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Bibliometric Analysis of Fuzzy Logic Research in International Scientific Databases

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Abstract

The purpose of this study is to explore the Web of Science Database (WOS) and review the significant contributions to the research of Fuzzy Logic or Fuzzy Sets theory from the beginning to the present. This study analyzes the most eminent authors, institutions, countries, and journals in Fuzzy Logic research by applying science mapping methods and bibliometric measures. Also, we paid attention to link strength and h-index to represent the visibility, influence, and link between the representative authors. Moreover, we added descriptive statistics to highlight strong linearity and a connection between fuzzy publications and Fuzzy Logic research. Also, we applied regression analyses and prevision functions to predict the evolution of the Fuzzy Logic topic.

The results showed a significant increase in the number of papers published annually in a portfolio of internationally representative journals. This leads us to the idea that Fuzzy Logic research is now a transdisciplinary topic that continually develops. Therefore, it can be found in more and more related areas such as artificial intelligence, IoT, medicine, economics, or the environment. Most of the results are consistent with other bibliometric studies. Still, some results are different, results related to the current cited works that show a polarization in the Asia area and the top journals that is continuously changing depending on the number of papers and the quotations of scientific personalities that publish. We used the VOS Viewer software to map the main trends in the field. The results indicate that the use of concepts has long exceeded traditional boundaries.

Keywords: Fuzzy Logic, Fuzzy Sets, bibliometrics analysis, WOS, VOS viewer.

1 Introduction

The development of ICT and the Internet has led to the expansion of Fuzzy Logic or Fuzzy Sets theory concepts and the definition of derivative concepts used in solving any medium and high complexity problem that underlies the simulation process for decision making [2]. The Research on Fuzzy Logic and Fuzzy Sets was initiated in 1965 by Zadeh LA, who has analyzed Fuzzy Sets' concept from classical Boolean sets to multi-valued logic [33].

Fuzzy logic is a generalization of standard logic, in which a concept can possess a degree of truth anywhere between 0 (null) and 1 (truth) by using real numbers [39]. Fuzzy Sets theory allows the gradual assessment of the elements of belonging to a set. This is described using a member function evaluated in the real numbers range [0,1], [5], [7]. For Fuzzy Sets, it was necessary to define the elementary operations. It was proposed to use the complement 1 for negation, the Max operator for reunification, and the Min operator for intersection [38]. Then fuzzy numbers, operations with fuzzy numbers [1], fuzzy intervals, and relationships between fuzzy quantities were defined [9], [37].

If in 1990 only 7% of the documents identified as being in the fuzzy field had the Fuzzy Logical topic, after 1991, interest in Fuzzy Logic research increased significantly, reaching more than 40% of published works. The number of citations of these works has also increased exponentially. The fuzzy set theory can be used in a wide range of domains in which information is incomplete or imprecise, such as computer science, engineering, automation systems, mathematics, energy fuels, telecommunication, economics, medicine, and others [4], [12], [18]. The 1980s marked the first attempts at theoretical substantiation and practical development of Fuzzy Rule systems, based on fuzzy data sets, combined with fuzzy learning [24]. This study's motivation is determined by the size of multidisciplinary research involving Fuzzy Logic, the relevant factors that lead to such research in more and more fields. This motivation led us to analyze the Fuzzy Logic area from a bibliometric perspective and estimate its future evolution using statistical functions.

Within the multiple theoretical and practical developments, Fuzzy Sets or Fuzzy Logic stands out as a field of study of decision making. The survey on Fuzzy Sets or Fuzzy Logic also involves the analysis of derivative concepts mentioned in other studies, among which the most representative are: fuzzy algorithms [34], fuzzy environments [2], fuzzy numbers [1], fuzzy systems [26], [36] fuzzy parameters [10], fuzzy semantics [35], fuzzy linear programming [22], [25], [30] or fuzzy decision systems [2], [24]. In many applications, fuzzy numbers and Fuzzy Sets can be used equally, although presentations with fuzzy numbers are more straightforward. For general studies and facilitating Fuzzy Logic, fuzzy set theory is a very suitable tool [38].

This study provides a broad picture of Fuzzy Sets or Fuzzy Logic's implications at a keyword level. It assesses its expansion in multiple areas based on a systematic literature review and bibliometric analysis. In particular, the research focuses on the study of the most influential authors, starting from Zadeh as a promoter of these concepts [33], organizations, and countries, and investigating specialized journals and research publications that offer fuzzy keywords.

The paper is based on the quantitative analysis of published articles included in their title or topics, Fuzzy Logic as a keyword. Bibliometrics indicators analyze the patterns that appear in the publication and communication of documents. It allows us to assess the impact or influence, in quality or performance, of scientific publications by using a bibliometric indicator [19]. These indicators will enable us to analyze publications, quotes, and sources of information that include articles, journals, authors, institutions, and countries using a PRISMA(Preferred Reporting Items for Systematic reviews and Meta-Analyses) Statements line of investigation [20] and the WOS database. VOS viewer software is used to map the results and analyze the research structure [6], [28]. This software allows us to display information related to the co-author, bibliographic coupling, and co-citations in a bibliometric map [27].

To study Fuzzy Logic research's size globally, we analyzed the WOS database that provides information on scientific works since 1975. Thus, this database allows us to evaluate over 45 years in which numerous scientific personalities have published works in the field of fuzzy research. The first ten years of fuzzy research (1965 – 1975) are globally found in the WOS database as reference papers, cited by most authors [18]. The scientific approach for the last 45 years (1975-2020) is affected by WOS database size, even though it's a reference in international scientific research. It has certain

limits, such as the small number of books published in the field and some researchers' low interest to publish at the database level, such as French or African researchers [14].

In today's literature, there are various bibliometric studies concerning Fuzzy Logic research. A group of authors made an overview of fuzzy research [12], [18]. Some authors have conducted timely research on the use of concepts that highlight the use of fuzzy [3], [31] or have performed bibliometric analysis for a specified period [14], [15]. Other authors have developed bibliometric studies of the associated concepts at the level of scientific papers published in a particular journal [13], [29], or the analysis of research in a specific country [16], [32].

The study's main objective is to support academics and researchers to obtain a quick and insightful overview of research on Fuzzy Sets or Fuzzy Logic. The paper is organized as follows - section 2. Research Methodology - describes the methodology and data collection process - section 3. Results - presents results obtained by referring to different criteria based on the investigation methods. After that, in Section 4, we present concluding remarks and summarized the conducted study.

2 Research Methodology

The investigation method for conducting the research follows the PRISMA Statements methodology structured in five steps [21]: (1) data search strategy, (2) data collection, (3) data screening and data filtering, (4) quantitative analysis, and (5) interpretation (Figure 1). Bibliometric research includes a set of measurements based on graphical representations and statistical tables used to present the current state and development potential for future research. For data collection, filtering models were applied to present the works, authors, organizations, countries, and journals in the field. The main elements that form the network of citations and co-appearances were analyzed [8].

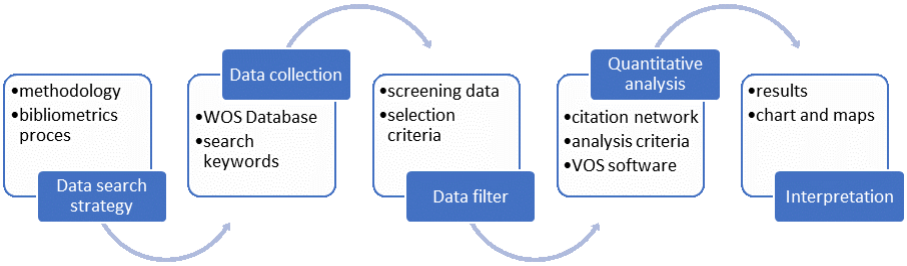

Figure 1: Steps for conducting bibliometric research.
(Source: authors contribution)

The bibliometric analysis includes co-citation, co-authorship, and co-occurrence concerning various items. Therefore, we clustered them by similarity and presented them as colored results with the help of mapping software.

The citations represent the merit of previous research, especially of their authors, referring to the pioneers of the intellectual base in the field, revealing the emergence of research trends and presenting an image of the field's polarization. Co-citation indicates the frequency with which two papers are cited together by other research papers and represents a useful index for the emergence of new scientific topics. Citation and co-citation are a relevant indicator for disseminating research and leads to the emergence of new scientific topics by investigating previously published works. This indicator's current dimensions refer to the works' co-citation, their authors, or the journals that published the research.

Co-authorship is the indicator that analyzed international recognition and collaborations between authors from other countries and identifies the relevant nodes that lead to these collaborations.

Co-occurrence networks are generated when connecting pairs of articles using a specific set of co-occurrences that define the criteria set when using the software [28]. Therefore, co-occurrence was used to identify fuzzy topical logic in the fuzzy dimension and analyze the subject through other indicators such as statistical functions.

The bibliometric analysis uses the Web of Science (WOS Core Collection) database as a source of information. The choice of this database source is determined, on the one hand, by the high level of

international recognition in terms of published scientific papers quality, and on the other hand, because it brings together researchers from a broad international academic community with a multidisciplinary character.

In addition to the indicators specific to bibliometric analysis, we used link analysis and H-index to highlight the international links and recognition of authors, journals, institutions, works, and some researchers' intense concerns. In network theory, link analysis is a data-analysis technique used to evaluate relationships (connections) between nodes. Relationships may be identified among various types of nodes (objects), including organizations, people, and papers. The total link strength attributes analysis the total strength of a given researcher's co-authorship links with other authors. In addition to the Total link strength and Standard Links indicators, some items may also have custom weight attributes [27]. The h-index is calculated based on a list of publications ranked in descending order by Times Cited. The calculated value of h is equal to the number of papers (N) in the list with N or above N+1 citations. H-index is useful because it discounts the disproportionate weight of highly cited papers or papers that have not yet been cited. The h-index reflects more than the number of documents or the number of citations. It also reflects some indication of the number of well-cited papers. This provides an interesting complement to other performance metrics since a single highly-cited paper does not influence it [28].

The application of statistical and forecasting functions is a novelty of this study that creates the potential to predict and interpret the results obtained. This research is relevant for specialists to identify positioning concerning the charts made to identify representative works, influential authors, journals, and reference institutions more efficiently. It also provides a predictive picture of the evolution of research in Fuzzy Logic research.

The search was performed through the WOS advanced search interface, searching for Fuzzy Logic terms using Boolean OR or NEAR / 10 operations (Table 1). The NEAR / 10 operator searches for registered keywords separated by the other words to form a logical phrase.

Table 1: Data selection in WOS Core Collection

Query (Terms Searched; Years; Document Types)	**Results**
TS=fuzzy Web of Science Core Collection Publication Years (1975-2020) All Document Types / English	140,994
TS = (Fuzzy Logic *) OR TI = (Fuzzy Logic *) Web of Science Core Collection Publication Years (1975-2020) All Document Types	57,423
TS = (Fuzzy Logic *) OR TI = (Fuzzy Logic *) Web of Science Core Collection Publication Years (1975-2020) ARTICLE/PROCEEDINGS PAPER/BOOK CHAPTER/REVIEW/BOOK	**56,910**
TS = (fuzzy near/10 logic) Web of Science Core Collection Publication Years (1975-2020) All Document Types	52,204
TS = (fuzzy near/10 logic) and TI = (fuzzy near/10 logic) Refined by: DOCUMENT TYPES: (ARTICLE) Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC.	17,259

Source: Data selection with WOS advanced research engine

In December 2020, 235,014 items had the word fuzzy as a keyword in a topic. This number includes all types of papers published in all languages supported by the database. We refine the search by limiting ourselves to documents published in English (140,994 items) and focused our research on the term Fuzzy Logic. There were 57,423 documents published on Fuzzy Logic decision research in Web of Science Core Collection. We also included all types of documents such as articles, book chapters, proceedings papers, books, reviews, and others. For this study, we have excluded early access

materials, news items, and all documents under 1% out of the total number of records. Therefore, we selected 56.910 relevant documents for our study (Table 2).

Table 2: Documents Structure on Fuzzy Logic in WOS Core Collection

Document Types	**No. of publications**	**% Out of 56,910**
ARTICLE	29,345	51.56%
PROCEEDINGS PAPER	25,827	45.38%
BOOK CHAPTER	798	1.40%
REVIEW	689	1.21%
BOOK	251	0.44%
TOTAL	**56,910**	**100.00%**

Source: Data analyzed with Excel

We note that more than 50% of publications are on Computer Science and 47% on Engineering in terms of research. But in the top 15 research areas, we find publications that fall into fields such as Mathematics, Telecommunications, Energy Suits, Operations Research Management Science, Environmental Sciences Ecology, Business Economics, Agriculture and Construction.

At the WOS database level, the total number of publications between 1975 and 1990 was 202 published documents on Fuzzy Logic research (Table 3). For the last ten years, Fuzzy Logic research is on an upward trend in the number of documents published. The minimum number of publications was 2,104 in 2011, and the maximum number of publications was 3,960 in 2018.

In fact, in the last ten years, more than 50% of the scientific papers published with Fuzzy Logic (31,399) have been published. Referring to the total number of works on Fuzzy, Fuzzy Logic's topic has reached over 40% in the total volume of articles.

Table 3: No. of publications published on Fuzzy Logic research between 1975-2020

Period	**No. of publications Fuzzy**	**No. of publications Fuzzy Logic**	%
1975-1990	2,713	202	7.45%
1991-2000	18,418	7,503	40.74%
2001-2010	45,027	17,806	39.55%
2011-2020	74,836	31,399	41.96%

Source: Data analyzed with Excel

3 Results

Following the research carried out, with the help of investigative tools, we were able to put the base of some bibliometric aspects related to the number of publications, the most influential authors, the most cited papers, most representative journals, institutions, and most representative countries for Fuzzy Logic research.

3.1 Bibliometrics results on the publications on Fuzzy Logic

Analysis of the evolution of research paper numbers on the Fuzzy Logic area still indicates an increased interest. Before 1990 the number of publications on Fuzzy Logic research was relatively low (202, see Table 3). The reduced number of documents for that period is justified because of the lack of communication possibilities. Due to no internet network, low development on ICT, the fuzzy research area is in its early development stages.

After 2010, more than 3,000 papers are published annually, which led to a 5% increase in the number of documents per year. On the one hand, the explanation is determined by the interest in the research theme, and on the other hand, by the multidisciplinary and extension of the Fuzzy Logic scope in diverse fields.

In Figure 2, it can be seen that the annual number of publications is increasing by more than 5% per year.

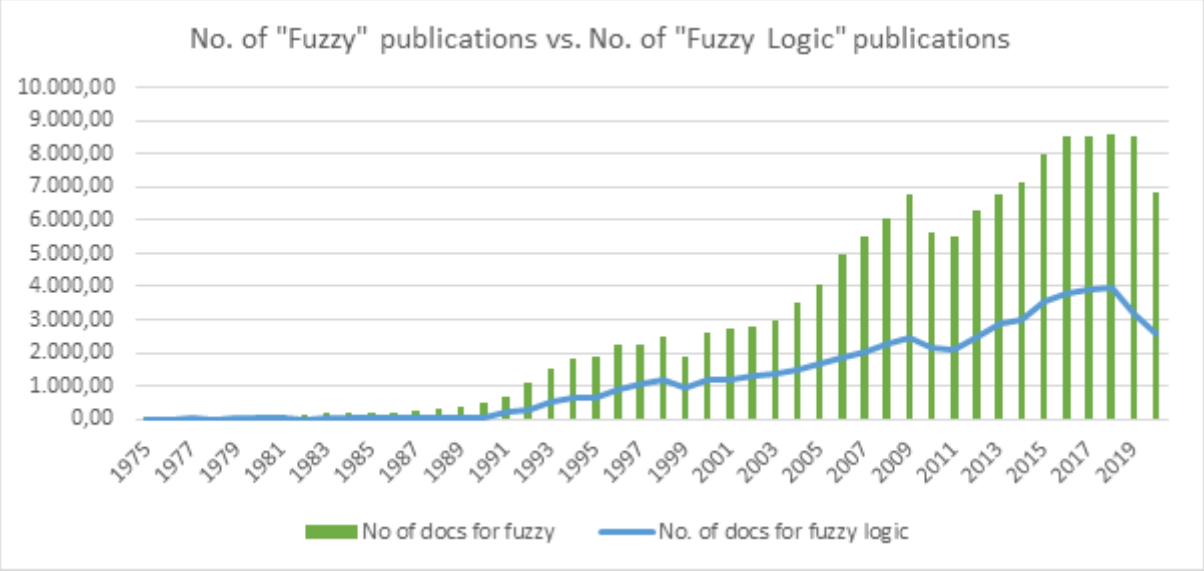

Figure 2: Number of annual publications in WOS in Fuzzy vs. Fuzzy Logic research since 1975

The green bars indicate the number of publications per year in WOS in Fuzzy research, and the blue line shows the number of publications per year in WOS in Fuzzy Logic research.

To illustrate this comparison, we appreciate that Fuzzy Logic research is much more used in light of other terms like Fuzzy Sets, Fuzzy Numbers, Fuzzy Systems, etc.

The barriers of the research broke after 1997 when the no. of publications has multiplied considerably. After 2010, the average of publications in the Fuzzy Logic research exceeded the barrier of 3,000 publications per year, frequently representing 42% out of the total articles in the "fuzzy" area of research (Table 4).

Table 4: Periods means for Fuzzy and Fuzzy Logic research

Period	**Mean for "fuzzy" docs**	**Mean for "Fuzzy Logic" docs**
1975-1990	169.56	12.63
1991-2000	1,841.80	750.30
2001-2010	4,502.70	1,780.60
2011-2020	7,483.60	3,139.90

Source: Data analyzed with Excel

The annual increase in the global number of publications on Fuzzy Logic exhibited the second-degree polynomial ($R^2 = 0.983$). The multiple R shows how closely two analyzed variables move in tandem (Multiple R=0.99). Our regression output indicates that the fuzzy research explains that 99.16% of variation in Fuzzy Logic docs research is explained. And only 1.77% of the variation is caused by factors other than fuzzy research. To confirm the results, statistical functions were determined using Excel (Table 5).

Table 5: Descriptive statistics for no. or publications on Fuzzy Logic research published between 1975-2020

Mean	1237.17	Skewness	0.71009
Standard Error	186.658	Range	3959
Median	999.5	Minimum	1
Mode	1	Maximum	3960
Standard Deviation	1265.98	Sum	56910
Sample Variance	1602695	Count	46
Kurtosis	-0.6881	Confidence Level (95.0%)	375.948

Source: Data analyzed with Excel

The descriptive stats show us that per year on average, 1237 papers were published. The positive value of data asymmetry (0.710) shows that the median and the mode are lower than the mean. Calculating the ratio of publications in the field of research (search by number of publications - after fuzzy in Topics vs. Fuzzy Logic in TS) was variable. Between 1975 and 1990, a maximum of 10% of the published articles on fuzzy research was on Fuzzy Logic. Between 1991 and 1996, the publication of documents increased to almost 39% of the total publications on fuzzy research explaining the high importance of research in Fuzzy Logic. After 1997, the percentage remained consistently variating between 40-50%, which means that out of 1000 published articles, almost 500 works were on Fuzzy Logic.

Application of forecast functions (FORCAST.ETS) at the number of annually published papers during each period has shown that after 2025 interest in the topic Fuzzy Logic reaches 50%, where it will remain until 2030. The result defines Fuzzy Logic as the critical reference term in fuzzy research and will cause the expansion of the research area by publishing interdisciplinary papers. In this forecasting, the number of publications published on Fuzzy Logic research between 2021-2030 will be over 42,200 of the total fuzzy publications estimated at nearly 83,700, i.e., over 50.5% of the research papers will have associated this topic.

In Figure 3, we observe a bibliometric map made with VOS software, where the existing link between author keywords with a threshold of 50 and the 100 most representative connections. The graph (Figure 3) shows the influence that Fuzzy Logic has on our research. Although the terminology is diversified, Fuzzy Logic covers over 50% of the research in the field.

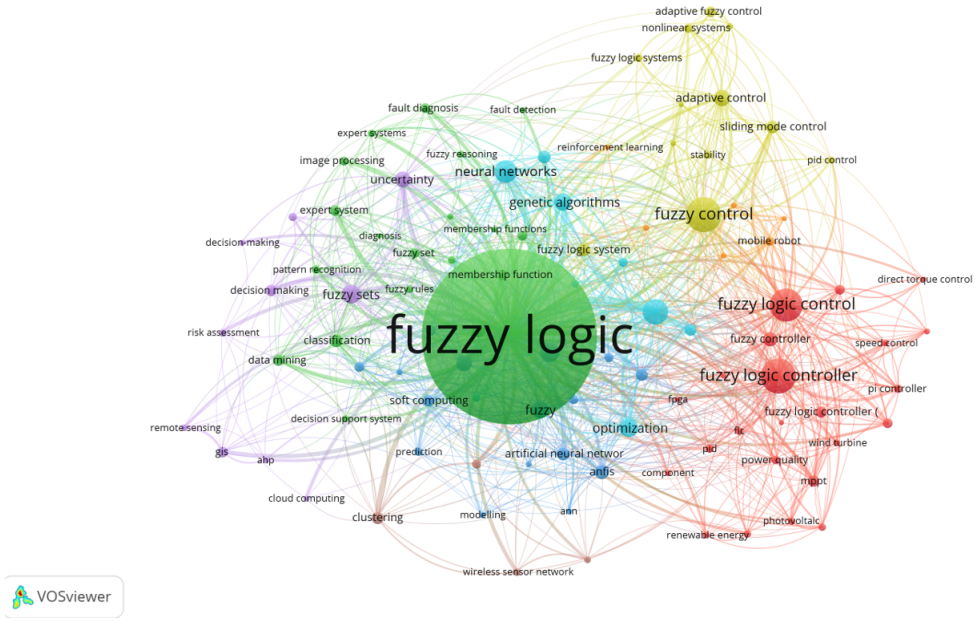

Figure 3: Mapping of co-occurrence author keywords with a threshold of 50 and the 100 most representative connections

3.2 Most cited authors on Fuzzy Logic research

To characterize the most influential authors, we will start from the question of Zadeh L.A. [39] Is There a Need for Fuzzy Logic ?. Many authors answered this question, and so, they became representative authors in the research area. One way to emphasize the importance of an author is by counting the number of citations that published papers have, and that is the H-index value used by WOS to highlight an author's influence. Within the research in the Fuzzy area, the most cited author is Zadeh L.A. Zadeh has 37,100 citations at the WOS database level, and out of these, 9,432 citations are strictly related to Fuzzy Logic research (Table 6). The general influence given by the promoter of Fuzzy Sets or Fuzzy Logic remains highly accentuated. Zadeh L.A.'s works are further seen as promoters for the present research, and so he has become an essential reference in multidisciplinary research.

To show which authors are the most influential in Fuzzy Logic research, we present Table 6 with the 15 most productive and meaningful authors in this field. Table 6 is organized considering the number of publications/authors; the H Indexed calculated by WOS, the number of articles containing Fuzzy Logic as keyword; overall citation oh author; general citation of documents that contain Fuzzy Logic and an H index for Fuzzy Logic.

Table 6: Top 15 most cited authors in Fuzzy Logic research

No.	Name	Institution	Total citation	Citations Fuzzy Logic	H-index	H-index on Fuzzy Logic	Total Articles published	Articles published on Fuzzy Logic
1	Zadeh, L. A.	University of California Berkeley	37,510	9432	46	19	138	48
2	Yager, Ronald R.	Iona College	32,197	773	77	12	692	28
3	Pedrycz, Witold	University of Alberta	26,633	518	73	14	1290	38
4	Tong SC	Liaoning University of Technology	21,012	9402	78	6	386	170
5	Mendel, Jerry M	University of Southern California	15,766	6.526	49	24	191	24
6	Takagi, T	Tokyo Institute of Technologyy	11,820	9,120	8	9	11	9
7	Jang, J. -S. R.	National Taiwan University	11,658	650	19	6	91	16
8	Dubois, Didier	Universite de Toulouse	10,685	624	53	7	371	13
9	Castillo O.	Tijuana Inst Technol	10,285	4.449	56	38	768	217
10	Lin, Chin-Teng	University of Technology Sydney	10,221	23	51	3	406	14
11	Mamdani, Ebrahim	Imperial College London	8739	6015	14	9	37	15
12	Wang, L. X.	South China University of Technology	4054	62	11	4	37	5
13	LEE, CC	University of California Berkeley	3957	3,851	5	7	8	7
14	Karnik, Neha N.	University of Mumbai	2,720	1558	7	5	11	5
15	Hajek P.	Czech Academy of Sciences	2,121	1074	22	18	119	46

Source: Authors research based on WOS database

As we can see, Zadeh is the most influential author on the Fuzzy study in general, with more than 37,000 citations. Yager follows closely with more than 32,000 citations. However, Pedrycz is the most productive in terms of the published number of articles with 1290 works. Some key issues that explain this is that in the 1960s, 1970s, and 1980s, it was not as common to publish many papers.

Moreover, co-authorship was not as expected, and most of the documents written by Zadeh were as single author. Looking to the citation record for Fuzzy Logic, Zadeh obtains the best result with 9,432 citations, followed closely by Tong, Takagi, Mamdani, Lee, and Karnik. Tong SC obtains the highest H-Index – 78, and the most productive author in Fuzzy Logic research is Castillo with 217 published documents. Castillo O. also obtains the Highest H Index on Fuzzy Logic (38) Research meaning that for 38 articles on Fuzzy Logic, he has a minimum of 38 citations per each document.

Figure 4 shows the bibliometric map made with VOS software and highlights the existing link between the authors who have more than 500 citations. These links allow us to observe the relationship between the authors' works. In this map, several primary nodes are highlighted. Each node has a reference author. In the first node, Zadeh appears as the most influential. In the second, we observe Mendel J.M., and in the third, we notice Dubois D.

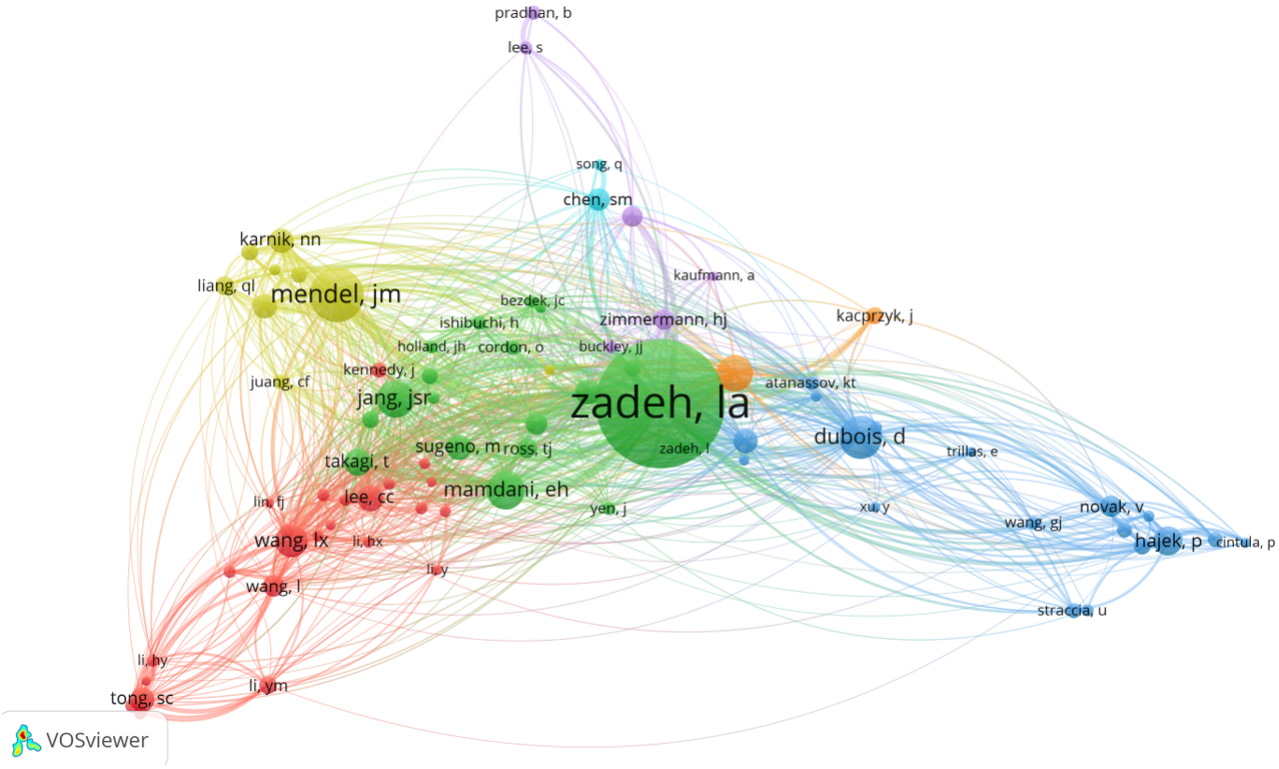

Figure 4: Mapping of articles co-citations with a threshold of 500 citations and the 100 most representative connections

3.3 Most cited articles on Fuzzy Logic research

One way to emphasize the importance of published articles is by using citations that published papers have in WOS. Table 7 exhibits the 15 most cited papers in Fuzzy Logic research. It shows only the works in the title or topics, Fuzzy Logic as a keyword, and excludes all other concepts related to Fuzzy Research (Fuzzy Sets, fuzzy number, fuzzy system, etc.). Out of 56,910 results, 237 are most cited. The total citation number for these 237 papers is 36,355. The most cited article is Jang J.S.R. (1993), with 8,489 citations, 143% more than the second place, eight times higher than the last article.

Table 7: Top 15 most cited papers in Fuzzy Logic research

No.	Title	Authors	J. Abbrev.	Publ. Year	Times Cited, Wos Core	Average /Year
1	Anfis - adaptive-network-based fuzzy inference system	Jang, JSR	ITSMC	1993	8489	314.41
2	Experiment in linguistic synthesis with a Fuzzy Logic controller	Mamdani, EH; Assilian, S	IJMMS	1975	3654	81.20
3	Fuzzy-logic in control-systems - fuzzy-logic controller	Lee, CC	ITSMC	1990	2893	96.43
4	Fuzzy logic equals Computing with inference system	Zadeh, LA	ITFS	1996	1787	74.46
5	Fuzzy basis functions, universal approximation, and orthogonal least-squares learning	Wang, LX; Mendel, JM	ITNN	1992	1613	57.61
6	Toward a theory of fuzzy information granulation and its centrality in human reasoning and Fuzzy Logic	Zadeh, LA	FSS	1997	1504	65.39
7	Type-2 Fuzzy Sets made simple	Mendel, JM; John, RI	ITFS	2002	1412	78.44
8	Neuro-fuzzy modeling and control	Jang, JSR; Sun, CT	P-IEEE	1995	1304	52.16
9	Rudiments of rough sets	Pawlak, Z; Skowron, A	IS	2007	1246	95.85
10	Current control techniques for three-phase voltage-source PWM converters: A survey	Kazmierkowski, MP; Malesani, L	ITIE	1998	1236	56.18
11	Recommender systems survey	Bobadilla, J; Ortega, F; Hernando, A; Gutierrez, A	KBS	2013	1217	173.86
12	Condition monitoring and fault diagnosis of electrical motors - A review	Nandi, S; Toliyat, HA; Li, XD	ITEC	2005	1179	78.60
13	Interval type-2 Fuzzy Logic systems: Theory and design	Liang, QL; Mendel, JM	ITFS	2000	1145	57.25
14	A survey on analysis and design of model-based fuzzy control systems	Feng, G	ITFS	2006	1123	80.21
15	A modified fuzzy C-means algorithm for bias field estimation and segmentation of MRI data	Ahmed, MN; Yamany, SM; Mohamed, N; Farag, AA; Moriarty, T	ITMM	2002	1110	61.67

Source: Authors research based on WOS database

Abbreviations: **ITSMC**, IEEE Transactions on Systems Man and Cybernetics; **IJMMS**, International Journal of Man-Machine Studies; **ITFS**, IEEE Transactions on Fuzzy Systems; **FSS**, Fuzzy Sets and Systems; **ITNN**, IEEE Transactions on Neural Networks; **ITIE**, IEEE Transactions on Industrial Electronics; **P-IEEE**, Proceeding of IEEE; **IS**, Information Sciences; **KBS**, Knowledge-Based Systems; **ITEC**, IEEE Transactions on Energy Conversion; **ITMM** - IEEE Transactions on Medical Imaging.

Figure 5 shows a bibliometric map of co-citations with a threshold of 500 citations and the 25 most representative connections.

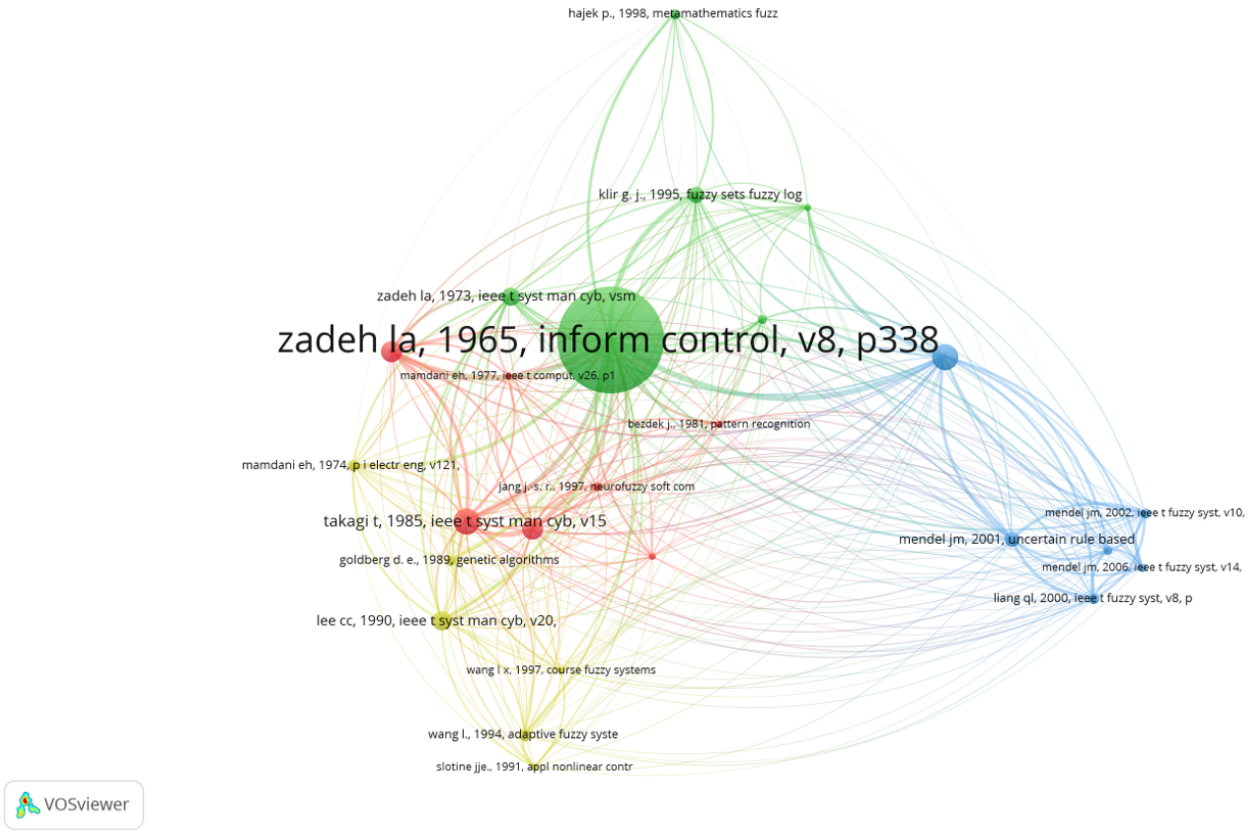

Figure 5: Mapping of references co-citations with a threshold of 500 citations and the 25 most representative connections

Zadeh L.A.'s 1965 reference work [33] is the work that represents the central node and creates connections with works by authors from around the world. We can also see Takagi T's contribution. [24], Mendel J.M. [23], Mamdami E.H. [17] or Jang J.R.S. [11]. If Zadeh L.A.'s co-citation value is 7,443, the following relevant works have a co-citation value below 2,000, which gives an insight into its ego-centrist position.

3.4 Most representative journals on Fuzzy Logic research

Fuzzy Logic research is published in many specialized or multidisciplinary journals. Its applicability in various fields has led to the definition of a portfolio of journals that have become vectors in scientific research. The selection of data collected from the WOS database led to creating the top 15 most influential journals in which Fuzzy Logic research was published (Table 8). Between the most influential journals in the Fuzzy Logic domain, we found: ITFS - IEEE Transactions on Fuzzy Systems, ITSMC - IEEE Transactions on Systems Man and Cybernetics or FSS - Fuzzy Sets and Systems.

Table 8: Top 15 most influential journals in Fuzzy Logic research

No.	J. Abbrev.	H-FL	H	TC	TCFL	TP	TPFL	%PFL	>50	>100	>250	>500	IF
1	ITFS	108	182	165,117	47,908	2,95	735	24.92%	113	95	22	9	8.8
2	FSS	90	190	260,601	37,702	8,438	1,198	14.20%	108	63	8	5	3.34
3	IS	71	126	98,302	22,929	2,577	499	19.36%	75	37	6	4	6.77
4	ESA	69	162	238,477	19,848	13,326	575	4.31%	86	24	5	0	7.89
5	ITIE	69	236	219,305	14,88	12,277	206	1.68%	56	33	4	3	7.51
6	ASC	54	123	140,56	10,5	6,435	411	6.39%	108	63	8	5	6.03
7	ITSMCB	50	150	117,782	9,299	2,104	162	7.70%	86	24	5	0	9.3
8	RSER	43	267	555,246	6,044	9,987	77	0.77%	15	14	4	1	12.11
9	IJEPES	40	109	120,919	5,657	6,713	184	2.74%	11	5	0	0	3.58
10	ITPS	39	228	409,971	4,667	9,944	81	0.81%	20	11	1	0	6.07
11	IJAS	36	88	42,533	6,045	2,15	234	10.88%	20	7	3	0	2.67
12	EAAI	36	88	64,7	5,341	3,549	253	7.13%	18	4	0	0	4.2
13	EPSR	36	102	101,155	4,373	6,386	155	2.43%	17	6	0	0	3.21
14	ITNN	31	195	220,445	7,027	3,149	56	1.78%	11	11	3	2	12.18
15	ITSMC	26	132	138,603	14,99	2,985	48	1.61%	6	6	2	3	8.88

Source: Authors research based on WOS database

Abbreviations: **R**, rank; **H**, H-index; **H-FL**, H-index only with Fuzzy Logic ; **TP**, total papers; **TPFL**, total papers only with Fuzzy Logic ; **TC**, total citations; **TCFL**, total citations only with Fuzzy Logic ; % **PFL**, percentage of Fuzzy Logic papers in the journal; **>500**, **>250**, **>100**, **>50**, number of papers with more than 500, 250, 100 and 500 citations; **IF**, impact factor 2020; **ITFS**, IEEE Transactions on Fuzzy Systems; **FSS**, Fuzzy Sets and Systems; **IS**, Information Sciences; **ESA**, Expert Systems With Applications; **ITSMC**, IEEE Transactions on Systems Man and Cybernetics; **ITIE**, IEEE Transactions on Industrial Electronics; **ASC**, Applied Soft Computing; **ITSMCB**, IEEE Transactions on Systems Man and Cybernetics Part B-Cybernetics; **ITNN**, IEEE Transactions on Neural Networks; **IJAS**, International Journal of Approximate Reasoning; **RSER**, Renewable & Sustainable Energy Reviews; **IJEPES**, International Journal of Electrical Power & Energy Systems; **EAAI**, Engineering Applications of Artificial Intelligence; **ITPS**, IEEE Transactions on Power Systems; **EPSR**, Electric Power Systems Research

Figure 6 shows that IEE Transactions on Fuzzy Systems obtain the most significant influence in the Fuzzy Logic area, whose H-FL of 108 reflects at the same time a large number of citations of Fuzzy Logic articles. Although not all calculations cause us to permanently position this journal in the first position, the Mapping analysis of journal co-citations with a threshold of 500 citations and the 100 most representative connections highlights two important nodes represented by Fuzzy Sets and Systems and IEEE Transactions on Fuzzy Systems Journal. These journals will further represent scientific research poles in the field of Fuzzy Logic.

Our calculations lead us not to consider permanently that this is the leading journal. Therefore, the following Mapping of the journal co-citations analysis with a threshold of 500 citations and the 100 most representative connections highlights two other essential nodes represented by Fuzzy Sets and Systems and IEE Transactions on Fuzzy Systems. These two journals will further represent huge poles in scientific research in the field of Fuzzy Logic.

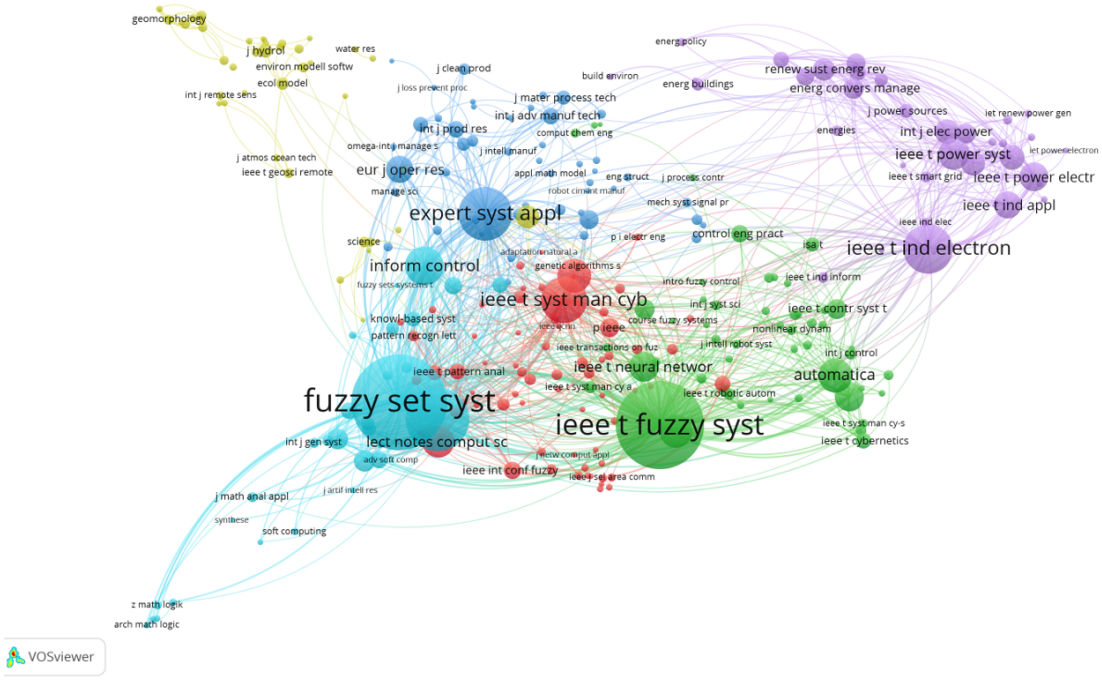

Figure 6: Mapping of journal co-citations with a threshold of 500 citations and the 100 most representative connections

3.5 Most influential institutions in Fuzzy Logic research

Fuzzy Logic research was initially concentrated at the level of research centers that have had limited resources. Over time, correlated with ICT development, universities became interested and brought together academics and researchers who rapidly contributed to the development of research. Table 9 shows the top 15 most influential institutions on Fuzzy Logic research by counting the number of articles published by their affiliated researchers, no. of citation, and the link strength.

Table 9: Top 15 most influential institutions in Fuzzy Logic research

No.	Institution Codification	Documents	Citations	Total link strength
1	ISLAMIC AZAD UNIV	716	6,384	382
2	TIJUANA INST TECHNOL	445	6,929	543
3	NATL INST TECHNOL	379	4,300	176
4	INDIAN INST TECHNOL	345	6,783	225
5	UNIV TEHRAN	312	4,053	202
6	CHINESE ACAD SCI	301	4,123	247
7	HONG KONG POLYTECH UNIV	286	5,056	212
8	NANYANG TECHNOL UNIV	251	5,241	281
9	LIAONING UNIV TECHNOL	250	11,776	860
10	NORTHEASTERN UNIV	244	3,982	661
11	HARBIN INST TECHNOL	219	2,965	244
12	ISTANBUL TECH UNIV	218	3,850	249
13	UNIV GRANADA	217	5,398	169
14	UNIV ALBERTA	208	3,808	225
15	AMIRKABIR UNIV TECHNOL	207	2,506	196

Source: Authors research based on WOS database

Islamic AZAD University is in the top position, counting the no. of published documents (716) on Fuzzy Logic research. The most cited articles were published by the researchers affiliated with Liaoning University Technology (11,776) even though the number of published articles related to Fuzzy Logic is relatively small.

Figure 7 displays the bibliometric map of universities' co-citations with a threshold of 500 and the

100 most representative connections. We observe four significant nodes were the most relevant nod is also represented by Islamic Azad University. We can observe the node with the highest number of relations with other nodes in the bottom right corner.

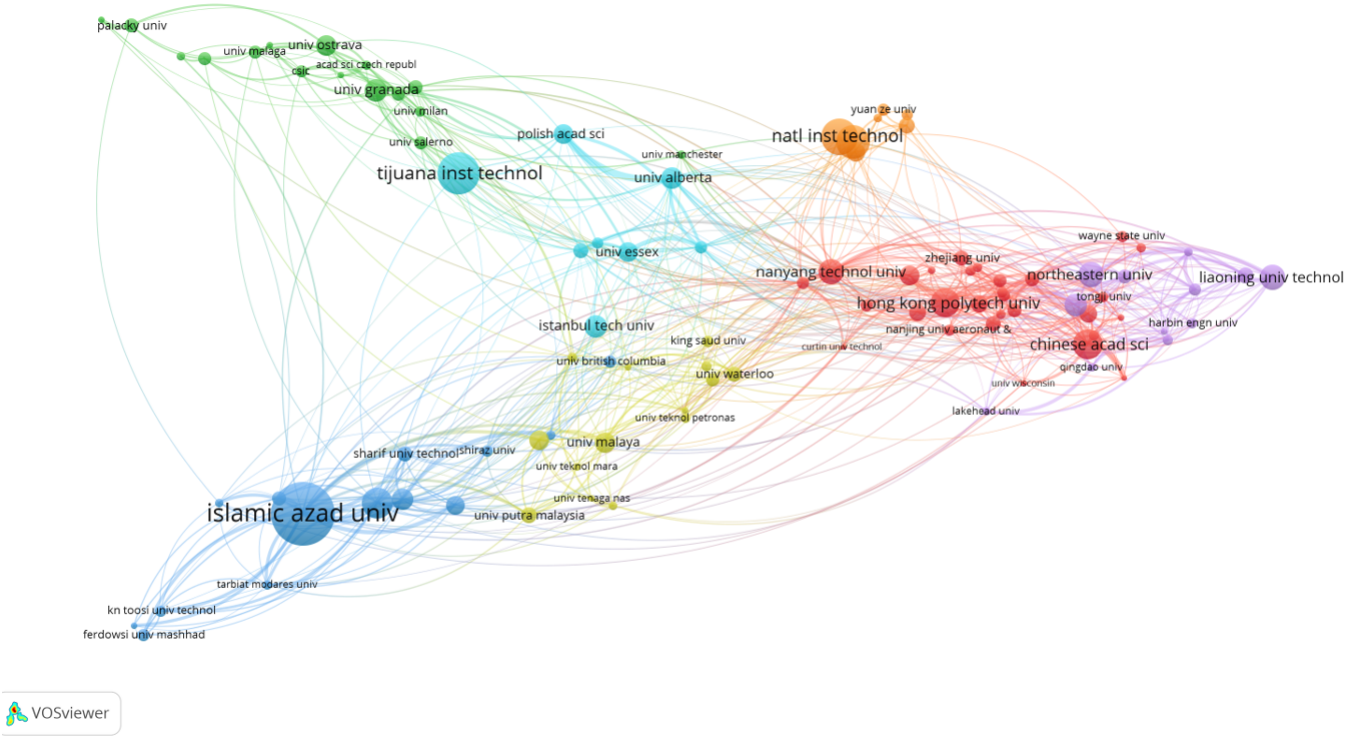

Figure 7: Mapping of institutions' co-citations with a threshold of 500 and the 100 most representative connections

3.6 Most representative countries in Fuzzy Logic research

The development of Fuzzy Logic research has experienced a particular dynamic, especially in Asian countries. If between 1975 and 1990, the USA dominates this ranking, the development of ICT, open access to international databases, and researchers' mobility have contributed to the realization of related research in China and India, which now occupy the first positions (Table 10). The arguments behind these rankings may also be consistent with the increase of China's population. India and the USA hold the same positions. Our first conclusion leads to the idea that the number of academics and researchers in these countries is higher and contributes to research development in the Fuzzy Logic field. A second conclusion concerns the quality of the researchers involved who, through the published papers, were able to determine a large number of citations.

Table 10: Top 15 most influential countries in Fuzzy Logic research published in WOS

No.	Country	Documents	Citations	Total link strength
1	CHINA	7549	85378	1084
2	INDIA	5577	40650	350
3	USA	4615	82312	1057
4	IRAN	2794	31681	523
5	SPAIN	2051	29718	325
6	ENGLAND	1915	32761	616
7	CANADA	1813	30361	548
8	TURKEY	1808	28915	229
9	ITALY	1613	21480	340
10	FRANCE	1309	16861	269
11	MALAYSIA	1238	15833	299
12	AUSTRALIA	1134	15898	453
13	GERMANY	945	13162	223
14	JAPAN	834	9779	216
15	SAUDI ARABIA	572	6722	255

Source: Authors research based on WOS database

The bibliometric graphic presentation from Figure 8 shows five interconnected central nodes for countries co-authorships with a threshold of 50 and the 75 most representative connections.

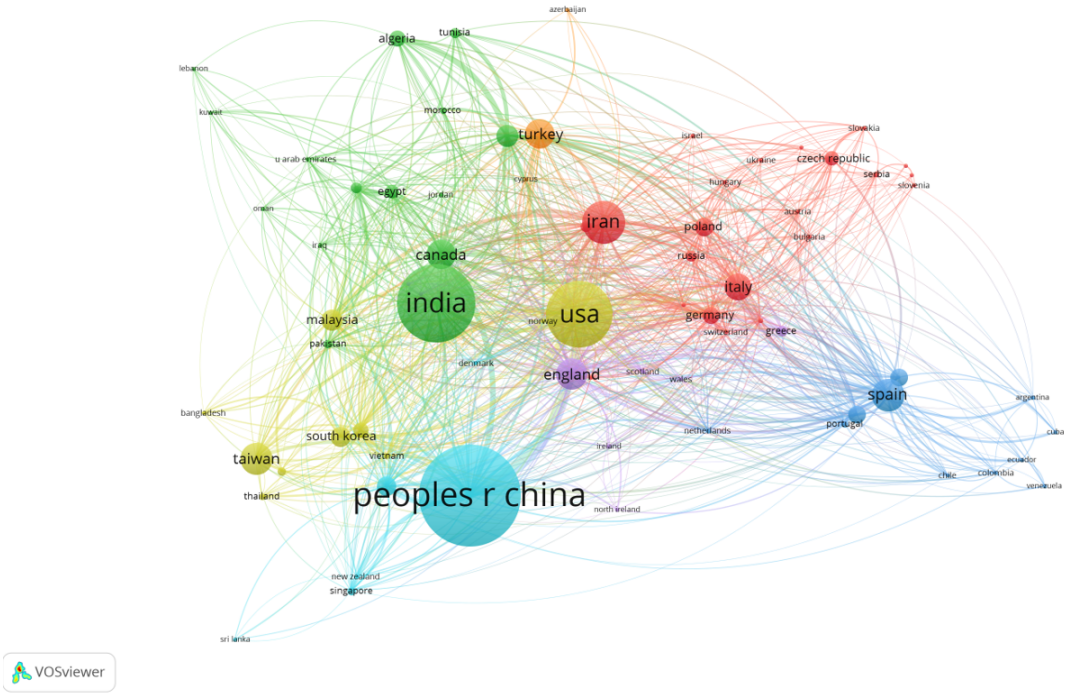

Figure 8: Mapping of countries co-authorships with a threshold of 50 and the 75 most representative connections

Each node identified becomes the pole of influence for many countries grouped by native language. Thus, the first node, represented by China, shows particular connections with Singapore, Taiwan, South Korea. India forms the second node, and its bonds are more evident in other Asian and African countries. The USA and England represent another node with branches in the Nordic countries, Iran represents an intermediate node with international ties. In contrast, the European node is centered around Spain, Italy, and other Latin origin countries.

In Figure 9, we observe the mapping of countries' bibliographic coupling with a threshold of 50 and considering the 75 most influential connections. We note that the geographical distribution specific to the five identified nodes is maintained, highlighting in a more precise way the links between researchers and published works in the Fuzzy Logic field.

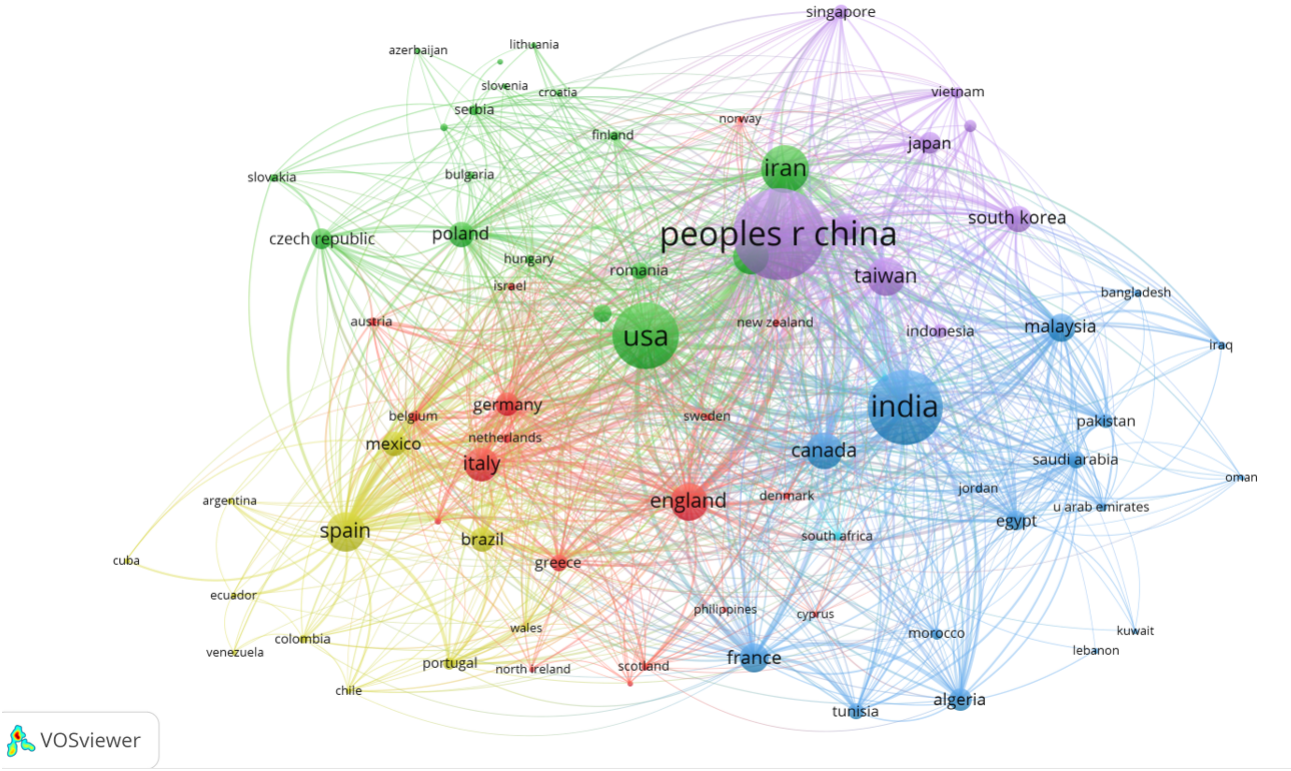

Figure 9: Mapping of countries bibliographic coupling with a threshold of 50 and considering the 75 most influential connections

4 Final remarks

We have illustrated a joined-analysis of the research in Fuzzy Logic using bibliometric indicators. The research results are highly analyzed, with statistical functions. We extracted and analyzed the WoS database information about authors' productivity and citations, the number of representative documents, highly cited journals, institutions, and countries. For graphic representation, bibliometric maps were developed using VOS viewer software to centralize co-citation analyses, co-author, network analysis, and co-emergence. Following the study of the 56,910 published documents in WOS on Fuzzy Logic research, conclusions are summarized as follows:

- The international cooperation relationship is highly developed, and the connection between authors, institutions, and countries is powerful. Thus researchers with concerns in the Fuzzy Logic field come together either on standard fields as their native language or through institutional cooperation. The graphic representation made to visualize the research structure better indicates the network nodes showing which authors and/or institutions are connected in bibliographic coupling and co-citation.

- Fuzzy Logic falls within the fuzzy field of research, and thus we identify a series of typical results that distort the separation of the topic. The great fuzzy family combines numerous concepts such as Fuzzy Sets, fuzzy numbers, fuzzy systems, etc., representing bibliometric research ideas. With Fuzzy Logic's incorporation in decision-making, a new research area began attracting researchers, universities, and overall worldwide research.

- The Fuzzy Logic topic accounts for almost 40% of all documents identified in the Fuzzy field in 2020. This reveals the researchers' interest in the matter, and the forecast analysis leads us to conclude that more than 50% of the research in fuzzy will be about Fuzzy Logic in 2025.

- The priority areas of publication of scientific documents related to Fuzzy Logic are Computer Science and Engineering, as seen from the top most influential journals list realized. The research areas are becoming broader, especially for applications related to Fuzzy Logic Research.

- Bibliometric analysis of Fuzzy Logical research reveals that the topic has interdisciplinary applicability. It's used by academics and researchers from various fields of research and institutions all

over the world.

- The central pole of influence in the field of Fuzzy Logic is located in the Asian Continent. China, South Korea, Taiwan, India, and Iran have a unique scientific production in terms of both the number of documents, the number of citations, the relations between authors, and the relevance of the journals and institutions involved. In Fuzzy Logic research, one of the most prominent authors is Zadeh LA, and his contribution to the research area is overwhelming. It also shows that China is the most influential and most productive country due to many researchers involved in developing this area. Another country that stands out is UK, which is in the top 10 document productivity and Mamdani stands out as the most influential European in this field of research, along with Dubois and Hadek. Finally, this paper gives a general picture of Fuzzy Logic research and emphasizes Zadeh LA., as the most important author of all, naming him "the father" of fuzzy.

The literature review revealed that the conducted investigations are grouped after a topic (fuzzy sets, fuzzy logic, fuzzy systems, fuzzy numbers, etc.). Fuzzy logic has the most critical weight (40% in 2020). On the one hand, fuzzy logical research has a continuous development in this research area. On the other hand, by the size of the areas of application, it has multidisciplinary implications. Fuzzy Logic research is part of a well-sized area with an internationally structured network represented by reference associations such as International Fuzzy Systems Association or Institute of Electrical and Electronics Engineers Computational Intelligence Society, essential journals such as IEEE Transactions on Fuzzy Systems or Fuzzy Sets and Systems to which are added many other internationally recognized institutions and journals. Let's also consider researchers from universities who publish theoretical and practical works in this field. We can say that Fuzzy Logic research will continue through the next generations, leading to new applications and new areas that will include fuzzy research. This conclusion was validated by applying the statistical forecast function (FORCAST.ETS), which determines that the published number of papers in Fuzzy Logic intensifies to over 50% of documents published in the fuzzy field.

Research may be expanded because of the limitations that have been encountered by filtering the information. Thus, almost 45% of the overall number of works concerning Fuzzy Logic research in the WOS database were eliminated from publication in other languages. If the Fuzzy Logic search initially identified 235,014 items representing all types of documents published in all languages, we refined the resulted and accepted only 140,994 papers. For further development, research-based on WOS database can be supplemented by the inclusion of other scientific databases (Scopus, Elsevier, Scholar, etc.). Moreover, a substantial amount of crucial information can be omitted by the lack of association of critical terms or the framing of works in types of documents that were not included in the analysis. The application of statistical and forecasting functions led us to interpretations and predictions that may constitute additional research elements.

Author contributions

The authors contributed equally to this work.

Conflict of interest

The authors declare no conflict of interest.

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