c]Year of publication

Table 5 Most productive authors by article production (1990 – 2019)

Rank	Authors	P[a]	FAP[b]	TCS[c]	MCS[d]	P (top10%)[e]	PP (top 10%)[f]
1	ZHANG, Y	544	113	8430	15.50	52	0.10
2	WANG, Y	536	138	8330	15.54	36	0.07
3	LIU, Y	465	92	8822	18.97	48	0.10
4	WANG, J	445	118	7374	16.57	41	0.09
5	KIM, J	417	110	7291	17.48	31	0.07
6	LI, Y	391	72	6774	17.32	31	0.08
7	LI, J	386	92	8086	20.95	37	0.10
8	ZHANG, J	373	88	7378	19.78	37	0.10
9	LEE, J	358	84	4680	13.07	29	0.08
10	WANG, L	349	62	7611	21.81	37	0.11

[a]Number of publications

[b]First Author Publication

[c]Total Citation Score

[d]Mean Citation Score

[e]Number of publications in top 10%

[f]Proportion of publications in top 10%

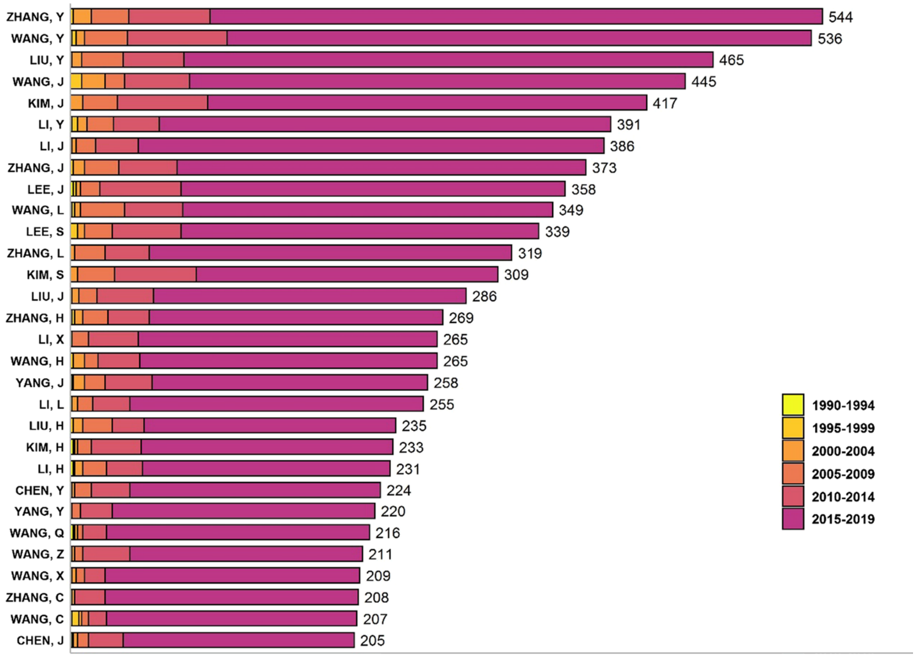

Fig. 4 Most productive authors by period

Figure 4 shows the top 30 publishers of scientific articles related to AI in the WoS in the period evaluated. The analysis is performed for five-year periods. This figure shows that all the authors have published most of their papers in the last five years and more than 80% of them are in the range of the last 10 years, which allows inferring that it is an emerging and fast-growing branch of knowledge. Likewise, it is observed that all of them have published more than 200 articles in the period considered, 17 have less than 300 publications, eight have less than 400 publications, three have less than 500 publications, and two have more than that number. This means that these first 30 researchers are highly productive. To be more specific, it was found that there is a difference between the first two publishers of only eight articles in the entire period (544 and 536). The author with the most publications in the evaluated period was ZHANG L, managing to surpass the author WHAN Y in the last 5 years because the latter was the largest publisher in the period 2010–2014. Finally, this information allows observing the sustained growth of this branch of knowledge, but the data should be interpreted relatively since there is no direct relationship between greater quantity and the potential quality or visibility of each article published in this database.

In Table 6, the institutions with the highest number of affiliated authors are identified. This indicator is established by counting only once the assignment of an article to an organization regardless of the number of co-authors participating in it. In the Top 10, there are 6 institutions from the USA and 4 from China, indicating that these 2 countries are the global leaders in investment in science and technology in AI. The Chinese Academy of Sciences appears in the first place in the table with 2469 articles associated with it, almost a 1000 more publications than the Massachusetts Institute of Technology (MIT) of the USA, but it should be clarified that the former is a national organization of the People's Republic of China that brings together several research institutes nationwide. The differences between the remaining 8 institutions listed in the table do not show significant variations in the number of publications affiliated to each of them and they are also independent units. The total number of publications assigned in the study period to institutions in the USA was 7049 and to the People's Republic of China was 5470, which indicates the dominance of the world context in terms of the generation of new scientific knowledge in this topic.

Figure 5 shows the Top 10 organizations with the highest number of publications affiliated to them, which are dominated by 6 from the USA and 4 from the People's Republic of

Table 6 Most relevant Institutions per production (1990–2019)

Institution	P[a]
Chinese Acad Sci	2469
MIT	1510
Stanford Univ	1425
Harvard Univ	1131
Tsinghua Univ	1089
Carnegie Mellon Univ	1047
Nanyang Technol Univ	979
Univ Illinois	971
Univ Michigan	965
Shanghai Jiao Tong Univ	933

The names of the institutions that appear in the Table are written as the algorithm to perform the downloads identified them

[a]Number of publications

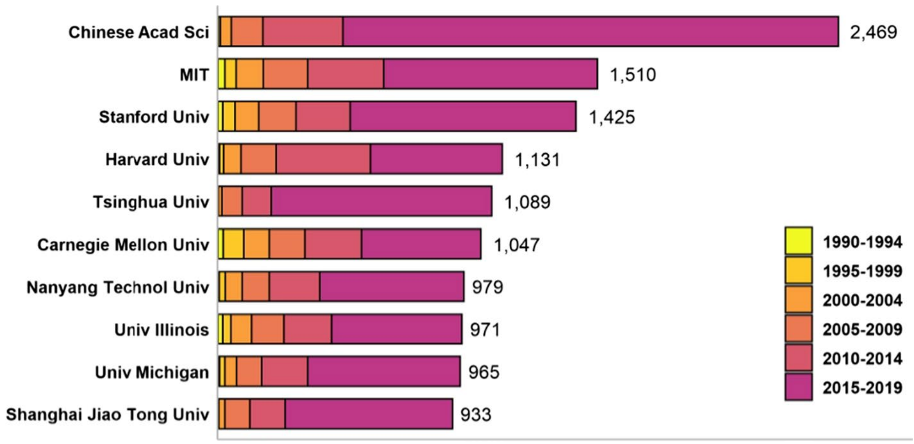

Fig. 5 Most relevant institutions per production (1990–2019) by 5 periods

China. The importance of the figure lies in the appearance of the number of publications per five-year period and the relevance in terms of the total assigned per period. This allows longitudinal measurement of the initial efforts and the evolution of each organization. An important difference between the USA and China is that, except for Harvard, the other 5 US institutions were already publishing articles in AI in the first five-year period of the 1990s (1990–1994) and this institution appears in the second five-year period (1995–1999). The only Chinese institution that appears in the same five-year period is Nanyang Technological University; the other 3 appear in the first five years of this century. An indicator of the constant growth of this topic is that in the 10 organizations the largest number of published articles appears in the last five years (2015–2019), exceeding in all cases at least 40% of the total and in other cases more than 50%.

Table 7 shows the Top 10 of the countries with the highest production of articles on AI in the WoS in the period evaluated. This group of countries is geographically located in the northern hemisphere of the planet and makes up the so-called Triad that dominates the current world economy. The table shows that the leading country in the production of articles in this branch of knowledge is the USA, almost doubling that of China, which appears in the second position. A third group identifies the remaining eight countries in the Top 10, and in this case, all with less than half the number of articles published than those published by China, but in a relatively close relationship among them. A second indicator referred to as the Percentage of Total Articles Published, which is interpreted as a relative measure of frequency in which at least one author from a given country appears, shows the USA with 30.72% and China with 17.33%. Likewise, it can then be seen that the remaining eight countries in the Top 10 appear with similar frequencies, all less than 10%, which indicates that they are at a significant distance from the two leaders. Other evaluation indicators in the table refer to the Single Country Articles and Multiple Countries Articles that allow analyzing, for example, issues such as leadership in research, since the capacities of each country to generate endogenous knowledge in this field and the need for collaboration with other countries can be deducted. In this line, the USA collaborates relatively with 35.09%, China with 37.34%, while the countries that collaborate the most with others are England with 60.65%, France with 56.45%, and Germany with 55.60%. Another indicator that allows an aggregate assessment of the production of papers in the WoS, regarding the

Table 7 Top Ten Most Productive Countries (1990 – 2019)

Rank	Country	P[a]	% of Total[b]	SCP[c]	MCP[d]	MCP (%)[e]	TCS[f]	MCS[g]	P (top 10%)[h]	PP (top 10%)[i]
1	USA	41,910	30.72%	27,202	14,708	35.09%	1,220,556	29.12	5977	0.14
2	China	23,641	17.33%	14,813	8828	37.34%	346,393	14.65	1693	0.07
3	England	10,019	7.35%	3942	6077	60.65%	244,113	24.37	1170	0.12
4	Germany	8093	5.93%	3593	4500	55.60%	201,956	24.95	986	0.12
5	Italy	6745	4.94%	3463	3282	48.66%	129,847	19.25	667	0.10
6	Canada	6586	4.83%	3185	3401	51.64%	162,534	24.68	701	0.11
7	Spain	6388	4.68%	3596	2792	43.71%	100,579	15.74	482	0.08
8	Korea	5823	4.27%	3936	1887	32.41%	86,528	14.86	454	0.08
9	Japan	5688	4.17%	3699	1989	34.97%	101,049	17.77	415	0.07
10	France	5428	3.98%	2364	3064	56.45%	146,936	27.07	608	0.11

[a]Number of publications

[b]Percentage of total publications

[c]Single country publications

[d]Multiple countries publications

[e]Percentage of multiple countries publications

[f]Total citation score

[g]Mean citation score

[h]Number of publications in top 10%

[i]Proportion of publications in top 10%

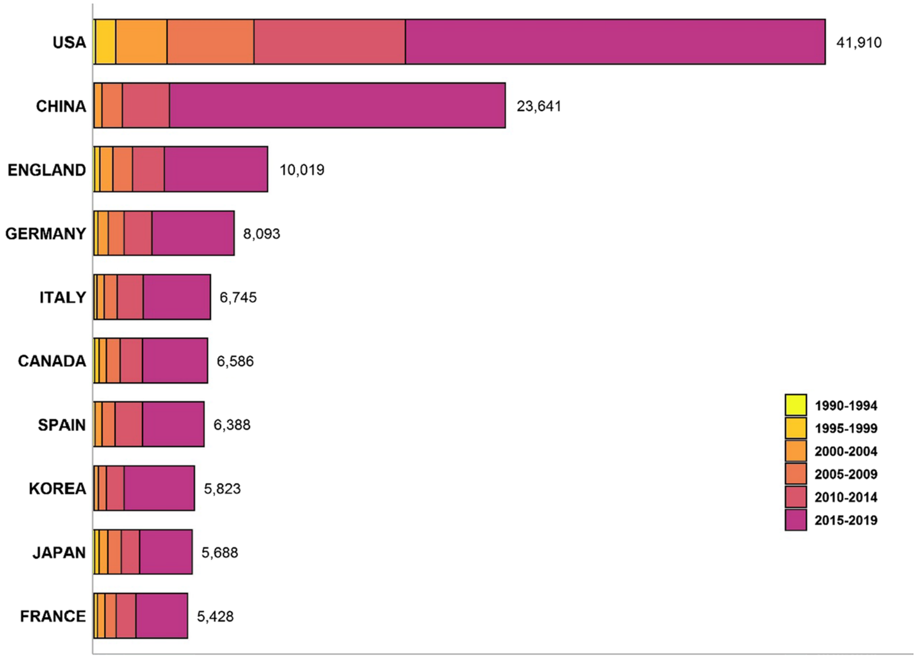

Fig. 6 Articles by countries

most cited articles, is the one referring to the upper decile, PP (top 10%), which, in this case, indicates that the USA has produced the highest proportion of articles in this decile and, on the contrary, China has the second-lowest proportion of articles in this segment. The growth observed in the number of articles from this group of countries cannot be interpreted as a competition but understood as a process in which funds are invested and more researchers are trained to generate new knowledge in this emerging field.

Figure 6 shows the Top 10 countries that have published the most articles on AI in the WoS in the 30 years studied. By having the data aggregated by five-year periods, the analysis can also be scaled to decades to understand the behavior of each country. First, it is observed that the Top 10 have published more articles in the last five years. In fact, China produced more than 70% of all its production in the last five years, almost equaling that of the USA. This marks a growth trend that suggests that, in the short term, China will lead the production of knowledge in this field. These two countries lead world production by a wide margin with respect to the other eight registered in the Top 10. It can be indicated that there are two groups, the first two, and the rest. One aspect that stands out in the figure, referring to the eight followers, is that they all show sustained growth every year. This group of eight countries makes up the second world force of intellectual production in AI.

Table 8 is composed of nine indicators that are contrasted with six five-year periods and its purpose is to show the longitudinal trajectory of each country; it is divided into five sections and each of them presents two countries from the Top 10. This first table shows the USA and China and in Appendix A, the other 4 tables with the other 8 countries with the most publications in AI in WoS are appended. When examining the number of publications per country, the USA appears as the largest producer in the overall total, but the growth trend indicates that China will be the leader in this field of knowledge in the next five years.

Table 8 Most productive countries by year

	1990–1994	1995–1999	2000–2004	2005–2009	2010–2014	2015–2019
USA						
P[a]	153	1169	2930	4990	8660	24,008
% of Total[b]	4.21%	20.29%	34.09%	34.21%	34.11%	30.61%
SCP[c]	140	963	2272	3786	6018	14,023
MCP[d]	13	206	658	1204	2642	9985
MCP (%)[e]	8.50%	17.62%	22.46%	24.13%	30.51%	41.59%
TCS[f]	6502	60,760	238,067	263,668	333,991	317,568
MCS[g]	42.50	51.98	81.25	52.84	38.57	13.23
P (top 10%)[h]	31	191	462	679	1087	2776
PP (top 10%)[i]	0.20	0.16	0.16	0.14	0.13	0.12
China						
P[a]	16	77	436	1180	2683	19,249
% of Total[b]	0.44%	1.34%	5.07%	8.09%	10.57%	24.54%
SCP[c]	15	50	287	800	1686	11,975
MCP[d]	1	27	149	380	997	7,274
MCP (%)[e]	6.25%	35.06%	34.17%	32.20%	37.16%	37.79%
TCS[f]	66	1,688	17,845	47,114	74,931	204,749
MCS[g]	4.12	21.92	40.93	39.93	27.93	10.64
P (top 10%)[h]	0	8	42	110	219	1,870
PP (top 10%)[i]	0.00	0.10	0.10	0.09	0.08	0.10

[a]Number of publications

[b]Percentage of Total Publications

[c]Single Country Publications

[d]Multiple Countries Publications

[e]Percentage of Multiple Countries Publications

[f]Total Citation Score

[g]Mean Citation Score

[h]Number of Publications in top 10%

[i]Proportion of Publications in top 10%

By evaluating the total production of the ten countries examined, it was found that in the last five years, the growth of this group of countries was exponential. When studying the percentage of publications of each country in the last five years, taking this indicator as a relative measure, it was observed that the USA and China outstandingly lead the world; the rest of the 10 countries in the Top 10 make up a second group, quite homogeneous among themselves, which represents the other large percentage of the world. When examining the indicators that allow comparing articles from a single country and articles from several countries for the Top 10, it can be seen that, on the one hand, except for Korea, the other nine countries significantly increased their collaboration with third parties over the period. On the other hand, when looking at the relative percentage values in the last five-year period studied, Korea is the country that collaborated the least with other countries with 33.3% and England was the one that collaborated the most with 70.9%. With the analysis of the variable referring to the average number of citations per article in the last five-year period, it was found that the United States was once again number one with 13.23, but the second country was England with 13.05; in this indicator, China dropped to the sixth position with 10.64, leaving Japan in the last position of the Top 10 with 8.37. These indicators show development gaps between the Top 2 and the rest of the Top 10, but when comparing this group of countries leading the field of Artificial Intelligence with the rest of the world, the differences are insurmountable and generate a high dependence on this type of knowledge.

Figure 7 represents a network diagram that allows analyzing the relationships between the countries with the highest number of collaborations in terms of scientific production on AI in the WoS during the period studied. The density of each sphere is explained by the relative importance of each country and refers to the number of authors who publish with affiliation to institutions in each one of them. The figure shows three well-defined clusters, although these are not the only ones. The proximity between the spheres in each cluster establishes the number of co-authorships and is measured by the thickness of the lines connecting them. The country with the greatest density in the diagram is the USA, and it is the epicenter of the red cluster, which is made up of China, Canada, Japan, and South Korea, among others, and these five countries are part of the Top 10 examined in Table 8 and Appendix A. The second cluster in order of relevance is the green one and is composed of

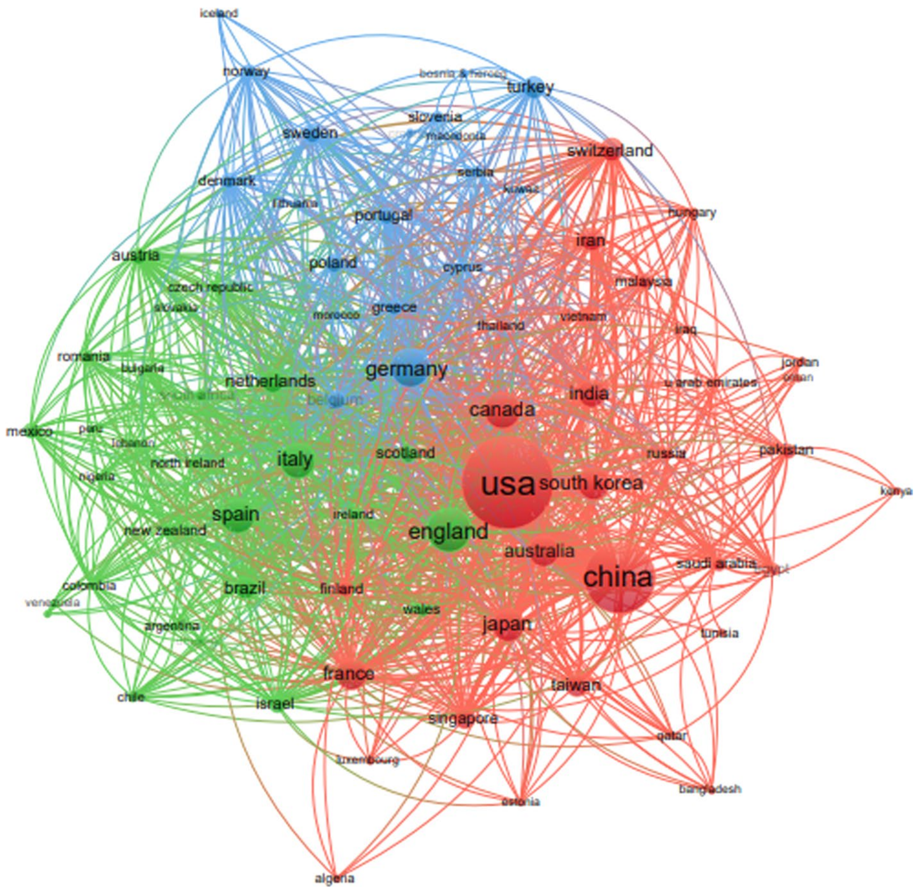

Fig. 7 Collaboration by clusters of countries

England, Italy, France, and Spain, among others, and these four countries are also part of the aforementioned Top 10. The third cluster in order of relevance in the diagram is blue and is led by Germany, the last of the Top 10 countries. This country appears in a central and equidistant position with respect to the other two clusters.

3.3 Major themes in AI research

Table 9 presents the Top 10 journals in which the most publications on the topic related to AI have appeared in the WoS in the 30 years studied. This table allows identifying the journals that belong to publishing platforms that offer fast publication services for a fee, which ensures an initial response in a maximum of six weeks, through the double-blind arbitration process. This Fast Review system that appeared in 2013 has changed the rules of the scientific game in terms of response time. Among them is IEEE ACCESS, which has the highest number of total articles, almost doubling the second one, which also belongs to a similar platform. The data in the table are affected by the percentage of total articles published on these new platforms, mainly in the last five years. On the other hand, when examining the correlation that allows observing the impact factor, by contrasting the indicator of the number of total citations in this Top 10 of Journals with the total number of published articles, IEEE drops from first to seventh place and the International Journal of Robotics Research placed in ninth place in the table, and created in 1982, moved to first place in this important line. This journal appears with 0.32 in the top decile indicator registered by the PP indicator (Top 10%), being significantly different from the other Top 9.

Figure 8 shows the first 30 journals measured by the number of articles published related to AI in the period evaluated. It can be seen that IEEE ACCESS occupies the first

Table 9 Journals (Most Relevant Sources by Production)

Rank	Source	P[a]	% of Total[b]	TCS[c]	MCS[d]	P (top 10%)[e]	PP (top 10%)[f]
1	IEEE access	2,941	2.16%	12,876	4.38	32	0.01
2	Expert systems with applications	1,544	1.13%	37,660	24.39	243	0.16
3	Sensors	1,484	1.09%	12,750	8.59	40	0.03
4	Plos One	1,440	1.06%	20,632	14.33	103	0.07
5	Neurocomputing	1,284	0.94%	21,814	16.99	110	0.09
6	Scientific reports	988	0.72%	11,982	12.13	57	0.06
7	Robotics and autonomous systems	956	0.70%	20,961	21.93	116	0.12
8	Advanced robotics	870	0.64%	10,289	11.83	48	0.06
9	International journal of robotics research	801	0.59%	39,542	49.37	259	0.32
10	BMC bioinformatics	795	0.58%	15,242	19.17	94	0.12

[a]Number of publications

[b]Percentage of Total Publications

[c]Total Citation Score

[d]Mean Citation Score

[e]Number of publications in top 10%

[f]Proportion of publications in top 10%

place, almost doubling in number the second. What is relevant about this data is that most papers were published in the last five years, which allows inferring that it is a fast-growing platform of high importance for researchers, even within the WoS database. This is significant because to climb rapidly up the quartile, it is necessary to receive many citations and meet all the Clarivate Analytics criteria. Of the 30 journals identified in the figure, there are seven that do not appear registered in the WoS before 2010 and this allows inferring that the ramification of new disciplines in the field of AI has produced an expansion in several science activities, one of them, new journals.

Table 10 presents 10 categories used by the WoS database as general descriptors that allow specialized searches in this database. The purpose of this exercise was to link these descriptors to AI in the period evaluated to find relationships with the Keywords and with the Journals, since they connect topics and disciplines. When observing the trajectories of each Category by five-year period, it can be seen that they have been changing over time. For example, Category number 1 in the final total (COMPUTER SCIENCE, AI) was the first in all five-year periods, except in the period 2015—2019. For its part, the second Category in the final total of publications (ENGINEERING, ELECTRICAL & ELECTRONIC) has been ranked second, third, or first in the different five-year periods evaluated. A revealing fact about the growth of topics related to AI is that the categories have grown in all the periods evaluated except for COMPUTER SCIENCE, INFORMATION SYSTEMS in the five-year period 1994–1999. When comparing the 10 categories taking into account the base five-year period (1990–1994) with the final five-year period (2015–2019), It is found that, in the least of cases, the growth was eight times greater and this confirms the constant expansion of the research activity around AI.

3.4 Directions researchers should pursue to advance AI research

Table 11 shows the Top 10 keywords linked to AI and this term is one more descriptor. The data in the table are grouped by five-year periods to segment the 30 years studied. This type of analysis of keywords is relevant because it allows determining the ramifications of a topic, the time of appearance, and the evolution of each descriptor. The table

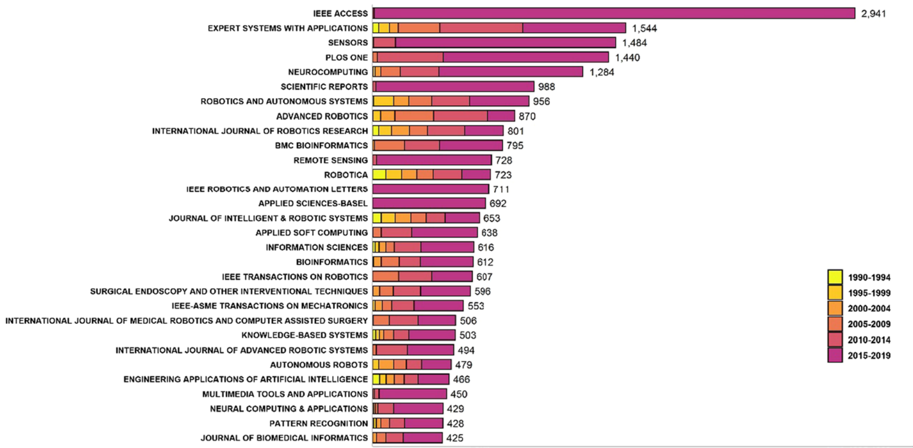

Fig. 8 Total number of top journals

Table 10 Most relevant categories (Web of Science)

Rank	Category	1990–1994	1995–1999	2000–2004	2005–2009	2010–2014	2015–2019	Total
1	Computer science, artificial intelligence	652	1614	2694	3793	4665	10,486	23,904
2	Engineering, electrical & electronic	583	849	946	1588	3146	13,788	20,900
3	Computer science, information systems	374	342	740	1064	1555	8070	12,145
4	Robotics	358	888	1181	1646	2528	4286	10,887
5	Computer science, interdisciplinary applications	400	488	668	1182	2069	5354	10,161
6	Automation & control systems	369	810	871	1103	1629	3352	8134
7	Computer science, theory & methods	350	535	1127	1255	897	3105	7269
8	Telecommunications	27	48	71	153	379	5114	5792
9	Surgery	19	93	364	610	1512	3110	5708
10	Computer science, software engineering	191	228	358	501	836	2743	4857

shows that in the first decade, AI was the term with the highest number of appearances, followed by Robotics and Machine Learning. In the second decade studied, Machine Learning moved to first place and Robotics to second place, displacing AI to third place. For the last decade examined, the patterns changed again, leaving Machine Learning as the number one descriptor, but Deep Learning quickly emerged to position itself as the second term, leaving AI in third place. The rest of the terms in the Top 10 grew steadily but at different rates, all of them being the core related to AI and considered as ramifications of new fields of knowledge.

Figure 9 allows studying not only the number of occurrences of the keywords but also the order of appearance of the terms related to AI and this analysis of co-words helps to identify conceptual structures and topics. In the figure, it is observed that Machine Learning is the most frequent term with 17,624 occurrences, doubling Deep Learning and tripling AI itself and Robotics as the two terms that follow it with the most occurrences. The difference between them is that Deep Learning is a new branch of knowledge that emerged abruptly in the last five years and it is placed as the one with the greatest growth potential. Another aspect that stands out in the figure is that most of the terms appear from 2010 onwards, but the growth curves increase substantially in the last five years, except for Genetic Algorithms, which maintains a similar average number of appearances in the six five-year periods examined.

From the network diagram shown in Fig. 10, it can be seen how each of the key terms that are part of the study are related. The proximity between the spheres establishes the number of co-occurrences, measured by the thickness of the lines connecting them. In Fig. 10, three clusters related to broad subjects are visible. The red cluster is more related to the development of theoretical knowledge, the green cluster is associated with more applied topics and the light blue cluster is more related to medical topics. The largest of the three clusters incorporates Machine Learning as the most relevant keyword, followed by Deep Learning and AI, all closely related. In the second cluster, Robotics is the keyword with the highest density, followed by Design and other topics such as Calibration, sensors, or Locomotion, demonstrating the level of technological applicability and the greater co-occurrence between them. The third cluster is represented by keywords such as Cancer, Surgery, Mortality, or Surgical Robotics, presenting specific characteristics of topics associated with developments linked to AI.

Figure 11 represents a term density map that allows performing another evaluation of the keywords most used by scientists in research associated with AI in the period evaluated. The density of each term shows the Ranking in which the importance of each one and its position regarding the centrality and density of the clusters represented are identified. The most relevant group of co-words is formed by Machine Learning, Deep Learning, and AI which, in addition, in Fig. 10, it can be seen that they are in the same cluster and this is measured by the co-occurrence between the terms. In order of importance, due to the density reflected in the map, Robotics and Design appear and belong to the second cluster and then, Cancer and Surgery are identified as the other most relevant terms and are in the third cluster. This term density map confirms the previous analysis of Figs. 9 and 10, with a different view of the results.

Table 11 Most relevant keywords

Rank	Keyword	1990–1994	1995–1999	2000–2004	2005–2009	2010–2014	2015–2019	Total
1	Machine learning	112	320	521	1133	2534	13,004	17,624
2	Deep learning	0	5	3	19	76	7797	7900
3	Artificial intelligence	426	505	450	576	834	2671	5462
4	Robotics	190	377	518	952	1322	1573	4932
5	Classification	17	32	86	285	467	1553	2440
6	Natural language processing	37	75	120	209	445	1354	2240
7	Neural networks	72	199	204	281	293	975	2024
8	Robotic surgery	0	4	47	171	543	939	1704
9	Evolutionary computation	1	59	142	320	446	614	1582
10	Data mining	1	26	122	225	358	774	1506

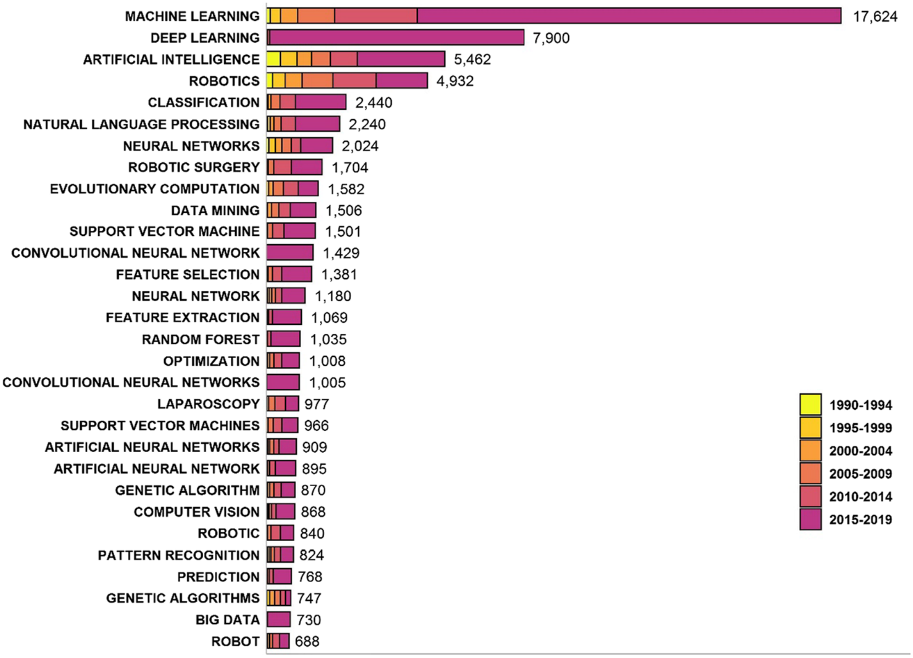

Fig. 9 Number of keywords by period

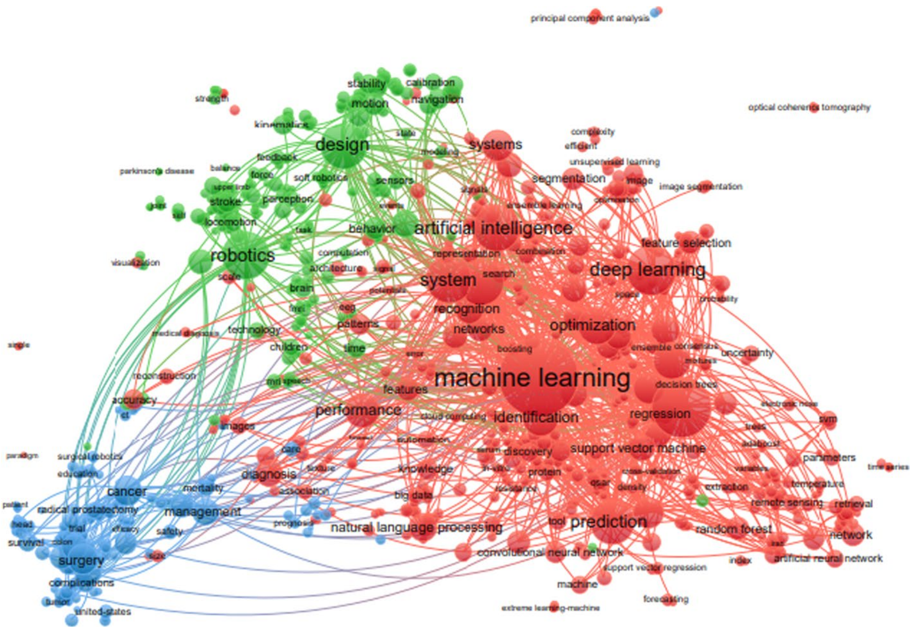

Fig. 10 Longitudinal Cluster of Keywords

Fig. 11 Density Term Map of Keywords

4 Discussion

The bibliometric mapping carried out in the period 1990–2019 on the branch of knowledge of AI showed its relevance as a research topic, its sustained growth, and its branching out into new specialties that are acquiring their own activity.

When analyzing the overall volume of the production of AI-related scientific articles published in WoS and the citations received by each of them, the data contained in Tables 3 and 4, and Figs. 2 and 3 showed a sustained growth throughout the period evaluated. A relevant point is that, in the last four years, the line of increase became exponential. When specifically examining the number of citations per year, the evidence showed that this indicator remained in a strip with high bands throughout the entire period, which allows inferring the topic relevance. However, in 2019, the line decreased, due to the closeness of the publications and, therefore, this behavior is considered within the logic of this type of bibliometric analyses.

When examining the most productive authors and countries in the subject of AI in the three decades evaluated, the data in Tables 4, 5, and 6 and Figs. 4, 5, and 6 show that there is a sustained growth in which new authors appear; there is also evidence of a high production of articles concentrated in a group of authors and this is detected, mainly, between 2015 and 2019. A pattern identified in the last two five-year periods is the relationship between authors, institutions, countries and types of journals where, in greater proportion, published in WoS. The countries with more publications have different policies, strategies, programs and instruments to support this activity; however, when analyzing the countries with the highest scientific production in the field of AI, the question allows relating Table 6 and 7 and it is included Annex A and Figs. 5, 6, and 7, from which data are extracted that provide information to identify a total of three subgroups of countries within the Top 10. The first is formed by the Top 2, consisting of the USA and China; these two countries contribute for 30.72% and 17.33%, respectively, of the total number of publications worldwide. The second group of countries is made up of the set of eight countries as the world's second productive force in a range of less than 4% among them, in terms of their relative percentage of world production. The third group includes the rest of the world. The data allow establishing that the first 10 dominate the generation of new knowledge in this branch and this fact creates a differential factor between development and underdevelopment and, therefore, widens the gaps in strategic scientific and technological areas.

When analyzing the AI-related categories of Journals and WoS, Tables 9 and 10 and Fig. 8 allow identifying the central themes associated with these branches of knowledge according to this database. The relationship between these categories is analyzed as it is possible to identify the most relevant associated topics. In this case, Computer Science and Electrical and Electronic Engineering are identified as current topics in research, but new branches of knowledge such as Machine Learning and Deep Learning also emerge, and given their growth, it can be stated that they have already acquired autonomous properties. When answering the question about the challenges that AI will face in the coming years, it is found that this multidisciplinary branch of knowledge is certainly generating disruptions on a global scale, impacting the entire business ecosystem but also transforming people's lives. Its impact is associated with all areas of development, which indicates that it is not a branch exclusive to computer science or mathematics; in fact, it is reflected in topics such as clean energy (climate change improvement), agriculture, education, medicine, new businesses, social networks, human talent management, among others, and all at exponential scalability levels. The inference made from the bibliometric results obtained in this study, together with the impact that AI is generating, indicates that its future will be related to the greatest technological changes seen so far, causing direct impacts on the life and functioning of planet Earth. Moreover, its potential is still largely unknown and therein lies the importance of these studies. The dynamics have been changing due to the emergence and use of publishers with platforms that support the use of rapid article reviews. Table 9 and Fig. 8 identify the two platforms on which the most articles were published in the last five years, and both are fast review platforms. This allows inferring that most of the articles published were done through these platforms, which are connected to a group of the top journals in this database.

Finally, the descriptors that constitute a relevant part of the bibliometric techniques are examined, as they allow revising different facets of a specific topic. The data in Table 11 and Figs. 9, 10, and 11 allowed establishing that there are ten keywords with the highest number of appearances in WoS throughout the period evaluated. The term Machine Learning stands out with more than twice as many occurrences as the second term, Deep Learning, followed by AI, these being the three most relevant descriptors. In a second block appear Robotics, Classification, Natural Language Processing and Neural Networks, which have appeared mainly in the last ten and five years. In the last block of the ten most relevant keywords, Robotic Surgery, Evolutionary Computing and Data Mining appear, indicating that they are important topics associated with the central theme of study. The clusters identified in the figures allow observing three groups that interact around broad topics oriented to basic and applied sciences and medicine, and it is in these areas where the most knowledge is being generated in this field.

This work demonstrated the relevance of AI, its ramifications and the neuralgic points where it is operating with the greatest demand for knowledge.

5 Conclusions

The bibliometric mapping carried out in the WoS in the period 1990–2019 showed that the scientific production in the branch of knowledge identified as AI is concentrated in ten countries that are located in the northern hemisphere of the world (North America, Asia, and Europe).

The study identified the USA and China as the two great leaders in the generation of scientific knowledge in the aforementioned branch. There is a second group of eight countries with similar capacities among them that can be called the followers, which concentrate the other large percentage of knowledge production on this subject. This means that there are asymmetries in the world, in terms of the distribution of the world production of knowledge and, consequently, this translates into gaps that mark insurmountable differences in the mastery of a key scientific activity such as AI.

A relevant finding identified in the study when longitudinally examining the data on AI is that China has been growing in recent years at a faster rate than the USA in terms of scientific production in the WoS. The projection indicates that in a few years, it will become the world leader. This is corroborated by identifying the affiliation of the most prolific authors in recent years.

Another finding identified in the study refers to the high number of publications in Fast Review platforms that contain groups of important journals in terms of number and impact factor. This can be considered as a strategy of these countries to position themselves in the first places in a short time and they have achieved it. However, this requires the construction of a sophisticated socio-technical fabric that demands substantial funds to invest not only in personnel but also in infrastructure, equipment, supplies, new doctoral courses, creation and consolidation of scientific events, among other aspects, that will guarantee them greater productivity in the medium term.

The ten most productive countries in terms of scientific production in the branch of knowledge referred to in the study present different collaborative strategies. For example, the USA and China collaborate more with their national peers, while countries such as England, France, and Germany do so more than 50% with colleagues from other countries. It can be inferred from the study data that the difference may be associated with the capabilities of one or the other.

Finally, this study identified emerging specialties that are creating their own capabilities and becoming autonomous. For future studies, it is recommended to conduct specific research on topics such as:

- Machine Learning
- Deep Learning (which includes topics such as neural networks),
- Robotics
- Natural Language Processing

This study shows that these 4 fields are acquiring relevant autonomous properties and for that reason, they are proposed as new fields of study independently. Another area that can be explored and contrasted with the scientific one is related to patent production.

Appendix A

See Table 12.

Table 12 Most productive countries by year (continued)

Most productive countries						
	1990–1994	1995–1999	2000–2004	2005–2009	2010–2014	2015–2019
England						
P[1]	102	314	748	1131	1815	5909
% of Total[2]	2.81%	5.45%	8.70%	7.75%	7.15%	7.53%
SCP[3]	79	242	528	630	746	1717
MCP[4]	23	72	220	501	1069	4192
MCP (%)[5]	22.55%	22.93%	29.41%	44.30%	58.90%	70.94%
TCS[6]	1907	10,058	30,654	44,460	79,937	77,097
MCS[7]	18.70	32.03	40.98	39.31	44.04	13.05
P (top 10%)[8]	12	38	68	107	202	630
PP (top 10%)[9]	0.12	0.12	0.09	0.09	0.11	0.11
Germany						
P[a]	66	235	583	917	1,588	4,704
% of Total[b]	1.82%	4.08%	6.78%	6.29%	6.26%	6.00%
SCP[c]	46	173	371	511	716	1,776
MCP[d]	20	62	212	406	872	2,928
MCP (%)[e]	30.30%	26.38%	36.36%	44.27%	54.91%	62.24%
TCS[f]	1012	7015	21,240	41,161	71,150	60,378
MCS[g]	15.33	29.85	36.43	44.89	44.80	12.84
P (top 10%)[h]	6	20	45	112	195	524
PP (top 10%)[i]	0.09	0.09	0.08	0.12	0.12	0.11
Italy						
P[1]	61	183	409	741	1490	3861
% of Total[2]	1.68%	3.18%	4.76%	5.08%	5.87%	4.92%
SCP[3]	49	142	280	486	756	1750
MCP[4]	12	41	129	255	734	2111
MCP (%)[5]	19.67%	22.40%	31.54%	34.41%	49.26%	54.67%
TCS[6]	1080	3992	13,508	25,820	45,888	39,559
MCS[7]	17.70	21.81	33.03	34.84	30.80	10.25
P (top 10%)[8]	4	16	33	73	147	365
PP (top 10%)[9]	0.07	0.09	0.08	0.10	0.10	0.09
Canada						
P[1]	105	246	422	810	1265	3738
% of Total[2]	2.89%	4.27%	4.91%	5.55%	4.98%	4.77%
SCP[3]	78	173	261	483	669	1,521
MCP[4]	27	73	161	327	596	2,217
MCP (%)[5]	25.71%	29.67%	38.15%	40.37%	47.11%	59.31%
TCS[6]	2224	7329	19,038	40,291	49,563	44,089
MCS[7]	21.18	29.79	45.11	49.74	39.18	11.79
P (top 10%)[8]	11	18	45	78	127	365
PP (top 10%)[9]	0.10	0.07	0.11	0.10	0.10	0.10
Spain						
P[a]	16	116	404	745	1565	3542
% of Total[b]	0.44%	2.01%	4.70%	5.11%	6.16%	4.52%
SCP[c]	13	93	304	529	986	1671

Table 12 (continued)

MCP[d]	3	23	100	216	579	1871
MCP (%)[e]	18.75%	19.83%	24.75%	28.99%	37.00%	52.82%
TCS[f]	157	1882	7903	19,253	38,771	32,613
MCS[g]	9.81	16.22	19.56	25.84	24.77	9.21
P (top 10%)[h]	1	5	14	42	109	247
PP (top 10%)[i]	0.06	0.04	0.03	0.06	0.07	0.07
Korea						
P[a]	9	80	225	456	1027	4026
% of Total[b]	0.25%	1.39%	2.62%	3.13%	4.05%	5.13%
SCP[c]	5	57	174	328	683	2689
MCP[d]	4	23	51	128	344	1337
MCP (%)[e]	44.44%	28.75%	22.67%	28.07%	33.50%	33.21%
TCS[f]	89	1886	5,829	12,984	28,002	37,738
MCS[g]	9.89	23.57	25.91	28.47	27.27	9.37
P (top 10%)[h]	0	7	12	34	92	318
PP (top 10%)[i]	0.00	0.09	0.05	0.07	0.09	0.08
Japan						
P[a]	111	248	509	761	1066	2993
% of Total[b]	3.06%	4.30%	5.92%	5.22%	4.20%	3.82%
SCP[c]	96	194	393	533	705	1778
MCP[d]	15	54	116	228	361	1215
MCP (%)[e]	13.51%	21.77%	22.79%	29.96%	33.86%	40.59%
TCS[f]	1386	5827	16,531	20,444	31,816	25,045
MCS[g]	12.49	23.50	32.48	26.86	29.85	8.37
P (top 10%)[h]	6	26	39	37	60	213
PP (top 10%)[i]	0.05	0.10	0.08	0.05	0.06	0.07
France						
P[a]	75	191	438	636	1127	2961
% of Total[b]	2.06%	3.31%	5.10%	4.36%	4.44%	3.77%
SCP[c]	57	133	298	327	521	1028
MCP[d]	18	58	140	309	606	1933
MCP (%)[e]	24.00%	30.37%	31.96%	48.58%	53.77%	65.28%
TCS[f]	1494	7535	21,108	28,344	53,315	35,140
MCS[g]	19.92	39.45	48.19	44.57	47.31	11.87
P (top 10%)[h]	4	20	39	66	107	305
PP (top 10%)[i]	0.05	0.10	0.09	0.10	0.09	0.10

[a]Number of publications

[b]Percentage of Total Publications

[c]Single Country Publications

[d]Multiple Countries Publications

[e]Percentage of Multiple Countries Publications

[f]Total Citation Score

[g]Mean Citation Score

[h]Number of Publications in top 10%

[i]Proportion of Publications in top 10%

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