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Scientometric Exploration of Fuzzy Research in Saudi Arabia

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Abstract

This bibliometric research investigates the development, productivity, and academic influence of fuzzy research from 1981 to 2024 in Saudi Arabia. We retrieved the bibliometric data from the Scopus database and analyzed 5,719 publications, leading to 111,381 citations. The metric analysis shows that Mohammad A. Abido is leading the country with the highest number of publications. At the same time, King Abdulaziz University and King Saud University are the most productive institutes in fuzzy research. Journals such as the IEEE Access and MDPI are leading quite often as the publishing venue, and a trend of publication towards high-impact journals. International collaborations with Pakistan, India, China, and Canada significantly impacted the research productivity. The visual analysis was done using VOS viewer and Bibliometrix software, which includes co-citation, bibliographic coupling, co-occurrence, word cloud mapping, and emerging or declining thematic maps. These evaluations illustrate strong interdisciplinary ties of literature, while top research topics and trends involve artificial intelligence, optimization, decision making, and sustainability. The current direction is to increase the application of fuzzy logic in the energy, health, and environmental sciences. More generally, this study highlights the trends and themes of Saudi Arabia in the world of fuzzy set theory and its applications, facilitated by institutional backing, inter-institutional collaboration, and increasing demands for cross-disciplinary research.

Keywords: Bibliometrics; Web of Science; Scopus; Fuzzy; VOS Viewer; Saudi Arabia.

1 | Introduction

The fuzzy set theory (FST), first introduced by Iranian American scientist Lotfi Asker Zadeh [1], has had a transformative global impact. Over time, this foundational concept has expanded across various disciplines, including control systems, decision-making, artificial intelligence, and data analysis. As the theory evolved, it led to significant breakthroughs in fields such as healthcare, engineering, and economics, solidifying its influence worldwide. Fuzzy set theory and fuzzy logic play an increasingly important role in Saudi Arabian research, especially in areas like decision-making, control systems, healthcare, and energy. This aligns well



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with Saudi Arabia's Vision 2030 goals, which emphasize artificial intelligence, sustainability, and technological innovation.

Bibliometric analysis (Broadus [2] and Pritchard [3]) provides valuable insights into scientific publications, helping to evaluate trends (Tukey [4]), the influence of research in specific fields (Glanzel et al., [5]), and scholarly impact (Diem & Wolter, [6]). At the same time, numerous bibliometric studies have focused on fuzzy set theories, for instance (Merigó et al., [7]; Alfaro-García et al., [8]; Blanco-Mesa et al., [9]; Chen et al., [10]; Liu & Liao, [11]) and (Yu et al., [12]) visualized the fuzzy linguistic knowledge domains. The bibliometric research on fuzzy logic has been widely conducted globally, evaluating the contributions of various countries, particularly in China (Yu et al., [13]), the USA and Canada (Merino-Arteaga, [14]), Spain (López Herrera et al., [15]), and its interdisciplinary applications by Shukla [16], and Radu et al. [17] conducted a bibliometric analysis of Iran's position in the global fuzzy logic landscape using international scientific databases.

In recent studies, the Saudi authors have demonstrated the growing use of bibliometric and scientometric methods across various fields. For example, Gulzar et al. [18] analyzed mobile learning research, while Ghalambaz et al. [19] examined AI applications in fluid flow and heat transfer. Al-Jamimi et al. [20] discussed bibliometric indicators in emerging economies, and Majeed et al. [21] explored self-citation and h-index correction. Regional analyses include hypertension research in Saudi Arabia (Anwer & Malik, [22]), scientometrics of leading anesthesia journals by Mowafi [23], and a decade of AI in energy storage systems by Hakeem & Alqutaibi [24]. The research performance in developing countries explored by Soroya et al. [25], and the neurosurgical research progress of 98 low and lower-middle-income countries examined by Abdelwahab et al. [26]. The scientometric exploration of the machine learning contribution in energy storage (Ajibade et al., [27]). (Ahmad et al., [28]) investigated big data and citation analysis, while Hakeem et al. [29] studied regenerative endodontics research performance and trend in Saudi Arabia. These studies collectively underscore the significance of bibliometric methodologies in mapping research landscapes, evaluating scholarly impact, and identifying future research trajectories across scientific and geographic boundaries.

However, a similar study on fuzzy research's thematic evolution, institutional productivity, and citation performance in Saudi Arabia is yet to be explored. To address this gap, this study aims to provide a comprehensive bibliometric analysis of fuzzy research in Saudi Arabia, evaluating its development, influence, and scholarly profile. This study will examine the following:

- Identify the influential keywords and research topics in Saudi Arabian fuzzy research.
- Determine the leading journals and research fields publishing work from Saudi Arabia.
- Examine publication and citation trends, identifying the most influential papers.
- Identify the authors, institutions, and countries most productive in collaborating with Saudi Arabian researchers.
- Provide recommendations for further development based on existing trends and gaps in the field.

The proposed study is organized as follows: Section 2 presents the methodology employed. Section 3 showcases the results, including the annual publications and citation structure, highly cited authors, and key contributors such as authors, institutions, and countries. Section 4 presents the visual study of bibliometric indicators through VOS viewer and Bibliometrix software. Finally, section 5 discusses the findings and conclusions of the study.

2 | Methodology

Bibliometric analysis has evolved significantly over the years, with various contributions to the foundational concepts and methods. Broadus [2], Pritchard [3], and Rousseau [30] laid the groundwork for defining bibliometrics, while Bar-Ilan [31] and Ding et al. [32], expanded on general bibliometric ideas. Garfield's pioneering work (Garfield, [33-35]) on the origin and history of bibliometrics, along with Bensman [36], shaped the understanding of the field's development. Bibliometric indicators, such as the *h*-index introduced by Hirsch [37] and Alonso et al. [38], have become essential in measuring academic impact. The databases,

especially the Web of Science (Clarivate, [39-41]) and Scopus (Scopus, [42]; Elsevier, [43]), are widely used for bibliometric studies. For visualizing the data, *VOS viewer* (Van Eck & Waltman, [44-45]) and *bibliometrix* and *biblioshiny* (Aria & Cuccurullo, [46]) tools are used for visualizing bibliometric networks. Pereira et al. [47] proposed a Python library for bibliometric and scientometric analysis powered by artificial intelligence tools. Further detailed analyses, such as co-citation (Small, [48]), bibliographic coupling (Kessler, [49]), and co-occurrence of keywords (Callon et al., [50]), have played pivotal roles in understanding the relationships between scientific works. Moreover, Ozturk et al. [51] proposed a structured framework for such studies, and Moed et al. [52] provided a foundational tool for assessing research performance, supporting robust bibliometric analysis.

Recent bibliometric work has helped explore the impact of fuzzy logic, its development, and its application in other disciplines. Nica et al. [53] explored the integration of fuzzy logic and AI in financial analysis. The evolution of fuzzy set theory was investigated by Cobo et al. [54].

The study of fuzzy and decision-making related research journals has increased in the recent decade. Wang et al. [55] examined 25 years of the International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, and Tang et al. [56] analyzed a decade of the International Journal of Fuzzy Systems. Merigó et al. [57] reviewed 30 years of the International Journal of Intelligent Systems, a decade review of Neutrosophic Sets and Systems (Saqlain et al., [58]), analysis of the Iranian Journal of Fuzzy Systems (Lei et al., [59]), and López-Herrera et al. [60] explored the early years of the International Journal of Information Technology & Decision Making. Other notable studies include overviews of Group Decision and Negotiation (Laengle et al., [61]), IEEE Transactions on Fuzzy Systems (Yu et al., [62]), and International Journal of Information Technology & Decision Making (Liao et al., [63]). Recent research also reflects the increasing work of Saudi researchers in the fields of fuzzy logic, AI, and computational intelligence, specifically in decision-making systems, machine learning systems, and healthcare. Recent bibliometric studies have explored national contributions to fuzzy research, highlighting its global expansion. Saqlain et al. [64] analyzed Turkey's growing influence in the field, while Saqlain et al. [65] examined Pakistan's advancements from 1989 to 2023. Likewise, Kumam et al. [66] reviewed fifty years of fuzzy logic research in Iran, tracing its evolution from theory to modern applications. However, the influence of these contributions on international academic assessment has barely been investigated, and further bibliometric research is required to understand the fuzzy research activity of Saudi Arabia.

Figure 1 presents the procedure of systematic literature review (SLR) followed in the proposed work according to the SPAR-4-SLR method (Donthu et al., [67]; Paul et al., [68]) and see also [69-71]. These organized steps are assembled, arranged, and assessed. In Step 1 (assembling), the main task is to identify the research domain (fuzzy research in Saudi Arabia) and to develop specific research questions: main author keywords, most cited authors, as well as a broad assessment of publication patterns and citations. Data acquisition is based on the Scopus database for the period of 1981–2024, collected in March 2025, covering 458,280 documents related to the search topic “fuzz*”. Step 2 (arranging) is related to cleaning and normalization of the collected information. Exclusions are used to remove 2025 publications and filter the document type to articles and reviews, resulting in 258,002 documents. Setting publication stage to final and country as Saudi Arabia, the dataset is further constrained to 5,719 records.

The entire study is based on this number. For data cleaning, organizing, metric, and graphical analysis, the tools used are *MS Excel*, *Bibliometrix*, and *VOS viewer*. Step 3 (evaluation): performance analysis, bibliometric indicators, and graphing mapping, for example, co-citation and co-occurrence analysis. This step aims to identify the hot topics and leading research areas, as well as productive authors and institutions, and suggest future research directions.

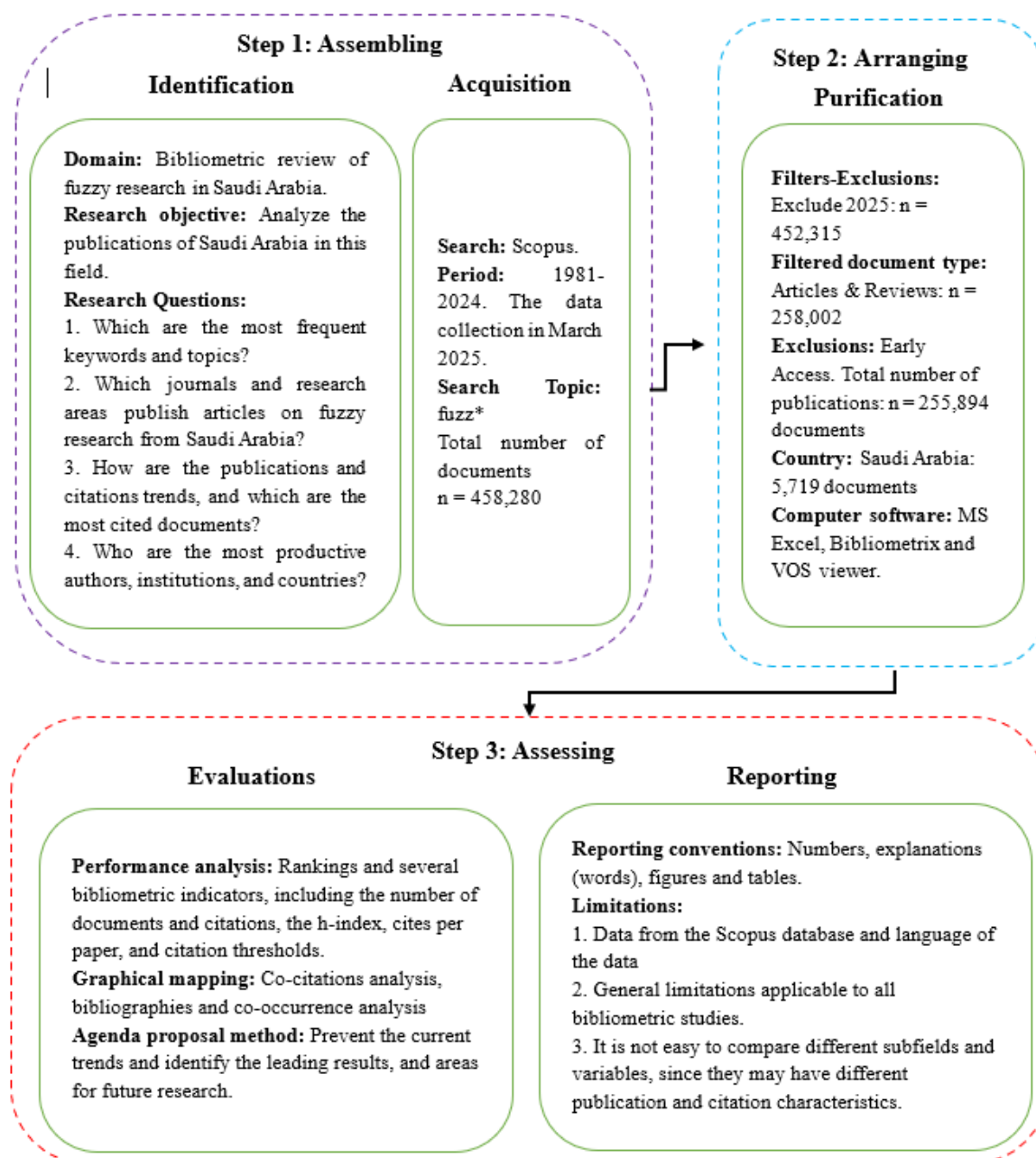


Figure 1. SPAR-4-SLR methodology for the proposed study.

3 | Results

In this section, we discuss the bibliometric analysis of fuzzy research in Saudi Arabia. It is divided into three subsections. The first subsection signifies the metric analysis of the publication and citation structure of fuzzy research from Saudi Arabia. Subsection 2 presents the most cited documents of Saudi authors and influential research papers cited by Saudi researchers. Subsection 3 represents the most productive authors, co-authors, influential institutes, most productive co-author institutes, and most productive collaborating countries.

3.1 | Publication and Citation Structure of Fuzzy Research in Saudi Arabia

Table 1 provides the annual citation report of fuzzy research in Saudi Arabia, capturing both the productivity (total papers, TP) and scholarly impact (total citations, TC) over the period from 1981 to early 2024. During this period, a total of 5,719 publications were produced, accumulating 111,381 citations using fuzzy sets. The early period from 1981 to 2001 was relatively modest, with only 85 publications and 2,439 citations.

Nevertheless, this period witnessed some influential contributions, as evidenced by two papers with at least 200 citations and four papers with more than 100 citations, signifying the presence of early seminal work in the field.

From 2002 to 2011, fuzzy research in Saudi Arabia started a steady growth phase. The publication counts gradually increased from 9 in 2002 to 49 in 2011, while the number of citations also increased, reaching a total of 6,514 during this decade. This period was marked by consistent improvement in the proportion of cited papers, with many papers surpassing citation thresholds of 20 and 50, particularly in the years 2009 and 2011. In this period, only five papers were cited more than 200 times, and in the period 2007-2011, no paper was cited at such a frequency. In other categories of citation, a continuously increasing trend has been observed, which indicates the quality of fuzzy research produced. The period from 2012 to 2018 saw a rapid expansion in research activity. The number of publications increased significantly from 60 in 2012 to 216 in 2018, and this period alone generated 38,255 citations, about 34% of the total citations in the dataset. This phase is notable for its high-impact output: 26 papers with 200 citations, and this ratio is very high compared to the previous phases. It can also be seen in Table 1 that no category of citation was zero during this era, which means there has been steady progress in literature.

Table 1. Annual citation structure of fuzzy research in Saudi Arabia.

Year	TP	TC	≥ 200	≥ 100	≥ 50	≥ 20	≥ 10	≥ 5	≥ 1
1981-2001	85	2,439	2	4	15	28	40	54	72
2002	9	633	1	1	1	3	5	6	8
2003	12	1,478	3	4	4	5	6	6	10
2004	13	352	0	1	3	5	6	9	13
2005	17	581	0	1	5	9	12	15	16
2006	10	830	1	1	2	5	8	8	9
2007	13	160	0	0	0	2	5	10	12
2008	15	159	0	0	1	3	6	10	13
2009	26	814	0	3	6	9	13	18	24
2010	30	573	0	0	3	11	19	21	27
2011	49	1,044	0	2	8	15	21	30	40
2012	60	1,719	1	4	10	20	39	55	57
2013	97	4,249	4	10	22	38	56	70	90
2014	120	4,850	5	9	27	57	78	93	111
2015	154	6,249	4	17	27	75	98	122	144
2016	164	5,644	4	11	36	80	107	126	152
2017	184	6,998	4	19	36	87	118	145	179
2018	216	7,546	4	21	52	99	138	172	205
2019	344	10,448	1	19	68	156	225	267	323
2020	476	12,629	3	14	72	202	304	374	457
2021	728	16,547	1	16	81	292	465	595	701
2022	988	14,345	1	9	42	224	482	680	927
2023	984	7,943	0	0	14	94	242	482	871
2024	925	3,151	0	0	2	27	90	204	617
Total	5,719	111,381	39	164	532	1,546	2,578	3,558	5,078
%	100	100	0.68	2.87	9.30	27.03	45.08	62.21	88.79

Abbreviations: TP and TC = Total papers and citations; ≥ 200 , ≥ 100 , ≥ 50 , ≥ 20 , ≥ 10 , ≥ 5 , ≥ 1 = Number of papers with equal or more than 200, 100, 50, 20, 10, 5, and 1 citations.

The years 2019 to 2021 can be considered a peak period for fuzzy research in Saudi Arabia. An impressive 1,548 papers were published in just these three years, with 728 papers in 2021 alone, the highest annual figure

observed. Citation counts also peaked, with 16,547 citations recorded in 2021. More than 60% of the papers published in 2020 and 2021 received at least 10 citations, reflecting not only high productivity but also significant scholarly influence. While the number of papers receiving 100 or more citations remained stable, the consistency in citation performance indicates a wide-reaching impact across the broader scientific community.

However, in the most recent years (2022–2024), there has been a decline in terms of total publications and citation count. The total publication count of 14,345 in 2022 was reduced to 7,943 in 2023, and this trend continued in 2024 as well. Very interestingly, no paper has been cited more than 200 times during 2023 and 2024. Overall, the years 2015 to 2024 appear to be a golden era in terms of both productivity and impact, reflecting a strategic focus on computational intelligence, likely aligned with national initiatives and increased investments in AI-related domains. Although citation numbers have temporarily declined in the most recent years, this is a common trend in scientometric studies due to citation lag, and future evaluations may show further growth.

Figure 2 illustrates the annual trends in publications and citations related to fuzzy research in Saudi Arabia. The bar and box plots represent the distribution of publications each year, while green dots above specific years indicate peak citation counts, with the highest being 902 citations in 2015. Notably, 2003, 2005, and 2015 also stand out with significant citation spikes (689, 667, and 587 citations, respectively), suggesting highly influential works during those periods. Despite a steady increase in publication volume over the years, citations appear concentrated around specific standout years, highlighting sporadic bursts of impactful research.

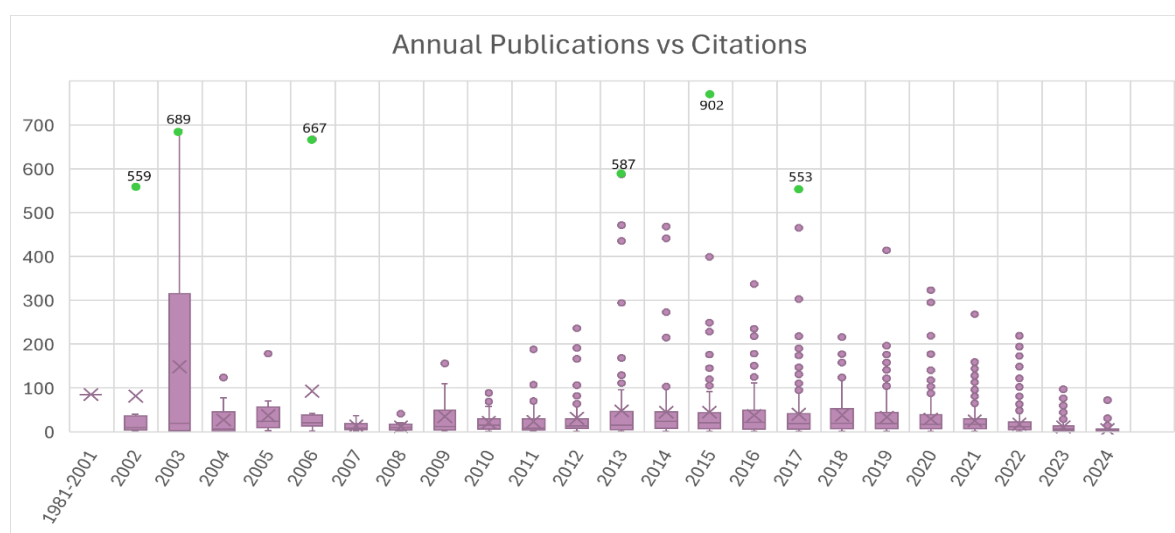


Figure 2. Annual citation and publication structure of fuzzy research in Saudi Arabia.

Table 2 provides a comprehensive overview of the publication performance of journals that have published fuzzy research with contributions from Saudi Arabia. The analysis includes a diverse set of journals, highlighting variations in output, impact, and time-period-specific productivity. The data clearly indicate that open-access journals are leading in terms of both the number of publications and citations, reflecting the increasing preference of researchers for high-visibility platforms. This trend may also reflect an awareness among authors regarding the time-sensitivity of publication processes, particularly since free-of-cost journals often have longer turnaround times. Among all, IEEE Access emerges as the most prolific outlet, publishing 345 papers with 6,878 citations, yielding a high h-index of 42 and an impressive average of 20.05 citations per paper. A noteworthy concentration of its output (244 papers) appears during the 2020–2023 period, indicating its growing popularity among Saudi researchers in recent years. Closely following are other open-access journals such as Mathematics (MDPI) and AIMS Mathematics, with 174 and 170 publications, respectively. Although their citation profiles differ, with Mathematics accumulating 1,701 citations (C/P: 9.77) and AIMS Mathematics collecting 1,062 (C/P: 6.39), they share a typical pattern of sharply increased output in the most

recent period (P3), where 145 and 127 of their papers were published, respectively. The journal Symmetry (MDPI) ranks fourth with 152 publications and 2,116 citations, while Sustainability (MDPI) follows with 148 papers and 2,724 citations. This cluster of MDPI journals occupying leading positions illustrates a growing synergy between fuzzy research and multidisciplinary open-access venues. Beyond these, several specialized journals have shown consistent progress over time in both productivity and citation impact. Journals such as the Journal of Intelligent & Fuzzy Systems, IEEE Transactions on Fuzzy Systems, Soft Computing, Fuzzy Sets and Systems, International Journal of Fuzzy Systems, and Arabian Journal of Science & Engineering demonstrate stable contributions across all three time periods (P1 to P3). For instance, IEEE Transactions on Fuzzy Systems, while featuring fewer total publications (101), stands out with a high citation impact of 4,475 citations, an h-index of 39, and an average of 44.31 citations per paper. It also produced 10 papers cited over 100 times, underlining its status as a high-impact venue. Likewise, Fuzzy Sets and Systems, though with 61 papers, amassed 1,451 citations (C/P: 23.79), publishing a significant portion of its articles during P1, suggesting a historical strength in foundational contributions. Meanwhile, journals such as Scientific Reports, Mathematical Problems in Engineering, and Energies reflect moderate productivity and impact. For example, Energies published 68 papers with a commendable average of 21.46 citations per article. In contrast, lower-impact journals like Heliyon and International Journal of Neutrosophic Sciences have limited visibility and citation metrics, with average citations per article falling below 3, despite publishing over 40 articles each. A special note must be made for journals with zero publications during a specific period. For instance, the Journal of Mathematics (Hindawi) did not have entries during P1 and P2, likely due to the journal not being indexed in the Web of Science during those years.

Overall, Table 2 demonstrates that the period P3 (2020–2023) is the most productive in terms of journal research on fuzzy sets, with most of the publications across nearly all journals concentrated in this recent period. This shows the continuous acceleration in research publications in the fuzzy sets environment. The other fact of this acceleration is the continuous institutional and government financial support to publish in high-quality open-source journals, which not only saves the time of publication but also showcases the recent development of fuzzy sets' research well in time for the readers.

Table 2. Publication record of journals in fuzzy research from Saudi Arabia.

R	Journal name	TP	TC	H	C/P	≥100	≥50	≥10	P1	P2	P3
1	IEEE Access	345	6,878	42	20.1	9	32	175	0	12	244
2	Mathematics	174	1,701	21	9.8	0	5	63	0	2	145
3	AIMS Mathematics	170	1,062	16	6.4	0	1	33	0	0	127
4	Symmetry	152	2,116	26	13.9	1	13	60	0	8	128
5	Sustainability	148	2,724	28	21.6	3	13	79	0	3	124
6	Journal of Intell & Fuzzy Syst	133	1,732	23	12.8	2	5	49	5	27	91
7	Comp Materials & Continua	114	979	16	8.6	0	2	34	0	0	104
8	IEEE Trans on Fuzzy Syst.	101	4,475	39	44.3	10	33	82	3	40	53
9	Scientific Reports	86	433	13	5.3	0	0	19	0	0	29
10	Mathematical Prob in Engineering.	74	848	17	11.5	0	2	29	2	8	64
11	Soft Computing	73	1,575	20	21.3	3	5	34	3	22	45
12	Energies	68	1,438	20	21.5	1	6	34	0	4	56
13	Applied Sciences Switzerland	66	843	18	12.8	0	1	34	0	0	62
14	Fuzzy Sets and Systems	61	1,451	23	23.8	1	8	37	32	16	11
15	International J Neutro Sciences	43	119	5	2.2	0	0	2	0	0	12
16	Heliyon	53	151	6	2.8	0	0	2	0	0	11
17	International J of Fuzzy Syst.	47	1,497	21	31.9	4	10	30	2	13	23
18	Arabian J Science & Eng	45	584	14	13.0	0	1	12	13	8	23
19	Journal of Mathematics	43	393	10	9.1	0	2	13	1	0	39
20	Alexandria Engineering Journal	41	632	15	13.7	1	2	21	1	0	28

Abbreviations: TP, TC, C/P and H = Total publications, citations, cites per paper and *h*-index available in WoS; ≥ 100 and ≥ 10 = Number of articles with equal or more than 100 and 10 citations; P1 = 1981-2014; P2 = 2015-2019; P3 = 2020-2024.

Table 3 presents the 20 highly cited sources in fuzzy research in Saudi Arabia. The documents are ordered according to citation count (TC), and Zadeh's 1965 article titled "Fuzzy Sets" received the most citations (1,147). This demonstrates the profound impact of Zadeh's seminal paper in forming fuzzy logic. Atanasov's 1986 paper "Intuitionistic Fuzzy Sets" is the second most cited document with 430 citations, so it has been a major contributor to developing the theory of fuzzy models. The next follows Bezdek's 1981 book, which was published by Springer with 105 citations, and gives again an indication of the influence of some of the early fuzzy logic publications.

Other important studies include those of Yager, cited 95 times. The paper represents the growing application and innovation of fuzzy systems in different areas, such as decision-making and artificial intelligence. Xu (2007), Torra (2010), and Ramot (2002) have citation counts between 87 and 82. These papers represent the increasing interest in fuzzy systems and their applications to intelligent systems and decision-making processes. Concerning document types of top-cited work, the majority are journal articles (labeled as "A") and some books and conference proceedings. The table further shows a variety of authors and publication years, which illustrates the long evolution of fuzzy logic and the importance of such research to the present arena. For instance, the recent papers published by authors such as Zhang (2014) and Mahmood (2019) are indicative of continuous progress in the field, especially in the neural computing and artificial intelligence areas, which are increasingly intertwined with fuzzy systems.

Table 3. Top 20 most cited documents in Fuzzy research in Saudi Arabia.

Rank	Year	First Author	Reference	Vol	Page	Type	TC
1	1965	Zadeh L. A.	Inf. Cont.	8	pp. 338-353	A	1,147
2	1986	Atanassov K.T.	Fuzzy Sets Syst.	20	pp. 87-96	A	430
3	1981	Bezdek J.C.	Springer	-	-	B	105
4	2013	Yager R. R.	2013 Joint IFSA World Congress	2013	pp. 57-61	C	95
5	2007	Xu Z.	IEEE Trans. Fuzzy Syst.	15(6)	pp. 1179-1187	A	87
6	2010	Torra V.	Int. J. Intell. Syst.	25	pp. 529-539	A	83
7	2002	Ramot D.	IEEE Trans. Fuzzy Syst	10	pp. 171-186	A	82
8	1987	Kaleva O.	Fuzzy Sets Syst	24	pp. 301-317	A	54
9	1980	Saaty T.L.	Mathe. Modelling	9(3-5)	pp. 161-176	A	51
10	1999	Molodtsov D.	Comput. Math. Appl	37	pp. 19-31	A	39
11	2013	Pedrycz W.	CRC Press	-	-	B	37
12	1994	George A.	Fuzzy Sets Syst	64	pp. 395-399	A	35
13	1971	Rosenfeld A.	J. Math. Anal. Appl	35	pp. 512-517	A	32
14	2014	Zhang X.	Int. J. Intell. Syst.	29(12)	pp. 1061-1078	A	32
15	1999	Podlubny I.	Academic Press	-	-	B	28
16	1975	Kramosil I.	Kybernetika	11	pp. 336-344	A	27
17	2019	Mahmood T.	Neural Comput. Appl	31	pp. 7041-7053	A	27
18	2015	Peng X.	Int. J. Intell. Syst.	30(11)	pp. 1133-1160	A	27
19	2012	Allahviranloo T.	Soft Comput.	16	pp. 297-302	A	26
20	1988	Grabiec M.	Fuzzy Sets Syst	27	pp. 385-389	A	25

Abbreviations: TC = Total citations; A = Article; B = Book; C = Conference.

Overall, the table shows that the early significant work had a strong impact on the subsequent development of fuzzy research, especially those by Zadeh and Atanasov. It also shows how fuzzy logic has been extended in the past and describes the newly developed tools of fuzzy logic, some of which shape newly emerging concepts in artificial intelligence, neural computing, and decision making.

3.2 | Influential Papers of Fuzzy Research in Saudi Arabia

Table 4 presents the 30 most-cited publications in fuzzy research associated with Saudi Arabia, highlighting significant contributions from prominent scholars. The highest-ranked publication, authored by Rade D. Paravina, is titled “Color Difference Thresholds in Dentistry,” published in the *Journal of Esthetic and Restorative Dentistry* in 2015. This interdisciplinary research has garnered 836 citations, averaging an impressive 92.89 citations per year, reflecting its broad recognition and relevance beyond the primary field of fuzzy systems. Mohammad A. Abido stands out as a prominent figure in the landscape of fuzzy research in Saudi Arabia, with four high-impact papers included in the top 30 list, collectively garnering 1,995 citations. His work primarily focuses on multi-objective optimization and power system operations, reflecting substantial contributions to the application of fuzzy logic in energy and engineering decision-making.

Following Mohammad A. Abido, two other prominent researchers, Iván Palomares Carrascosa and Rosa María Rodríguez, have each contributed two influential publications to the list. Iván Palomares Carrascosa’s work on consensus modeling in fuzzy group decision-making has received a combined total of 741 citations. These include “A consensus model to detect and manage noncooperative behaviors in large-scale group decision making” (468 citations) and “Consensus under a fuzzy context: Taxonomy, analysis framework AFRYCA and experimental case of study” (273 citations). Similarly, Rosa María Rodríguez’s research on hesitant fuzzy sets has received 676 citations, notably through “Hesitant fuzzy sets: State of the art and future directions” (441 citations) and “A position and perspective analysis of hesitant fuzzy sets on information fusion in decision making”. Towards high-quality progress (235 citations), both contributed significantly to the theoretical advancement of fuzzy set theory. Other noteworthy contributions include studies in fuzzy clustering, renewable energy, sentiment analysis, and healthcare applications. Year-wise, Shokri Z. Selim's contribution in 1991, “A simulated annealing algorithm for the clustering problem,” is the oldest paper with 388 citations, and Tie-Hong Zhao's contribution, “A fuzzy-based strategy to suppress the novel coronavirus (2019-ncov) massive outbreak,” is the latest publication with 268 citations. Notably, the data indicate an absence of top-cited publications from the years 2022 and 2024, suggesting that the most impactful research in this domain has yet to emerge from the most recent publication period.

Table 4. The 50 most cited documents of fuzzy research in Saudi Arabia.

R	Title	Authors	Source	Year	TC
1	Color difference thresholds in dentistry	Paravina R.D.; Ghinea R.; Herrera L.J.; Bona A.D.; Igiel C.; Linninger M.; Sakai M.; Takahashi H.; Tashkandi E.; Del Mar Perez M.	J Esthet Restor Dent	2015	902
2	Environmental/Economic Power Dispatch Using Multiobjective Evolutionary Algorithms	Abido M.A.	IEEE T Power Syst	2003	689
3	Multiobjective evolutionary algorithms for the electric power dispatch problem	Abido M.A.	EEE T Evolut Comput	2006	667
4	Multiobjective intelligent energy management for a microgrid	Chaouachi A.; Kamel R.M.; Andoulsi R.; Nagasaka K.	IEEE T Ind Electron	2013	587
5	Electric load forecasting: Literature survey and classification of methods	Alfares H.K.; Nazeeruddin M.	Int J Syst Sci	2002	559
6	An extended TODIM multi-criteria group decision-making method for green supplier selection in an interval type-2 fuzzy environment	Qin J.; Liu X.; Pedrycz W.	Eur J Oper Res	2017	553

7	Construction projects selection and risk assessment by fuzzy AHP and fuzzy TOPSIS methodologies	Taylan O.; Bafail A.O.; Abdulaal R.M.S.; Kabli M.R.	Appl Soft Comput	2014	482
8	IAMP-2L: A two-level multi-label classifier for identifying antimicrobial peptides and their functional types	Xiao X.; Wang P.; Lin W.-Z.; Jia J.-H.; Chou K.-C.	Anal Biochem	2013	471
9	A consensus model to detect and manage noncooperative behaviors in large-scale group decision making	Palomares I.; Martínez L.; Herrera F.	IEEE T Fuzzy Syst	2014	468
10	Fuzziness-based semi-supervised learning approach for intrusion detection system	Ashfaq R.A.R.; Wang X.-Z.; Huang J.Z.; Abbas H.; He Y.-L.	Inform Sciences	2017	465
11	Hesitant fuzzy sets: State of the art and future directions	Rodríguez R.M.; Martínez L.; Torra V.; Xu Z.S.; Herrera F.	Int J Intell Syst	2014	441
12	MPPT techniques for photovoltaic applications	Eltawil M.A.; Zhao Z.	Renew Sust Energ Rev	2013	435
13	State of the art of machine learning models in energy systems: a systematic review	Mosavi A.; Salimi M.; Ardabili S.F.; Rabczuk T.; Shamshirband S.; Varkonyi-Koczy A.R.	Energies	2019	414
14	A comprehensive comparison of different MPPT techniques for photovoltaic systems	Rezk H.; Eltamaly A.M.	Sol Energy	2015	399
15	A simulated annealing algorithm for the clustering problem	Selim S.Z.; Alsultan K.	Pattern Recognition	1991	388
16	Some aspects of variational inequalities	Noor M.A.; Noor K.I.; Rassias T.M.	Comput Appl Math	1993	348
17	Numerical solutions of fuzzy differential equations using the reproducing kernel Hilbert space method	Abu Arqub O.; AL-Smadi M.; Momani S.; Hayat T.	Soft Comput	2016	337
18	A novel multiobjective evolutionary algorithm for environmental/economic power dispatch	Abido M.A.	Electr Pow Syst Res	2003	328
19	An Experimental Estimation of Hybrid ANFIS-PSO-Based MPPT for PV Grid Integration under Fluctuating Sun Irradiance	Priyadarshi N.; Padmanaban S.; Holm-Nielsen J.B.; Blaabjerg F.; Bhaskar M.S.	IEEE Syst J	2020	323
20	A niched Pareto genetic algorithm for multiobjective environmental/economic dispatch	Abido M.A.	Int J Elec Power	2003	311
21	Double hierarchy hesitant fuzzy linguistic term set and MULTIMOORA method: A case study to evaluate the implementation status of haze controlling measures.	Gou X.; Liao H.; Xu Z.; Herrera F.	Inform Fusion	2017	303
22	Sentiment Analysis of COVID-19 tweets by Deep Learning Classifiers: A study to show how popularity is affecting accuracy in social media	Chakraborty K.; Bhatia S.; Bhattacharyya S.; Platos J.; Bag R.; Hassanien A.E.	Appl Soft Comput	2020	295

23	Building the fundamentals of granular computing: A principle of justifiable granularity	Pedrycz W.; Homenda W.	Appl Soft Comput	2013	294
24	Consensus under a fuzzy context: Taxonomy, analysis framework AFRYCA, and experimental case of study	Palomares I.; Estrella F.J.; Martínez L.; Herrera F.	Inform Fusion	2014	273
25	A fuzzy-based strategy to suppress the novel coronavirus (2019-nCoV) massive outbreak	Zhao T.-H.; Castillo O.; Jahanshahi H.; Yusuf A.; Allassafi M.O.; Alsaadi F.E.; Chu Y.-M.	Appl Comput Math	2021	268
26	Fuzzy clustering of time series data using dynamic time warping distance	Izakian H.; Pedrycz W.; Jamal I.	Eng Appl Artif Intel	2015	249
27	Modeling and simulation of an Adaptive Neuro-Fuzzy Inference System (ANFIS) for mobile learning	Al-Hmouz A.; Shen J.; Al-Hmouz R.; Yan J.	IEEE T Learn Technol	2012	236
28	A position and perspective analysis of hesitant fuzzy sets on information fusion in decision making. Towards high-quality progress	Rodríguez R.M.; Bedregal B.; Bustince H.; Dong Y.C.; Farhadinia B.; Kahraman C.; Martínez L.; Torra V.; Xu Y.J.; Xu Z.S.; Herrera F.	Inform Fusion	2016	235
29	Hesitant Fuzzy Linguistic Term Set and Its Application in Decision Making: A State-of-the-Art Survey	Liao H.; Xu Z.; Herrera-Viedma E.; Herrera F.	Int J Fuzzy Syst	2018	229
30	A Study on the Relationship Between Generalization Abilities and Fuzziness of Base Classifiers in Ensemble Learning	Wang X.-Z.; Xing H.-J.; Li Y.; Hua Q.; Dong C.-R.; Pedrycz W.	IEEE T Fuzzy Syst	2015	228

Abbreviations are in the previous tables.

The data also suggests that most cited papers have an applied nature rather than a fundamental theory. From the data, it is also clear that *IEEE.org* is the top publishing venue.

3.3 | Most Productive Authors, Institutions, and Countries

Table 5 provides a comprehensive overview of the top 20 most productive authors affiliated with Saudi universities who have contributed significantly to fuzzy research. At the forefront is Ghulam Muhiuddin from Tobruk University, who has the highest number of publications (88), reflecting exceptional productivity. However, his citation per paper (C/P = 11.32) and *h*-index (18) suggest a moderate impact per article. Similarly, Muhammad Naeem and Muhammad Aslam also stand out for high productivity, with 76 and 63 publications, respectively. Notably, Muhammad Aslam appears twice in the list, affiliated with both King Khalid University and King Abdulaziz University, indicating either concurrent appointments or a recent transition, which highlights his sustained contribution across institutions. In terms of scholarly impact, Mohammad A. Abido from King Fahd University of Petroleum and Minerals emerges as the most influential figure, with a total citation count of 3,324 and an exceptional citations-per-paper ratio of 85.23. His eight papers with ≥ 100 citations and 22 papers with ≥ 10 citations further underscore the high quality and influence of his work. Similarly, Abdulazeez Abdulraheem (TC = 1,299; C/P = 30.93) and Fuad E. Alsaadi (TC = 1,738; C/P = 69.52) also reflect high-impact contributions with substantial *h*-index scores. These authors demonstrate that while productivity is important, scholarly influence is better reflected through citations and the quality of output.

Another observation is the increasing trend in research productivity during the period 2019–2023 (P3), where most authors show their peak output. For example, Ghulam Muhiuddin published 73 of his 88 papers during this period, indicating a notable increase in activity, which reflects a rising interest in and institutional backing

for fuzzy research in Saudi Arabia. The prominent institutions contributing to this scholarly output include King Fahd University of Petroleum and Minerals, King Abdulaziz University, Prince Sultan University, and King Khalid University, which are becoming national centers for fuzzy research and fostering international collaborations.

Table 5. Top 20 most productive authors in fuzzy research in Saudi Arabia.

R	Author Name	University	Country	TP	TC	H	C/P	≥10 0	≥1 0	P 1	P 2	P 3
1	Muhiddin G	Tobruk U	SAR	88	996	18	11.3	1	32	0	11	73
2	Naeem M.	Umm Al Qura U	SAR	76	744	16	9.8	0	30	4	0	67
3	Aslam M.	King Khalid U	SAR	63	942	17	15.0	1	22	2	5	50
4	Elkatatny S.	King Fahd U	SAR	45	1,171	22	26.0	1	33	0	5	40
5	Abdeljawad T.	Prince Sultan U	SAR	44	599	15	13.6	0	22	0	0	35
6	Abdulraheem A.	KFUPM	SAR	42	1,299	23	30.9	2	34	3	7	31
7	Abido M.A.	KFUPM	SAR	39	3,324	22	85.2	8	27	2	12	4
8	Al Quran A.	King Faisal U	SAR	36	289	10	8.0	0	10	0	0	18
9	Al-Kenani A. N.	King Abdulaziz U	SAR	35	665	15	19.0	0	18	0	0	32
10	Aslam M.	King Abdulaziz U	SAR	34	882	17	25.9	1	25	0	8	25
11	Hezam I.M.	King Saud U	SAR	33	490	13	14.8	0	14	0	0	24
12	Haider H.	Qassim U	SAR	31	493	14	15.9	0	17	0	9	19
13	Ghoneim S.S.M	Taif U	SAR	31	646	15	20.8	0	20	0	2	23
14	Taylan O.	King Abdulaziz U	SAR	29	1,192	14	41.1	1	21	7	11	10
15	Abba S.I.	Prince MB U	SAR	28	281	9	10.0	0	9	0	0	18
16	Hussain N.	King Abdulaziz U	SAR	27	320	10	11.9	0	12	0	8	15
17	Soliman M.S.	Taif U	SAR	25	355	10	14.2	0	10	0	0	25
18	Mlaiki N.	Prince Sultan U	SAR	25	109	7	4.4	0	2	0	0	17
19	Alsaadi F.E.	King Abdulaziz U	SAR	25	1,738	19	69.5	8	22	0	16	9
20	Kchaou	U Hail	SAR	24	250	9	10.4	0	8	0	5	14
Co-authors from other countries												
1	Pedrycz, W.	U Alberta	CAN	278	9,362	51	34.7	16	198	16	127	120
2	Akram M.	Punjab U	PAK	80	1,859	25	23.0	1	59	5	12	58
3	Rezk H.	Minya U	EGY	80	2,691	29	33.6	5	54	0	2	72
4	Abdullah S.	AW Khan U	PAK	76	1,352	19	17.8	1	41	4	7	60
5	Herrera F.	U Granada	ESP	66	6,679	47	101.2	24	63	0	38	26
6	Khan R.A.	BBA Ambedkar U	IND	61	1,470	23	24.1	1	48	0	0	60
7	Khalifa H.A.E.-W.	Cairo U	EGY	56	264	9	4.7	0	8	0	0	31
8	Mahmood T.	Int. Islamic U	PAK	55	472	10	8.6	0	11	0	1	37
9	Kumar R.	ASC India	IND	54	1,595	25	29.5	1	45	0	0	54

10	Herrera-Viedma E	U Granada	ESP	54	2,844	29	52.7	10	46	0	21	33
11	Agrawal A.	BBA Ambedkar U	IND	53	1,352	22	25.5	1	43	0	0	52
12	Khan M. B.	Transilvania U	BSV	47	533	12	11.3	0	21	0	0	45
13	Mshra A. R.	Govt. C.Raigaon	IND	45	1,287	20	28.6	1	31	0	0	35
14	Rani P.	Deemed U	IND	44	1,238	19	28.1	2	29	0	0	33
15	Ashraf S.	Bacha Khan U	PAK	42	759	15	18.1	1	19	0	0	34
16	Siddique I.	U Sargodha	PAK	41	568	15	13.9	0	19	0	0	34
17	Li Z.	Macau U Sci. Tech	MAC	41	905	19	22.1	0	29	1	9	28
18	Liao H	Sichuan U	CHN	40	2,582	26	64.6	7	34	0	9	31
19	Zulqarnain R.M.	Saveetha S Engg	IND	39	681	16	17.5	0	19	0	0	33
20	Riaz M.	Punjab U	PAK	39	373	11	9.6	0	13	0	0	31

Abbreviations in previous tables.

The second section of the table emphasizes key international co-authors who have partnered with Saudi-based researchers in the field of fuzzy sets. Witold Pedrycz from the University of Alberta, Canada, boasting an impressive portfolio with 270 publications, 9,362 citations, and an *h*-index of 51, is leading the chart and 198 research papers with ten or more citations and 16 papers with a hundred or more citations, highlighting not only his extensive productivity but also a consistent record of influential research in fuzzy sets. Similarly, Francisco Herrera, who is associated with the department of computer science and artificial intelligence, Andalusian Institute on Data Science and Computational Intelligence (DaSCI), University of Granada, Granada, Spain, demonstrates an even higher citation per paper ratio ($C/P = 101.2$), with a total of 6,679 citations across 66 publications. Enrique Herrera-Viedma from the same University of Granada, another prominent Spanish scholar, further enhances this collaborative network with a strong *h*-index of 29 and high-quality contributions.

Contributors from Pakistan and India, prominently featured with Saudi institutions, are leading in terms of co-authorships with Saudi Researchers. Muhammad Akram (Punjab University), Saleem Abdullah (Abdul Wali Khan University), Tahir Mehmood (International Islamic University), Shahzaib Ashraf (Bacha Khan University), Imran Siddique (University of Sargodha), and Muhammad Riaz (Punjab University) are the key contributors from Pakistan. Raees Ahmad Khan (Babasaheb Bhimrao Ambedkar University), Rajeev Humar (Administrative Staff College of India), Alka Agrawal (Babasaheb Bhimrao Ambedkar University), Arunodaya Raj Mishra (Government College Raigaon), and Pratibha Rani (Deemed University) are the top co-authors from India with the Saudi Researchers in Fuzzy sets. Francisco Herrera and Enrique Herrera-Viedma from Spain are the key contributors. Egyptian mathematicians like Hegazy Rezk and Abd El-Wahed Khalifa contribute significantly as well, reflecting North African academic linkage. From China, Huchang Liao contributed, with a high citation average ($C/P = 64.55$) and 26 *h*-index, in fuzzy research methodologies. Another Pakistani-based Chinese Scholar, Rana Muhammad Zulqarnain from Saveetha School of Engineering of China, is the top contributor with 39 Publications. Again, we observed that during P3, there was an increase in publication production, and the co-authors mentioned in Table 4 (second section) played a crucial role in advancing fuzzy set research with Saudi researchers. This increase is also due to the strong financial support from the Saudi government to the Saudi institutions, and they have also expanded the co-authorship linkages with other countries.

Table 6 indicates the most productive and influential institutions in fuzzy research in Saudi Arabia. King Abdulaziz University (KAU) is the leading university in fuzzy research in Saudi Arabia, with 1,304 publications and 39,364 citations. The impressive *h*-index of 94 indicates, and the citation per paper (C/P) ratio of 30.19 highlights the significance and impact of the research produced at KAU in the fuzzy set domain. The university's performance is consistent across different periods, particularly with a significant number of publications (725) in the recent period (P3), suggesting sustained productivity and relevance in the field of fuzzy sets. King Saud University (KSU) ranked second with 769 publications, 14,372 citations, and an *h*-index of 53. Although its C/P ratio of 18.69 is slightly lower than KAU's, it still suggests that the university's research is highly regarded. KSU's research output has grown in P3 with 387 publications. Prince Sattam bin Abdulaziz University ranks third with 460 publications and 6,912 citations, *h*-index of 41. The C/P ratio of 15.03 further highlights the significance of the research produced at this university. Although its recent output in P3 is lower compared to earlier periods, the research conducted in P1 and P2 indicates that Prince Sattam bin Abdulaziz University has been a key contributor to fuzzy research over time, and its impact is growing steadily. King Fahd University of Petroleum and Minerals (KFUPM) ranks fourth with 446 publications and 12,736 citations, boasting a high C/P ratio of 28.56. In comparison, King Khalid University occupies the fifth position with 416 publications and 4,595 citations, and Taif University, ranked sixth, has 406 publications and 6,719 citations, with an *h*-index of 41. Qassim University is ranked seventh with 326 publications and 2,886 citations, with an *h*-index of 28 and a C/P ratio of 8.85, indicating that while Qassim University's research output is substantial, it is not as widely cited as some of the leading institutions. The University of Alberta, Canada, is the first international university ranked seventh after the top seven universities from Saudi Arabia, which have significantly contributed with 271 publications and 9,210 citations. The university boasts an impressive *h*-index of 51 and a C/P ratio of 33.99. The University of Alberta has been a key international collaborator. Its research output and influence in the fuzzy research domain have had a marked impact on the global academic community. This trend is continuously increasing in all the periods from P1 to P3. The C/P ratio of 33.98524 is the best among the top 8 institutions.

The University of Alberta in Canada stands first for its significant contributions to fuzzy research with 271 publications and 9,210 citations. The university boasts an impressive *h*-index of 51 and a C/P ratio of 33.99. Princess Nourah Bint Abdulrahman University (PNU), ranked eighth, has 268 publications and 2,623 citations, with an *h*-index of 25 and a C/P ratio of 9.79. Four Pakistani universities are also among the most productive and influential institutions in fuzzy research in Saudi Arabia. Punjab University is standing in 15th position with 148 publications, due to the research publications of Muhammad Akram and Muhammad Riaz, while Abdul Wali Khan University Mardan, International Islamic University, and Riphah International University are the other three Pakistani institutions standing at 23rd, 25th, and 29th.

Table 6. The most productive and influential institutions in fuzzy research in Saudi Arabia.

R	Institution	TP	TC	H	C/P	≥100	≥10	P1	P2	P3
1	King Abdulaziz U	1,302	41,628	98	31.97	95	801	14	128	1,169
2	King Saud U	781	15,882	57	20.34	22	340	54	81	646
3	Prince Sattam Bin Abdulaziz U	456	7,953	44	17.44	6	222	0	11	445
4	King Fahd U Petr & Minerals	428	13,364	55	31.22	20	257	43	84	30 ⁺
5	King Khalid U	414	5,329	34	12.87	5	156	0	8	406
6	Taif U	409	7,627	43	18.65	10	222	1	19	389
7	Faculty of Engineering, KAU	409	15,766	66	38.55	34	300	0	41	368
8	Qassim U	322	3,332	29	10.35	1	106	0	9	313
9	Princess NBA U	267	3,202	27	11.99	3	99	0	2	265
10	College of Sciences	260	3,825	32	14.71	4	96	14	11	235
11	Faculty of CIT, KAU	243	10,675	57	43.93	32	150	0	9	234
12	Umm Al-Qura U	241	3,794	31	15.74	4	113	0	13	228
13	Faculty of Sciences, KAU	226	5,997	41	26.54	12	129	4	24	198
14	Prince Sultan U	208	3,965	35	19.06	5	106	0	4	204
15	U of Tabuk	185	2,457	28	13.28	3	69	0	9	176
16	King Faisal U	168	3,630	32	21.61	6	77	1	9	158
17	Majmaah U	146	2,179	25	14.92	1	70	0	4	142

18	U of Jeddah	143	2,230	25	15.59	3	56	0	0	143
19	Jazan U	116	1,300	20	11.21	0	37	0	9	107
20	Al-Imam M ibn Saud Isl U	103	1,534	21	14.89	2	40	0	5	98
21	Taibah U	101	1,021	16	10.11	1	30	0	14	87
22	U Ha'il	100	1,814	21	18.14	1	43	0	4	96
23	Jouf U	92	1,868	25	20.3	2	45	0	2	90
24	Najran U	82	1,111	19	13.55	1	36	0	2	80
25	Imam A bin Faisal U	73	1,660	23	22.74	3	44	0	3	70
26	Northern Border U	69	688	15	9.97	0	25	0	0	69
27	Saudi Electronic U	60	676	17	11.27	0	21	0	0	60
28	U of Bisha	56	1,598	18	28.54	5	26	0	0	56
29	Shaqra U	50	568	15	11.36	0	19	0	4	46
30	Prince M Bin Fahd U	47	593	15	12.62	0	21	0	0	47

Abbreviations in previous tables.

Table 7 lists the 20 most productive co-author institutions in fuzzy research in Saudi Arabia, ranked by the total number of publications (TP). The top three institutions are the University of Alberta (Canada), the Polish Academy of Sciences (Poland), and SRI Polish Academy of Sciences (Poland), with a total papers 273, 230, and 227 respectively. These institutions also show high total citations (TC) and citations per paper (C/P), indicating both quantity and quality of research output.

Several Egyptian and Pakistani institutions also feature prominently, such as Cairo University (4th), University of Punjab (5th), and University of Management & Technology (6th). Notably, institutions like the University of Granada (Spain) exhibit high citations per paper (84.29), reflecting impactful publications despite lower overall output. H-index (H), which measures productivity and citation impact, is highest for the University of Granada at 55, reinforcing the influence of its research contributions.

QS rankings are provided for some institutions, highlighting their global academic standing. For example, Cairo University has a QS ranking of 371, while the University of Punjab ranks in the 741-750 range. Several institutions, like COMSATS University and Aligarh Muslim University, also appear in international QS rankings, illustrating their broader recognition in the academic community. The table underscores the international and collaborative nature of fuzzy research in Saudi Arabia.

Table 7. The most productive co-author institutions in fuzzy research in Saudi Arabia.

R	Institution	Country	TP	TC	H	C/P	≥100	≥10	QS
1	U Alberta	CAN	273	9,686	52	35.48	17	195	111
2	Polish Acad.	POL	230	8,560	48	37.22	15	172	-
3	SRI Polish Acad. Sci.	POL	227	8,351	48	36.79	15	170	-
4	Cairo U	EGY	149	1,988	23	13.34	2	48	371
5	U Punjab	PAK	148	3,030	30	20.47	1	89	741-750
6	U Manag & Tech	PAK	133	1,559	21	11.72	1	48	-
7	U Granada	ESP	126	10,620	55	84.29	36	112	-
8	China Medical U	CHN	104	1,764	23	16.96	1	56	-
9	Int. Islamic U	PAK	102	1,142	19	11.2	1	36	1201-1400
10	AW Khan U	PAK	102	1,615	20	15.83	1	46	-
11	Grad. SS Res.	EGY	102	635	12	6.23	0	21	-
12	Minia U	EGY	98	3,423	32	34.93	6	74	-
13	Riphah Int. U	PAK	95	1,159	17	12.2	1	39	-
14	Tanta U	EGY	90	2,457	29	27.3	3	55	1201-1400
15	Hazara U Pakistan	PAK	89	942	15	10.58	0	30	-
16	COMSATS U	PAK	85	1,180	20	13.88	1	48	651-660
17	Mansoura U	EGY	75	1,657	18	22.09	2	37	1001-1200
18	Bab. Bhimrao Amb. U	IND	74	1,980	26	26.76	1	57	-
19	Aligarh Muslim U	IND	74	1,349	21	18.23	1	41	1001-1200
20	Quaid-i-Azam U	PAK	74	2,387	23	32.26	7	39	315

Abbreviations in previous tables except QS = Quacquarelli & Symonds University Ranking.

Table 8 provides a detailed account of Saudi Arabia's 30 most productive international collaborators in fuzzy research, based on total publications (TP), total citations (TC), *h*-index, citations per paper (C/P), and the number of highly cited papers (≥ 100 and ≥ 10). Notably, this analysis excludes Saudi Arabia's statistics and focuses solely on its international partners. Pakistan emerges as the most prolific collaborator with Saudi Arabia, contributing 1,345 publications that garnered 19,008 citations and achieved an *h*-index of 59. Although the citation-per-paper (C/P) value of 17.83 is moderate, the breadth of collaboration is substantial, reflected in 948 publications in P3. India ranks second with 1,041 publications and 16,803 citations, along with a slightly higher *h*-index of 61 and a better C/P value of 20.77 than Pakistan. However, in all other ranking categories, the trend is lower than Pakistan. For instance, India has produced 742 research papers during P3, which is lower than Pakistan.

Egypt follows closely with 950 publications and 15,404 citations, maintaining a healthy C/P of 19.67 and 637 P3 papers, indicating significant trilateral collaborations within the Middle East and South Asia. China stands out for the high impact of its collaboration despite having fewer publications (841), ranking fourth. It boasts 26,886 citations, an impressive *h*-index of 84, and the highest number of papers cited over 100 times (65). With a C/P of 38.91, China represents a key high-impact collaborator. The *h*-index of 84 China is the highest in Table 7, and no other country has achieved such a remarkable position. Canada also shows a strong presence by standing in fifth position, contributing 402 papers with a high C/P of 34.21 and an *h*-index of 59, highlighting the quality of its contributions.

Among countries with high-impact performance, Spain is notable with 239 publications, an *h*-index of 59, and a remarkable C/P of 52.96. Poland (C/P of 36.76), Vietnam (C/P of 42.60), and Japan (C/P of 65.02, despite only 48 papers) further exemplify countries with fewer publications but strong citation performance, indicating that the quality of collaboration is sometimes more significant than the quantity. Regionally, Malaysia, Iran, Turkey, Jordan, Tunisia, Iraq, and the United Arab Emirates are very active in collaborative links with Saudi Arabian researchers. Malaysia, for instance, produced 356 papers with a strong *h*-index of 47 and a solid C/P of 26.26. Iran and Turkey contribute with relatively high-impact research as well, showing C/P values of 32.41 and 22.44, respectively. The United States (US) and the United Kingdom (UK) are also prominent partners. The US contributed to 280 publications with a C/P of 32.50, and the UK produced 253 papers with a slightly higher C/P of 34.43 and an *h*-index of 50. Similarly, Taiwan, South Korea, and Australia show moderate-to-high engagement and citation impact, contributing to Saudi Arabia's diversified research ties in East Asia and Oceania. Researchers from Bangladesh, Thailand, Nigeria, Romania, and Serbia have relatively fewer publications but remain essential in expanding Saudi Arabia's international research reach in fuzzy sets. France and Italy are contributing moderate volumes, show relatively strong C/P values, and are globally involved, indicating potential for deeper collaboration.

Table 8. The 30 most productive country collaborators of Saudi Arabia in fuzzy research.

R	Country	TP	TC	H	C/P	≥ 100	≥ 10	P1	P2	P3
-	Saudi Arabia	5,719	111,381	122	22.7	166	2,491	436	838	3,520
1	Pakistan	1,345	19,008	59	17.8	23	536	25	93	948
2	India	1,041	16,803	61	20.8	18	439	20	47	742
3	Egypt	950	15,404	55	19.7	17	380	60	86	637
4	China	841	26,886	84	38.9	65	477	14	152	525
5	Canada	402	12,998	59	34.2	24	273	38	154	188
6	Malaysia	356	7,668	47	26.3	15	177	18	54	220
7	Poland	284	9,485	52	36.8	19	195	19	117	122
8	United States	280	7,962	44	32.5	14	155	36	43	166
9	United Kingdom	253	7,333	50	34.4	14	147	16	55	142
10	Spain	239	12,604	59	53.0	36	181	2	82	146
11	South Korea	235	3,746	31	19.7	2	116	3	36	151
12	Turkey	216	3,815	32	22.4	5	99	13	25	132
13	Iran	176	5,705	44	32.4	7	122	6	43	127

14	Tunisia	169	2,170	23	12.8	2	75	2	17	150
15	Taiwan	157	3,270	31	20.8	3	91	3	4	150
16	Jordan	155	2,592	24	16.7	4	63	11	19	125
17	Iraq	132	3,189	32	24.2	4	77	2	5	125
18	United Arab Emirates	129	2,981	30	23.1	3	77	1	9	119
19	Yemen	126	1,683	23	13.4	0	50	1	1	124
20	Australia	121	4,121	36	22.7	5	89	5	10	102
21	Viet Nam	104	4,430	40	17.8	7	86	1	8	95
22	Algeria	83	1,896	25	20.8	3	51	9	11	63
23	Italy	79	2,017	25	19.7	3	51	4	9	66
24	Thailand	70	1,542	24	38.9	0	50	0	2	68
25	Bangladesh	64	1,094	19	34.2	0	35	1	3	60
26	Romania	62	1,135	17	26.3	3	28	4	9	49
27	Serbia	60	1,205	23	36.8	0	37	1	4	55
28	France	54	1,257	21	32.5	2	33	4	11	39
29	Nigeria	49	1,144	18	34.4	1	26	0	2	47
30	Japan	48	3,121	23	53.0	5	39	3	10	35

Abbreviations in previous tables.

Overall, Pakistan is leading with the total number of publications (1,345), followed by China (citation 26,886; *h*-index 84), Japan in the C/P ratio (65.020833), China with 65 papers having more than 100 citations, Pakistan with 536 papers having more than 10 citations, Egypt with 60 publications during P1, Canada with 154 publications during P2, and Pakistan with 948 publications during P3.

4 | Mapping Fuzzy Research in Saudi Arabia with VOS Viewer Software

This section presents the visual analysis of various bibliometric indicators. To understand fuzzy logic research patterns and trends, a visual bibliometric analysis was conducted using VOS viewer and bibliometric software (Van Eck & Waltman, 2010; 2023). It helps to identify the most cited journals, authors, collaborators, keywords, research areas, and research papers by uncovering the intellectual structure of the research area.

4.1 | Co-Citation Analysis

This subsection presents the co-citation analysis (Small, [48]) of authors, documents, and journals to visualize and understand the trends of fuzzy research in Saudi Arabia. Analyzing the co-citation of authors, journals, and documents highlights the key contributors, influential works, and research networks in fuzzy set theory and its multidisciplinary applications in the Kingdom. The co-citation analysis of journals identifies the major publishing outlets preferred by Saudi researchers and reflects the research directions and evolving landscape of fuzzy logic in the region.

Figure 3 presents the co-citation clusters of research journals contributing to fuzzy research in Saudi Arabia, visualized using VOS viewer with a minimum threshold of 200 citations and 100 co-citation links. In this network graph, each node represents a journal, where the size of the node indicates the frequency of citations, and the edges represent the strength of co-citation relationships between journals. The color-coded clusters signify journals grouped by thematic or disciplinary similarity, helping to map the structure and focus of fuzzy research in Saudi academia. This visual representation offers valuable insights into the intellectual organization and evolving publication trends in the domain of fuzzy logic research within the Kingdom. The network reveals several strongly connected nodes and dense clusters, highlighting central publication venues in the Saudi fuzzy research landscape.

The most prominent among them is the large green node representing “IEEE Access,” which occupies a central position in the network and connects with multiple journals across various clusters. This open-access journal acts as a multidisciplinary bridge, especially linking with other MDPI journals such as “Symmetry,” “Mathematics,” “Sensors,” and “Sustainability.” Additionally, within the green cluster, journals like IEEE

Similarly, the blue cluster, led by authors such as Huaguang Zhang and Yi Liu, focuses on modern extensions like Pythagorean and q-rung fuzzy sets. The green cluster represents a mathematical extension of fuzzy logic into fractional differential equations, linking authors such as Igor Podlubny, Tofiq Allahviranloo, and Osmo Kaleva. Notably, the orange and yellow clusters show interconnections between fuzzy logic and decision-making frameworks, such as the analytic hierarchy process (AHP), with notable co-citation links between Thomas L. Saaty and Lotfi Asker Zadeh, reflecting the synthesis of fuzzy methods with multi-criteria decision analysis (MCDA).

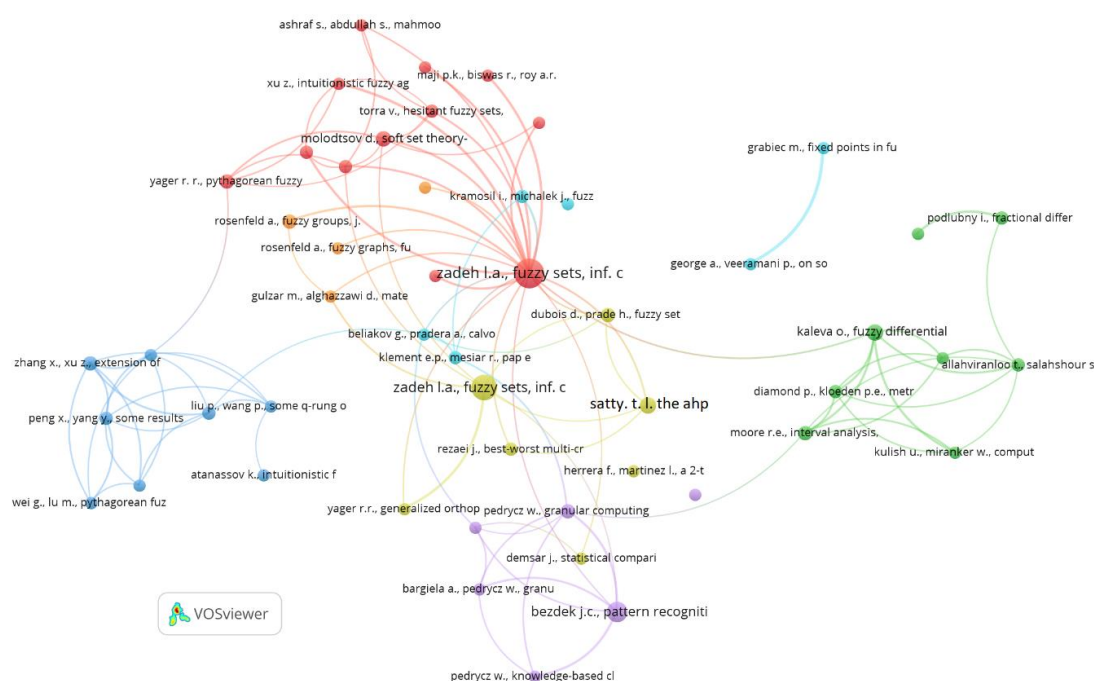


Figure 4. Co-citation of documents with min 20 citations and 100 links.

Despite the richness of interconnections, some areas in the map show limited or no co-citation links. For instance, the purple cluster, which includes works related to pattern recognition and granular computing (e.g., Bezdek and Pedrycz), appears somewhat peripheral, suggesting that these contributions, although significant, are less frequently co-cited with foundational fuzzy theory papers. Similarly, the light blue sub-cluster dealing with fixed point theory (e.g., works by Grabiec and Veeramani) appears isolated, indicating a niche or specialized topic with limited crossover to mainstream fuzzy set applications. These disconnected or lightly linked areas might represent emerging topics, less integrated lines of inquiry, or highly specialized subfields with their citation ecosystems.

4.2 | Bibliographic Coupling

Bibliographic coupling is a fundamental bibliometric analysis technique for detecting similarities between research works through shared references. It refers to the situation when two documents cite a common third source that is different from the two documents (Kessler, [49]).

Figure 5 depicts a bibliographic coupling network of scholarly documents generated using VOSviewer. Bibliographic coupling occurs when two documents cite a standard third document, thus establishing a relationship based on shared references. This figure includes documents with at least 50 items and 100 citation links. Nodes represent individual documents, while the links denote the strength of their shared bibliographies. The color-coded clusters represent distinct thematic or methodological groupings, and the

node size indicates the relative weight or influence of a document based on its citation and coupling strength. The map displays several densely interconnected clusters that reveal prominent areas of research. The yellow cluster forms the structural core of the network, with Palomares (2014a, 2014b), Cabrerizo (2014, 2015), and Liu (2017) acting as central nodes. These documents are heavily coupled, suggesting a strong thematic focus, likely on decision-making models and group decision frameworks using fuzzy logic. Surrounding this core, the purple cluster (e.g., Rodríguez, Liao, Gou) is closely integrated and linked to the yellow cluster, indicating conceptual overlap. Similarly, the cyan/light blue cluster, centered around Abido (2003a, 2003b, 2006), shows internal coupling, likely reflecting contributions in optimization or power systems using fuzzy or evolutionary approaches.

The blue cluster (e.g., Taylan, Tian, Wang) and the green cluster (e.g., Priyadarshi, Rezk, Khan) represent additional specialized domains, each forming internally strong yet relatively isolated knowledge bases. Despite the generally cohesive structure, several documents appear weakly coupled or isolated. For example, the red cluster, including Xiao (2013), Ashfaq (2017), and Izakian (2015), has limited bibliographic links with other groups, suggesting a divergent research focus or reliance on unique literature. Similarly, some green-cluster documents (e.g., Mohandes (2011), Al-Hmouz (2012)) and Nilashi (2019) in the red cluster show minimal connectivity, implying emerging or narrowly scoped work with distinct reference bases. These isolated positions may also indicate recent research that has not yet been integrated with the broader literature or deals with niche applications. Overall, the figure highlights both the converging and diverging intellectual paths within the domain.

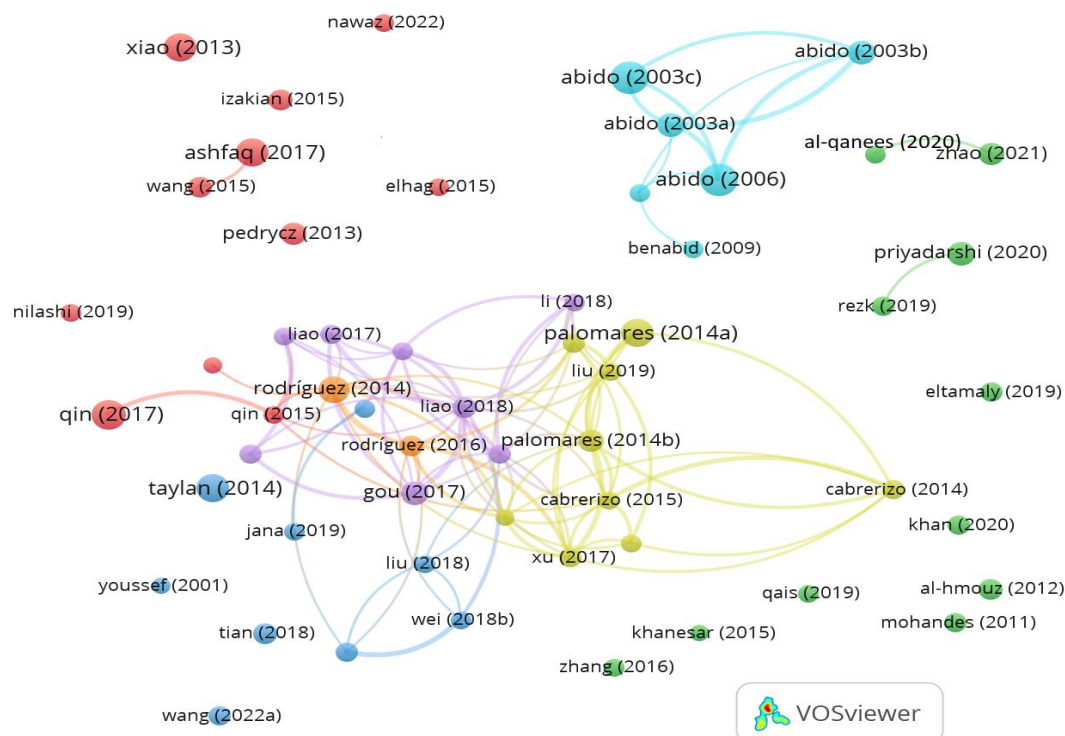


Figure 5. Bibliographic coupling of documents: min 50 documents and 100 links.

Figure 6 illustrates a bibliographic coupling map of academic journals, generated using VOS viewer, based on a threshold of at least 20 documents and 100 citation links. Each node in the visualization represents a journal, and the connecting lines (edges) indicate the degree of bibliographic coupling between them, meaning how frequently they cite the same documents. Node size is proportional to the number of documents published, while different colors denote clusters of journals that share similar reference patterns. This network map offers a snapshot of the disciplinary interconnectedness among journals in fields such as fuzzy logic, mathematics, computer science, and sustainability. The figure reveals a well-defined structure with multiple tightly knit clusters. The red cluster, which includes open-access journals, Mathematics, Journal of

blue cluster, composed of IEEE Transactions on Fuzzy Systems, Fuzzy

Figure 7 visualizes the bibliographic coupling of authors, created using VOSviewer, with a minimum threshold of 10 documents and 100 citation links. Each node represents an author, while the edges (lines) connecting them indicate the strength of their bibliographic coupling, i.e., how often they cite the same literature. The size of a node reflects the number of publications, and colors indicate clusters of authors who share similar citation behavior or work within a related research domain. This figure provides insight into the intellectual structure and collaboration patterns within a scholarly field, showing which authors are conceptually aligned through shared bibliographies.

At the center of the map, Witold Pedrycz appears as the most influential and well-connected author in the red cluster, closely linked with others such as Enrique Herrera-Viedma and Huachang Liao. This cluster likely represents foundational contributions to fuzzy systems and computational intelligence. Meanwhile, the green

cluster, which includes Muhammad Aslam, Saleem Abdullah, and Tahir Mahmood, forms another large and well-integrated group with strong internal bibliographic ties, indicating active research collaboration, possibly in decision-making or applied intelligent systems. The blue cluster (e.g., Shuaib U. and Alghazzawi, D) and light blue cluster (e.g., Hegazy Rezk, Ahmed M. Nassef) represent further subfields or regional networks of research. The yellow and purple clusters also display moderate coupling, centered around figures like Muhammad Akram and Arunoday Raj Mishra, respectively.

Several authors are more loosely connected or relatively isolated, suggesting limited bibliographic overlap with the central clusters. For instance, authors like Abdulazeez Abdurraheem, Salaheldin Elkatatny, and Mohamed S. Soliman are positioned on the periphery, with few connections to major research groups. Similarly, while Mehrbakhsh Nilashi and Ardashir Mohammadzadeh are included, their limited coupling hints at a more niche or emerging research focus. Additionally, the orange cluster involving Alka Agrawal and Raees Ahmad Khan shows strong internal links but weak ties to other clusters, perhaps indicating a localized or topic-specific collaboration.

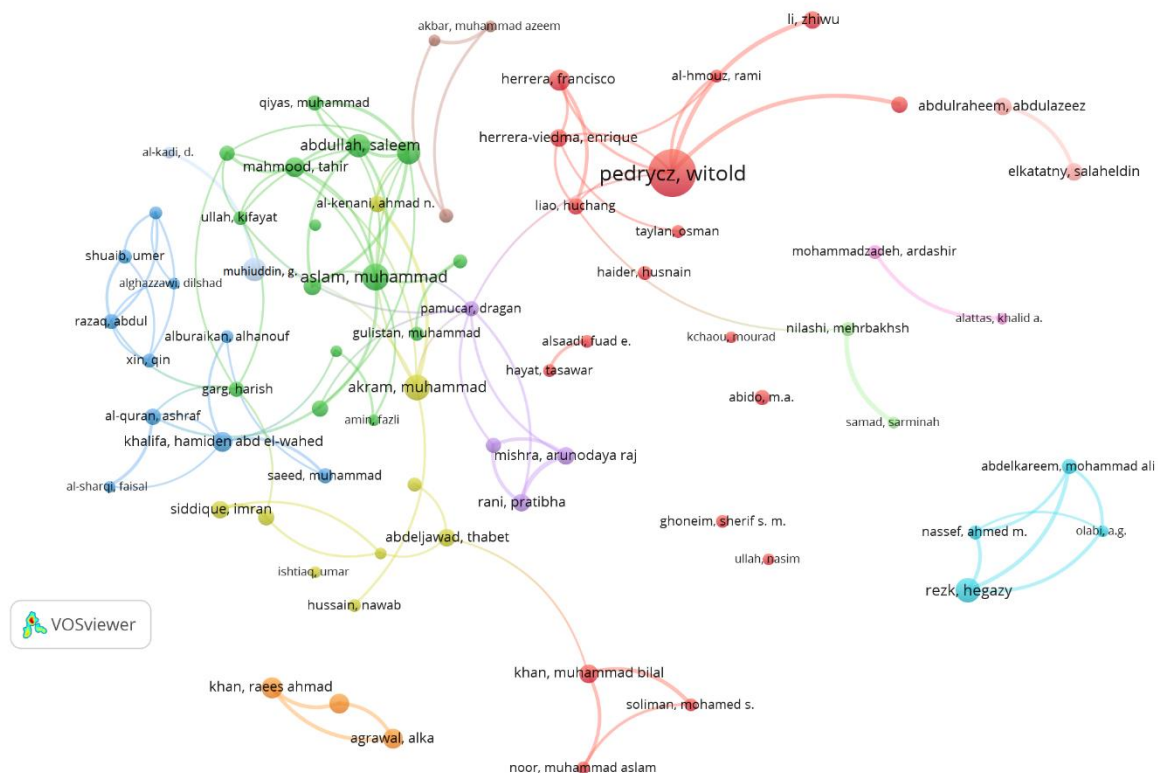


Figure 7. Bibliographic coupling of authors: min 10 documents and 100 links.

Figure 8 illustrates the bibliographic coupling among countries based on a threshold of at least 10 documents and 100 citation links. Each node in the network represents a country, and the connecting lines show how often researchers from these countries cite the same sources, an indicator of shared academic interests or collaboration in research themes. The size of each node corresponds to the number of documents produced, and colors denote clusters of countries with strong internal bibliographic coupling. The figure provides a global view of how countries are interconnected in scholarly output and shared intellectual foundations. At the center of the network is Saudi Arabia, represented by the largest node, indicating its dominant role in document volume and coupling strength. It is tightly linked with Pakistan, India, Egypt, Malaysia, and China, forming a dense web of scholarly alignment. These countries appear to be actively collaborating or working on overlapping research themes, likely within fields such as artificial intelligence, health sciences, or engineering.

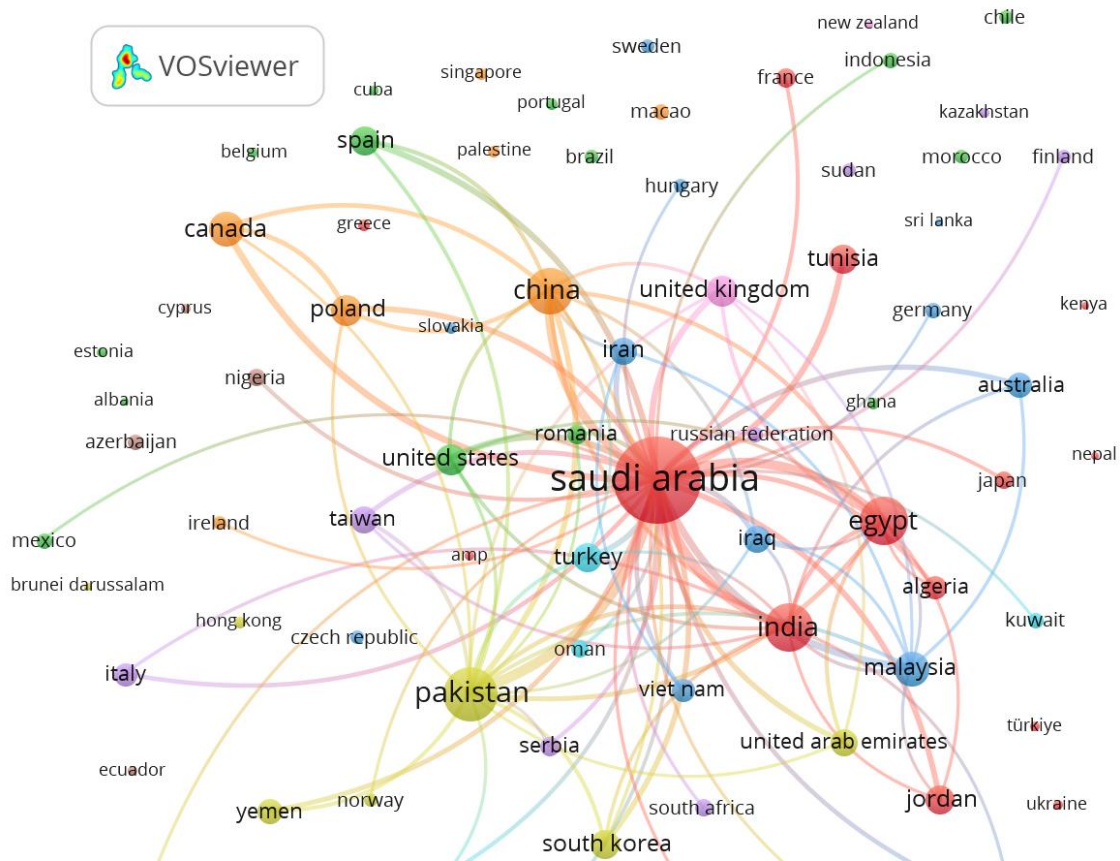


Figure 8. Bibliographic coupling of countries: min 10 documents and 100 links.

Clusters formed around Canada, China, and Iran show distinct collaborative paths as well, particularly with countries like Poland, Romania, the United States, and Turkey, revealing the geographical breadth of bibliographic coupling. Australia, Germany, and the United Kingdom also show notable connectivity, although with slightly fewer and thinner links than the core Middle Eastern and Asian countries. While many countries are strongly connected, some are relatively peripheral in the network, indicating limited bibliographic overlap or lower research activity. For instance, Sweden, Mexico, Ireland, Azerbaijan, and Estonia have fewer or thinner connections, suggesting minimal bibliographic coupling. Similarly, countries such as Nepal, Sri Lanka, Kenya, and New Zealand appear more isolated, reflecting either niche research topics or limited collaborative publishing in the dataset. This figure not only highlights key international collaborations but also points to underrepresented regions that may benefit from increased academic integration.

4.3 | Co-occurrence of Keywords

Bibliometric analysis of the co-occurrence of author keywords is a useful tool for investigating relationships among research topics, as certain words appear together in various papers (Callon et al., [50]).

Figure 9 presents a co-occurrence network of author keywords, where each node represents a keyword that has appeared at least 10 times and is linked to other keywords through a minimum of 100 co-occurrence links. The size of the nodes signifies the frequency of keyword usage, while the colors indicate clusters of related themes. The map provides a visual overview of how topics within the dataset are conceptually related based on authors' keyword usage across publications. This co-occurrence mapping helps identify dominant research trends and how various concepts are interlinked.

At the core of the network, keywords such as "artificial intelligence," "machine learning," "optimization," "decision making," "deep learning," and "COVID-19" appear prominently, showing their central role in the body of research. These central terms form a dense cluster primarily in red, which includes connected terms

excels. Other fields such as Environmental Sciences, Physics and Astronomy, and Materials Science show strong citation metrics and consistent growth over time, indicating a rising interest in the application of fuzzy logic in sustainability, modeling, and materials innovation. Social Sciences, Business, Management & Accounting, and Multidisciplinary research also reveal impressive citation-per-paper ratios, pointing to the expanding relevance of fuzzy approaches beyond traditional STEM fields.

On the biomedical front, Medicine, Neuroscience, Immunology, and Microbiology are featured at the lower end of the table in terms of volume. However, their respectable citation-per-paper values, particularly Neuroscience (21.7), indicate growing intersections between fuzzy logic and healthcare, perhaps in areas like medical diagnostics, neuroinformatics, or intelligent systems for patient monitoring. The temporal data (P1-P3) illustrate clear growth in most research areas. Fields such as Computer Science, Engineering, Environmental Sciences, and Energy show a significant rise in output in the most recent period (P3), reflecting growing institutional support and alignment with global trends. In contrast, some disciplines, such as multidisciplinary and decision sciences, maintain even distributions across periods, indicating sustained research interest rather than a recent surge.

Table 9. The top 20 leading subject areas in fuzzy research from Saudi Arabia.

R	Subject Area	TP	TC	H	C/P	≥100	≥10	D1	D2	D3
1	Computer Science	3,038	66,901	102	22.0	104	1,503	205	495	1,933
2	Mathematics	2,463	39,516	78	16.0	48	947	165	375	1,601
3	Engineering	2,454	49,808	89	20.3	71	1,166	176	320	1,572
4	Materials Science	675	11,403	49	16.9	11	305	19	33	503
5	Energy	550	15,950	61	29.0	30	326	47	58	376
6	Physics and Astronomy	517	8,459	47	16.4	8	230	17	31	399
7	Environmental Sciences	439	9,707	51	22.1	16	256	20	63	289
8	Multidisciplinary	293	2,501	26	8.5	2	74	26	27	126
9	Social Sciences	289	5,756	40	19.9	7	149	9	24	212
10	Chemistry	278	4,512	40	16.2	2	127	12	23	212
11	Chemical Engineering	203	2,772	29	13.7	0	89	21	10	147
12	Business, Management & Accounting	198	5,366	41	27.1	14	108	8	36	114
13	Biochem, Genetics, & Mole Bio	193	3,870	34	20.1	4	93	11	29	136
14	Decision Sciences	186	6,746	45	36.3	18	97	20	55	85
15	Earth and Planetary Sciences	126	2,856	32	22.7	4	75	13	17	77
16	Medicine	113	2,380	27	21.1	3	10	3	27	69
17	Agricultural and Biological Sciences	111	2,025	25	18.2	3	62	9	14	79
18	Neuroscience	86	1,866	24	21.7	2	53	5	28	48
19	Economics, Econometrics, and Finance	53	719	15	13.6	1	23	2	5	34
20	Immunology and Microbiology	22	510	11	23.2	1	12	2	3	16

Abbreviations in previous tables.

The temporal data (P1-P3) illustrate clear growth in most research areas. Fields such as Computer Science, Engineering, Environmental Sciences, and Energy show a significant rise in output in the most recent period (P3), reflecting growing institutional support and alignment with global trends. In contrast, some disciplines, such as multidisciplinary and decision sciences, maintain even distributions across periods, indicating sustained research interest rather than a recent surge.

The word cloud in Figure 10 depicts the cluster of author keywords generated using the Bibliometrix software and Biblioshiny online. The cluster around 'fuzzy logic' and decision-making in Saudi Arabia showcases the strongest areas of fuzzy logic applications, in numerous uncertain and non-linear decision-making problems. This cluster also contains "machine learning", "artificial intelligence," and "optimization", indicating the embedding of fuzzy logic in contemporary AI to improve the quality of decision making. Researchers in Saudi Arabia have been actively working on the use of fuzzy logic in many domains, ranging from energy efficiency, renewable energy, sustainability, health care, and others, to solve the urgent problems the nation and the world are facing.

On the other hand, the analysis of Saudi Arabian research trends reveals the significant focus on “fuzzy c-mean” and “fuzzy logic control”, particularly from the early period 2015-2019 term, whereas more recent research activity moves with global flow, featuring more machine learning and optimization-related keywords. The application of "sustainability", "energy efficiency", and "internet of things" in Saudi research also indicates the increasing interest in the application of fuzzy logic in solving problems related to emerging technologies and sustainable energy systems. Overall, while some terms remain ever relevant, such as "fuzzy logic" and "decision making", it is evident that the trend is in the direction of interdisciplinary solutions, including those of AI, machine learning, and optimization, a trend in fuzzy research globally and in Saudi Arabia.

Table 10 reveals a changing topography in fuzzy research as the global and Saudi Arabian keywords reflect common trends, particularly the intersection of Fuzzy logic with newer technologies such as machine learning and artificial intelligence. Over time, there has been a shift towards more complex, data-driven methodologies, which are likely to reflect broader technological advancements in computation and problem-solving. Yet, these fundamental issues, such as fuzzy logic, decision making, and optimization, continue to play a central role, ensuring that these areas will remain fundamental to the further development of fuzzy technology both globally and within Saudi Arabia.

Table 10. Most frequent author keywords used in Fuzzy research in Saudi Arabia: Global and temporal analysis.

	Global		2020-2024		2015-2019	
R	Keyword	Occ	Keyword	Occ	Keyword	Occ
1	Fuzzy Logic	415	Fuzzy Logic	271	Fuzzy Logic	87
2	Decision Making	207	Decision Making	188	Fuzzy C-Mean	50
3	Fuzzy Set	179	Machine Learning	161	ANFIS	44
4	ANFIS	176	MCDM	139	Fuzzy Set	28
5	Machine Learning	176	Artificial Intelligence	138	Granular Computing	27
6	Artificial Intelligence	155	ANFIS	136	Genetic Algorithm	19
7	MCDM	154	Optimization	102	Decision Making	17
8	Optimization	126	Fuzzy Set	96	Fuzzy Logic Control	17
9	Fuzzy Logic Control	108	Aggregation Operator	80	MCDM	17
10	Deep Learning	83	Deep Learning	79	Clustering	15
11	Aggregation Operators	82	Fuzzy Logic Control	79	Group Decision Making	15
12	ANN	72	Neural Network	53	Artificial Intelligence	14
13	Fuzzy Clustering	71	Intuitionistic Fuzzy Set	52	Big Data	14
14	Neural Network	68	Clustering	47	Fixed Point	14
15	Clustering	66	Fixed Point	45	Fuzzy Number	14
16	Fixed Point	66	Covid-19	44	Optimization	14
17	Genetic Algorithm	66	Fuzzy TOPSIS	44	Information Granules	13
18	Fuzzy C-Means	63	Renewable Energy	41	Particle Swarm Optimization	13
19	Particle Swarm Optimization	63	ANN	40	Machine Learning	12
20	Feature Extraction	59	Sustainability	40	Segmentation	11
21	Fuzzy System	58	Internet of Things	39	Uncertainty	11
22	Intuitionistic Fuzzy Set	56	Energy Efficiency	37	Classification	10
23	Fuzzy TOPSIS	55	Classification	36	Fuzzy TOPSIS	10
24	Classification	52	Fuzzy AHP	36	Hesitant Fuzzy Linguistic	10
25	Fuzzy Number	49	Fuzzy Control	34	Fuzzy Set Theory	9
26	Granular Computing	46	TOPSIS	32	Fuzzy System	9
27	Sustainability	45	Score Function	31	Consensus	8
28	Covid-19	44	Sensitivity Analysis	30	Fuzzy AHP	8
29	Fuzzy AHP	44	Remote Sensing	28	Fuzzy Inference System	8
30	Renewable Energy	44	Feature Selection	27	Support Vector Machine	8

Abbreviations: Occ = Occurrences.

The thematic map in Figure 11 visualizes the distribution of the most frequent author keywords in a fuzzy logic research paper. The map is created by applying the Walktrap clustering algorithm (Pons & Latapy, [68]) in bibliometrics. This algorithm groups keywords by their co-occurrence in the publications and represents the results as maturity level (density) and relevance level (centrality).

In this map, terms such as fuzzy logic, fuzzy inference, and fuzzy system are placed in the right upper quadrant, indicating these as core motor themes. These keywords are mature and have great relevance towards the state of the art in the field of fuzzy logic. They are central themes that receive much attention and play a significant role in the development of the field. The keywords in the lower left quadrant represent decision making, fuzzy sets, and mathematical operators. These are developing themes with some emerging and declining words. Despite their importance, they are perhaps not the central parts of contemporary research in comparison to motor themes. Also, fuzzy controller, MATLAB, and adaptive control system are recognized as thematic trends of the niche. As a summary, the thematic map clearly distinguishes among core, emerging, and niche topics of fuzzy logic research. This visualization offers a panoramic view of the development of fuzzy logic research trends.

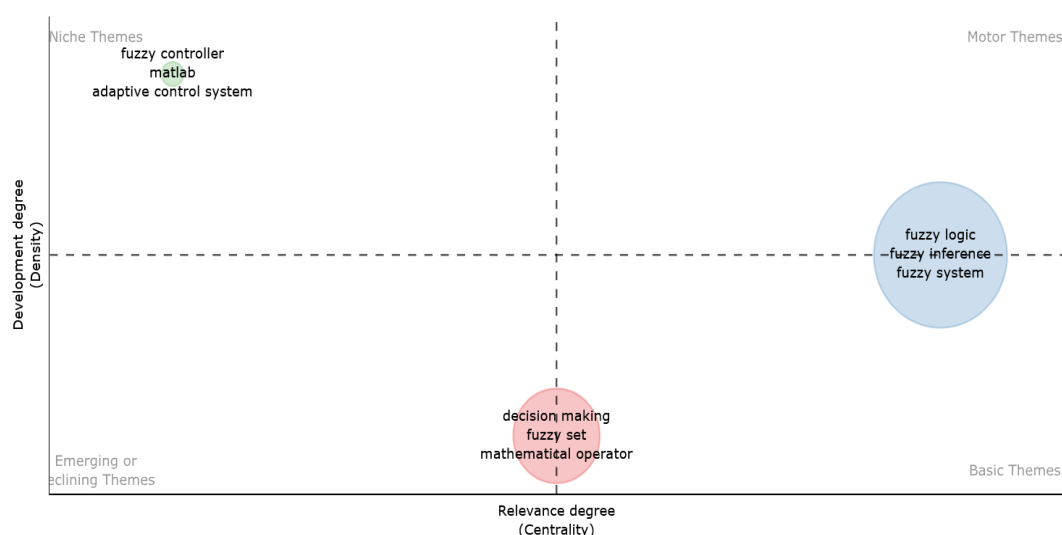


Figure 11. Thematic map with the 250 most frequent author keywords and a minimum cluster frequency of 5 (clustering algorithm: Walktrap).

In summary, the study of the co-occurrence of author keywords by means of bibliometric analysis presents practical implications for the fuzzy logic research landscape. The co-occurrence graph reveals the central themes (e.g., artificial intelligence, machine learning, and optimization) that play a pivotal role in the current research activity evidenced from P3 (2020-2024). The topic map characterizes topics as core, emerging, and niche themes, providing an overview of the direction of research and developing trends in fuzzy logic. The expanding work, especially in decision-making systems and optimization methods, illustrates the growing strength of fuzzy logic in the most complex of real-world computer applications. While the integration of fuzzy logic with AI, machine learning, and optimization is expected to further induce and accelerate advances and applications in various industry sectors in the future.

5 | Conclusions

This systematic review evaluates progressive fuzzy research development and emerging trends together with international research collaborations in Saudi Arabia through a bibliometric analysis. Using the SPAR-4-SLR methodology, this research performed an organized analysis of the studied field by focusing on Scopus-indexed publications. The results show that fuzzy research in Saudi Arabia has expanded rapidly because of expanded production output, rising citations, and enhanced international scholarly ties. The structured

approach used in this review provided an accurate way to evaluate Saudi Arabian fuzzy research contributions as the country strengthens its position in international fuzzy research.

5.1 | General Discussion

Research publications about fuzzy methods have exhibited continuous growth since 1981 through 2023, yet the period from 2019 to 2023 stands out due to its substantial publication explosion. Research production during the period from 1981 to 2001 grew slowly because academic output numbers declined steadily during those ten years. Between 2019 and the present day, the fuzzy domain underwent uncommon growth, which generated 3,520 publications and more than 62,493 citations. Research interest in fuzzy methodologies experienced a remarkable growth, which demonstrates the increasing discipline-wide acceptance of these methodologies because of advances in artificial intelligence, decision-making models, and computational intelligence.

IEEE Access has established itself as the most prominent journal for fuzzy research in Saudi Arabia because it has published numerous papers and received extensive citations. Various high-impact studies that cover artificial intelligence and power systems alongside energy management, security, and computational intelligence are among the most-cited research papers. Since 2015, the research paper by Esam Tashkandi et al. has been cited 836 times, being one of the most impactful papers in the field, along with contributions by Mohammad Abido that drive significant impacts on various research areas. Research studies from different fields prove the interdisciplinary nature of fuzzy research because they show its capability to solve complex problems in practical applications. Research developments now integrate fuzzy methodologies with machine learning and hybrid computational models, and intelligent decision-making systems to extend both the scope and practical value of the field.

The research field flourishes because of international partnerships that have created involvement among Pakistan, India, and Egypt as highly active research partners. Saudi Arabian academic institutions jointly conduct research projects with internationally known universities such as the University of Alberta in Canada and major research organizations in China, Poland, and the UK. International academic alliances between institutions acknowledge knowledge sharing, which supports multi-disciplinary research and promotes scientific and technological progress of fuzzy systems across various fields. The increasing number of research publications co-authored by Saudi Arabian scientists and international colleagues demonstrates Saudi Arabia's expanded participation in worldwide academic cooperation.

The co-citation, along with bibliographic coupling techniques, demonstrates how specific research fields integrate within fuzzy research domains. The co-citation network analysis discovers four essential clusters that examine artificial intelligence applications together with decision-making frameworks, as well as optimization techniques and computational intelligence within materials science. The research clusters demonstrate how fuzzy investigations span multiple scientific disciplines while applying across different scientific fields. The bibliographic coupling analysis shows that leading institutions and researchers maintain robust research connections, which are represented by central nodes that establish important contributions toward field advancement. Fuzzy research in Saudi Arabia receives significant support from three main institutions, including King Abdulaziz University, King Saud University, and Prince Sattam bin Abdulaziz University. These institutions produce numerous influential studies, which further validate their critical position as field leaders. International institutions based in Pakistan, along with Canada and the United States, now enhance Saudi Arabia's research environment by facilitating international collaborations that improve research quality. Research impact from Saudi Arabia becomes increasingly prominent worldwide based on the escalating number of citations and rising H-index values achieved by their researchers.

The incorporation of fuzzy logic systems with machine learning methods, artificial intelligence techniques, and decision support systems has expanded their practical usage throughout medical diagnosis areas and robotics systems, as well as environmental sustainability programs and financial risk evaluation applications. Keyword co-occurrence analysis demonstrates that these fields strongly relate to one another since key

concepts from fuzzy set theory, together with aggregation operators, multi-criteria decision-making, and computational intelligence, closely interact. Bibliometric evidence shows that fuzzy research in Saudi Arabia continues to expand dynamically because of higher publication numbers, along with increased citation results and broader international academic connections. Fuzzy methodology research in Saudi institutions maintains strong ties to global academic communities because of the country's dedication to advancing fuzzy methodology applications.

5.2 | Practical Implications

The expansion of fuzzy research in Saudi Arabia is raising many practical implications in several fields. Fuzzy techniques with artificial intelligence (AI) and machine learning (ML) have been successfully exploited in various fields, including medical identification. Furthermore, the utilization of fuzzy logic in energy management systems in relation to Saudi Arabia's pursuit of sustainability enhances the creation of efficient and adaptive models for the management of renewable energy resources and power system optimization.

- *Research Trend Identification:* Identifying emerging trends in fuzzy research, particularly in multi-criteria decision-making and optimization methodologies, can drive the development of practical solutions for industries like financial risk evaluation, environmental protection, and industrial control in Saudi Arabia.
- *Collaboration Opportunities:* The bibliometric analysis reveals potential for deeper collaboration between Saudi organizations and international research centers. By fostering partnerships, particularly in the areas of fuzzy systems, Saudi Arabia can leverage global expertise to tackle practical challenges like climate change and smart cities.
- *Research Impact Assessment:* Assessing the impact of publications, especially those related to optimization and decision-making systems, will help Saudi Arabia's academic community gain recognition for its contributions. This will further support the nation's position as a leader in developing applied solutions in sectors such as advanced manufacturing and environmental protection.
- *Funding and Resource Allocation:* Insights from the bibliometric analysis can guide the allocation of funding towards high-impact research areas, particularly those with potential applications in solving global challenges. This would ensure the continued development of fuzzy systems, enhancing Saudi Arabia's ability to address practical issues like financial risk and environmental sustainability.

5.3 | Limitations and Future Research

This study is a general overview of fuzzy research in Saudi Arabia till 2024. Future emerging topics, authors, and institutes can vary due to publication trends. The study was done using the Scopus database, which may have excluded significant contributions from platforms like Web of Science (WoS) or Google Scholar. The focus on citations, number of documents, and collaboration can overlook the qualitative impact of research, as well as the practical applications or societal benefits of fuzzy research in Saudi Arabia.

Consent to Participate

This article does not contain any studies with human participants or animals performed by any of the authors.

Availability of Data and Materials

The numerical data is not associated with this study.

Code Availability

No code or programming is associated with this study.

Ethical Approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for Publication

This article does not contain any studies with human participants or animals performed by any of the authors. Each author contributed to and agreed with this publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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