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Twenty-Five Years of Neutrosophic Sets: A Bibliometric Analysis

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ABSTRACT

In this study, a bibliometric analysis of the neutrosophic set research is conducted based on the Scopus database. The chronological time distribution of documents and citations is analyzed. Influential documents, authors, institutions, journals, countries, as well as thematic trends are identified. The findings showed that the neutrosophic set research has been growing rapidly, especially since 2011. Annual publication output, citation accumulation, and high–impact methodological contributions have been substantially developed. Key authors and institutions in fostering the field's intellectual development are identified, as well as major contributing nations to its global growth, such as the United States, India, China, Turkey, and Egypt. A co–citation, bibliographic coupling, and keyword co–occurrence analyses show that the neutrosophic set research is built on strong methodological bases connected to uncertainty modeling, decision–making frameworks, aggregation operators, and similarity measures. Thematic clusters indicated that multi–criteria decision–making, computational intelligence, medical diagnosis, and engineering optimization have remained the core areas of research interest. The analysis proves that the neutrosophic set research has reached some important conceptual maturity, and its interdisciplinary relevance continues to expand.

1. Introduction

The terms "neutrosophy" [1], "neutrosophic logic" [2,3], "neutrosophic set" (NS) [4,5], as well as "neutrosophic probability" [6,7] are important generalizations of the classical fuzzy [8] and intuitionistic [9] set theories of uncertainty, to characterize indeterminacy. Its algebraic construction with truth, indeterminate, and falsity membership functions has already led to powerful tools for analysis and decision making in many scientific and engineering fields. Driven by the complexity of computations, ambiguity in information systems, as well as challenges in real–world decision problems, there is a growing demand for modeling frameworks that can well represent multi–

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dimensional uncertainties. As a result, the NS theory has been increasingly applied in multi–criteria decision making (MCDM) problems like financial performance evaluation [10,11], project selection [12,13], outranking approach [14,15], knowledge management [16,17], sports [18], medical diagnosis [19,20], pattern recognition in medical images [21,22], heart diseases diagnostic [23], image processing [24], image segmentation [25,26], supplier selection [27,28], software selection [29], energy conservation and emission reduction [30], hydrogen technology in energy production [31], and sustainable green building indicators selection [32], etc., showing the increasing methodological as well as practical significance.

This rapid expansion of the field has not yet been studied systematically to explore the dynamics and development of NS research; e.g., citation patterns, thematic evolution, and collaboration patterns in NS publications. Therefore, there was a need to explore the foundation and current direction of the field. In this paper, we filled this gap by providing a bibliometric study [33] and bibliometric indicators [34,35] of NS scientific literature through the Scopus [36] database. The intellectual, thematic, and collaborative structures of the field were analyzed systematically by performance indicators [37], citation analyses [38,39], co–citation networks [40], bibliographic coupling [41], and keyword co–occurrence [42] methods.

The contributions of this paper include the first exploration of publications and citation structures. Second, analysis of productive authors, institutions, and countries through performance and impact indicators that allow for exploring the worldwide distribution and structural properties of publications. Third, the conceptual and thematic structure of the field using VOSviewer [43,44], network–mapping analysis to reveal the major research streams in it, methodological developments, as well as emerging fields of application. With these contributions, this work presents a systematic view of the development of the field and future research in neutrosophic theory and applications.

The paper is structured as follows: Section 2 presents the literature review and methodology, Section 3 demonstrates the metric analysis of publications, citation impact, influential authors, institutes, and countries. Section 4 visualizes bibliometric relationships using VOSviewer as well as Bibliometrix. Section 5 presents the findings and provides conclusions.

2. Methodology

Bibliometrics analysis [33] and indicators [34,35] is a quantitative approach used for the evaluation of scientific literature in terms of publications, citation counts, top authors, and productive countries within the scope. Such an approach is useful for identifying evolutionary trends, hot topics, structural changes, and even potential future directions in research [45]. Early investigators established the foundation for such studies [46,47], and the developments in computing and visualization methodologies provided an increased interest in this research area. Bibliometric analysis plays an important role in scientific literature as it identifies influential contributions, upcoming research themes, and main areas of investigation [48,49]. It is employed to monitor the advancement of scientific domains and identify those that require further investigation [50]. It also assists in finding highly cited papers, leading authors, and important research areas [51]. Guidance for institutions and policymakers to develop sound research policies and strategies can be obtained from bibliometric analysis on global research trends [52,53]. Bibliometric methods are widely used for studying research trends and evaluating research performance across various disciplines [54]. These methods have been extensively applied to journals such as the "Neutrosophic Sets and Systems" [55], "European Journal of Operational Research" [56], "International Transactions in Operational Research" [57], "Operations Research" [58], "IEEE Transactions on Fuzzy Systems" [59], "Journal of Universal Computer Science" [60], "Arabian Journal for Science and Engineering"

[61], and the "International Journal of Information Technology & Decision Making" [62]. Bibliometric studies in fuzzy decision–making have been studied by [63,64], citation analysis of fuzzy research journals [65], visualization of fuzzy research [66], and the 20 years of contributions of neutrosophic research by [67]. The contributions in fuzzy research by countries like China [68], the USA and Canada [69], and Italy [70] have been bibliometrically explored. Besides, the fuzzy research in Iran [71], Turkey [72], Saudi Arabia [73], and Pakistan [74] is also available.

Although bibliometrics have been widely applied in investigating the trends and performance on research activities across disciplines, it is still important to provide in–depth analysis and thematic direction to the researchers in the NS theory. This study aims to address this gap by offering insights that can guide the development of effective research trends and future research directions based on bibliometric findings.

We conducted this search in the Scopus database by searching "Neutrosophic" AND "Set" OR "Number" OR "Logic". In total, 5,648 documents were found. We further filtered the data by excluding 2025 and selecting the "publication stage final"; 4,669 documents were found. Selecting only "article + conference paper + book chapters" gives us 4,510 papers. Finally, selecting the source type "Journal" gives 3,897 publications in total. Further, we searched in secondary documents and found 90 research papers with citation metrics. This makes the total number of research papers 3,987 in NS under this bibliometric evaluation. A systematic and reproducible literature review process was ensured using the SPAR–4–SLR [75,76] methodology presented in Figure 1.

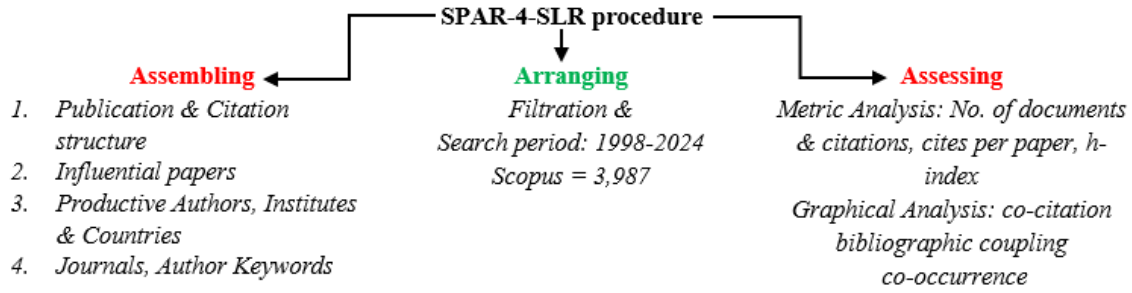

Fig. 1. Framework of the proposed bibliometric study for the neutrosophic set research

3. Metric Analysis

This section presents the bibliometric analysis of the NS research, divided into two subsections. The first subsection examines the publication, citation structure, most cited documents, and leading journals publishing papers on NSs. The second subsection presents the most productive authors, leading institutions, and countries in the NS research.

3.1 Publication and Citation Structure of Neutrosophic Sets

Table 1 presents the publication and citation trends of NS over the years. The definition of the NS logic was first proposed in 1998 [2]. During the period 1998–2006, a secondary document source shows that there are 95 documents that were cited 1716 times, retrieved as a secondary document source search in Scopus. A distinct wave of ambition came in 2011. Since then, the number of publications has grown gradually. From 2007–2012, an initial developing phase of the term notably accelerated with few publications and citations. The most dramatic increase occurred between 2013 and 2020, while in 2013 it was only 13 that increased to 51 in 2016, and this number increased to

575 in 2020 with 11,580 citations. It seems that the research sphere has entered the stage of comprehensive methodological development and intradisciplinary integration.

Table 1
Annual citation structure of the neutrosophic set research

Year	TRP	TC	≥100	≥75	≥50	≥20	≥10	≥5	≥1
1998–2006	2	1,716	2	2	2	2	2	2	2
2007	1	7	0	0	0	0	0	1	1
2008	6	232	1	1	2	2	3	4	5
2009	4	354	1	1	2	3	3	4	4
2010	3	205	1	1	1	2	3	3	3
2011	2	140	1	1	1	1	2	2	2
2012	3	212	2	2	2	2	2	2	3
2013	13	878	1	2	5	9	10	10	12
2014	23	4,229	12	18	20	21	23	23	23
2015	31	2,471	12	14	17	20	23	24	29
2016	51	4,017	14	20	28	44	50	50	51
2017	125	7,080	18	33	55	94	116	122	125
2018	288	10,965	27	43	67	158	233	263	283
2019	354	11,457	17	29	59	160	254	306	341
2020	575	11,580	10	27	55	179	323	431	548
2021	483	8,247	7	14	36	134	231	332	449
2022	513	5,732	5	7	15	85	184	288	458
2023	703	5,508	0	3	10	77	178	309	595
2024	717	3,033	0	1	2	32	88	195	507
1998–2010	16	611	2	2	4	5	7	10	11
2011–2020	1,465	41,330	103	161	253	508	711	801	867
2021–2024	2,416	11,362	5	10	25	162	363	597	1,053
Total	3,897	73,649	129	216	376	991	1,643	2,176	2,933
%	100	100	3.31	5.54	9.65	25.43	42.16	55.84	75.26

Abbreviations: TP and TC = Total papers and citations; ≥100,75, ≥50, ≥20, ≥10, ≥5, ≥1 = Number of papers with equal or more than 100, 75, 50, 20, 10, 5, and 1 citations.

The milestone of 2011–2020 also shows a notable growth with 1,465 publications and 41,330 citations, while the number of highly cited papers has increased. The period 2021–2024 continues the same trend with 2,416 publications and 11,362 citations. At the same time, highly cited papers have slightly decreased, which means a wider spectrum of studies. The newest documents have not received a full citation count. In summary, the total dataset comprises 3,897 publications and 73,649 citations, which is a sign of a quickly expanding research landscape. The distribution of citation–threshold data exhibits a high level of penetration: 75.26 percent received at least one citation, while 42.16 % got at least 5 citations. This pattern proves that the domain is widely established.

Figure 2 presents the annual Box–Whisker plot for the citation distribution of the NS research. It indicates a significant temporal increase in citation activity from around 2010 onwards. During the early stage (2001–2008), low dispersion indicates citation patterns of a few documents that received a substantial number of citations and with significant outliers. This is likely to be due to the developing nature of research in this area during this period, and small numbers of publications, as well as slow research interest in the field. There was a sharp change in patterns from (2011–2020), the ranges expanded greatly, as well as the medians of citations. The expansion of citation dispersion suggests that the focus of NS–related articles has been raised in differing fields, reflecting a

diversification not only in subject matter but also in scholarly impact. From 2013–2015, there was a remarkable increase in citations observed from the box plots and extended whiskers expressing higher median values as well as a larger spread of citations.

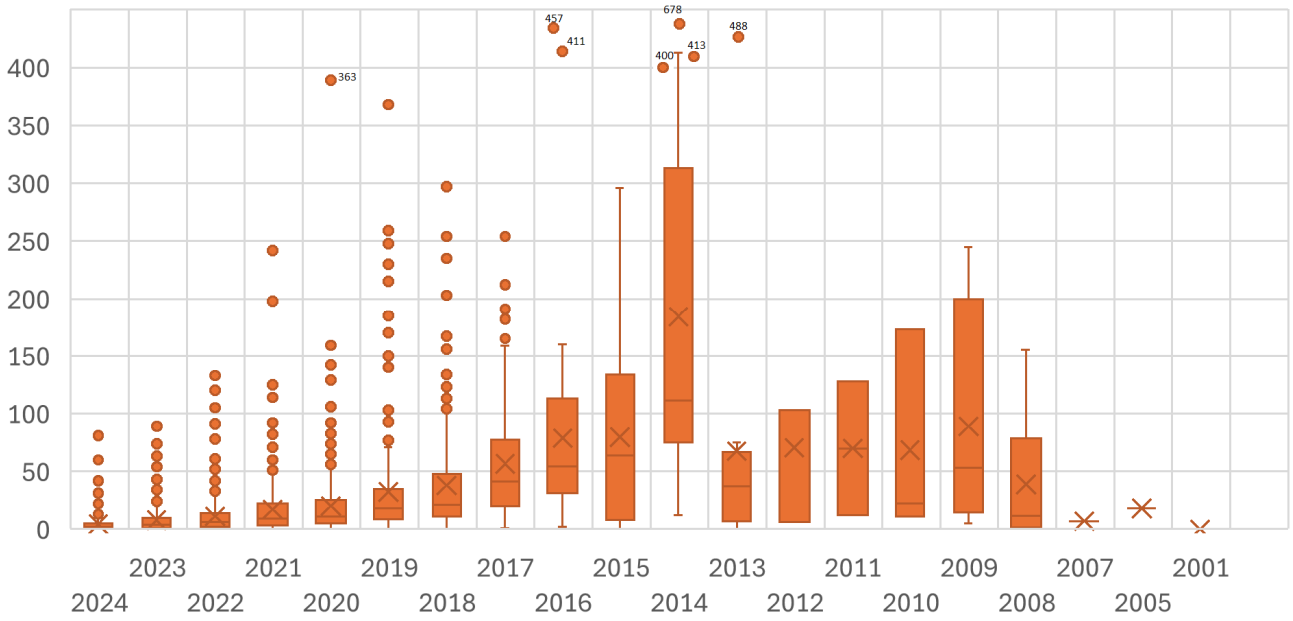

Fig. 2. Annual box–whisker plot for NS from 2000–2024

From Figure 2, it can be observed that 2014 was the most influential year, having the highest box and largest spread, corresponding to more frequent median citations and greater heterogeneity in citation effect. During this time, we can see several influential outliers marked in orange corresponding to papers that have received particularly high numbers of citations. The central role that documents published during 2014–2019 played a central role in the foundation of the field (Figure 2). Many outliers during 2014–2019 indicate that highly influential works were published with a growing number of documents as well. This implies that the field entered a mature phase in which both high–impact methodological developments and moderate–impact applied work were becoming common. The trend between 2021 and 2024 indicates that the median citation levels are decreasing as the number of publications increases, consistent with low citations. However, a few outliers suggest that some influential papers are already receiving attention from the scholarly community.

Overall, the Box–Whisker presentation (Figure 2) indicates that the NS research has sustained growth, and scholarly engagement indicates that NS research now occupies a stable and influential position within the broader scientific landscape, with strong potential for continued evolution and cross–disciplinary relevance.

The top 20 most cited documents in NS are presented in Table 2. It proves that the intellectual structure within the NS area has been heavily influenced by methodological developments in decision–making, similarity measures, and multi–criteria evaluation. Many most cited papers have been published between 2009–2019, suggesting that foundational papers during this decade contributed significantly to expanding research development and theory. The most influential paper published by Ye [77], which received 678 citations, presented an MCDM technique based on aggregation operators of simplified NSs. Another significant contribution by the same author [78], which received 488 citations, introduced a decision–making technique based on the correlation coefficient in single-valued neutrosophic settings. It shows that Ye's original theoretical formulations

[77,78] in the early years have been extensively employed during the methodological development of the theory.

Table 2
Top 20 most cited documents in the neutrosophic set research

Reference	Year	Rank	Total citations	Source
[77]	2014	1	678	JIFS
[78]	2013	2	488	IJGS
[79]	2016	3	457	NCA
[80]	2014	4	413	JIFS
[81]	2016	5	411	IJSS
[82]	2014	6	400	JIFS
[83]	2019	7	363	ASC
[84]	2014	8	349	SWJ
[85]	2014	9	340	AMM
[86]	2014	10	312	NCA
[27]	2018	11	296	DAES
[20]	2015	12	296	AIM
[13]	2014	13	268	ASC
[87]	2018	14	254	NCA
[88]	2017	15	253	IJMLC
[89]	2019	16	245	MJIMCP
[26]	2009	17	244	PR
[92]	2018	18	234	Symmetry
[91]	2019	19	229	JMS
[92]	2015	20	221	NCA

Biswas *et al.* [79] received 457 citations, whereas another document of Ye [80] published in 2014 received 413 citations. Another very influential paper on simplified NSs in multicriteria problems is Peng et al. [81], which has 411 citations. A strong presence is noticed for works on entropy, interval NSs, and some extensions of traditional decision models. Research conducted by Majumdar & Samanta [82], Abdel–Basset *et al.* [83], and Zhang *et al.* [84] emphasized the growing methodological diversity of NS frameworks.

Papers ranked between (9–15) again confirm the field's development, for instance, Liu & Wang [86], Abdel–Basset *et al.* [27], Ye [20], Peng *et al.* [13], as well as Peng & Dai [87] illustrate that new algorithmic developments were incorporated within neutrosophic logic. The multiple presence of Ye, Abdel Baset, as well as Peng, proves the dominance of these authors and the foundational role of these authors in the development of the theory.

Table 3 presents the journals publishing papers on NSs. Leading the list is the journal "Neutrosophic Sets and Systems" with 987 papers that received 8,377 citations. Followed by "International Journal of Neutrosophic Science" published 464 articles and received 2,498 citations. Both the leading journals have no impact factor, but they have published many NS papers and thus represent important thematic journals in the field. In the third place is the "Journal of Intelligent & Fuzzy Systems" with 228 papers that received 7,635 citations and with an impact factor (1.4). High–impact, multidisciplinary journals are also well represented on the list. Symmetry (rank 4) has published 178 papers with 5,457 citations and an impact factor of 2.2, showing NS methodologies are widely used in symmetrical modelling and applied mathematics. Soft Computing (rank 5) has published 76 papers with 2,773 citations and an IF of 2.5. IEEE Access (6), with 60 papers and 1,712

citations, showing high visibility in engineering/technology areas. Other mathematics-related journals, Mathematics (rank 7), AIMS Mathematics (rank 9), and Journal of Mathematics (rank 17) are also listed with a moderate citation rate as well as impact factor, indicating that the NS studies have been more incorporated in a broad range of mathematics.

Table 3
Top 20 Journals publishing the neutrosophic set research papers

R	Journal	TRP	Total citations	Impact factor
1	Neutrosophic Sets and Systems	987	8,377	–
2	Int. J. Neutrosophic Science	464	2,498	–
3	J. Int. and Fuzzy Systems	228	7,635	1.4
4	Symmetry	178	5,457	2.2
5	Soft Computing	76	2,773	2.5
6	IEEE Access	60	1,712	3.6
7	Mathematics	50	821	2.2
8	Expert Systems with Applications	40	704	7.5
9	AIMS Mathematics	37	241	1.8
10	Neural Computing and Applications	35	3,694	6.5
11	Engineering Applications of Artificial Intelligence	35	886	8
12	Int. J. Fuzzy Systems	34	1,459	3.6
13	J. Fuzzy Extension and Applications	31	218	–
14	Investigacion Operacional	30	88	–
15	Complex and Intelligent Systems	28	980	4.6
16	Mathematical Problems in Engineering	27	343	–
17	J. Mathematics	26	235	1.3
18	Information Switzerland	24	640	2.9
19	Int. J. Machine Learning and Cybernetics	23	1,394	2.7
20	Int. J. Knowledge Based and Intelligent Engineering Systems	23	38	1.5

The presence of "Expert Systems with Applications" (position 8), with 40 NS papers and 704 citations, confirms the importance of NS models for decision–support and intelligent systems. Similarly, "Neural Computing and Applications" (position 10) with 35 papers and 3,694 citations reflects a strong connection between NS theory and neural computation (Table 3). The presence of "Engineering Applications of Artificial Intelligence", "Complex and Intelligent Systems", and "International Journal of Machine Learning and Cybernetics" shows that NS research has widespread application in the field of artificial intelligence (AI)/machine learning/complex system modelling.

There are some journals in the list, like "Investigacion Operacional" and "Journal of Fuzzy Extension and Applications", which do not have impact factors, yet regular publications from them imply NS NS-based niche but at least relatively stable communities (Table 3). The presence of journals on applied engineering, optimization, mathematics, and computational intelligence proves heterogeneous methodological interest. Overall, journal distribution indicates that research on NSs has been scattered between specialized NS journals, fuzzy and uncertainty modelling journals, and influential venues in AI and computational sciences. This proves the theoretical foundation and growing applied importance of NS approaches across modern research fields.

3.2 Productive Authors, Institutes, and Countries in the Neutrosophic Set Research

Most productive authors in the field of NS research are presented in Table 4. The most productive author in the list is Florentin Smarandache, with 345 total research papers published and 9,128

citations, and an h–index 52. Followed by Broumi Said, who has published 170 articles and received 2,245 citations. The citation per–paper ratio is 13.21, which indicates that the author's works have been steadily acknowledged. Ye holds the third position with 154 papers that gained 7,161 citations, yielding a remarkably high citation impact of 46.51 cites per paper. This measure highlights Ye's importance as a methodological influencer in the development of decision-making and similarity measure frameworks in NS research.

Table 4
Top 20 most productive authors in the neutrosophic set research

Rank	Author name	University	Country	TRP	TC	H	C/P	≥25	≥5
1	Smarandache, F.	U of New Mexico	USA	345	9,128	52	26.46	106	250
2	Broumi, S.	U Hassan II	MOR	170	2,245	25	13.21	25	99
3	Ye, J.	Shandong Jiaotong U	CHN	154	7,166	41	46.53	70	120
4	Abdel–Basset, M.	Zagazig U	EGY	60	4,826	35	80.43	36	51
5	Liu, P.	Shandong U Finance & Econ	CHN	49	2,649	28	54.06	31	46
6	Saeed, M.	U Management & Tech	PAK	48	1,019	17	21.23	17	38
7	Pramanik, S.	Nandalal Ghosh B.T. College	IND	48	1,597	22	33.27	20	40
8	Iampan, A.	U Phayao	THA	47	218	9	4.64	2	13
9	Aslam, M.	King Abdulaziz U	KSA	47	840	19	17.87	12	37
10	Al–Quran, A.	King Faisal U	KSA	45	855	20	19	17	28
11	Palanikumar, M.	SRM Vall. Engg College	IND	44	343	10	7.8	4	14
12	Garg, H.	Thapar Institute Engg & Tech	IND	43	1,723	26	40.07	28	39
13	Das, S.	Tripura U	IND	42	531	15	12.64	11	25
14	Nagarajan, D.	CAR Education	IND	37	552	12	14.92	7	24
15	Al–Sharqi, F.	U Anbar	IRQ	35	643	16	18.37	16	19
16	Akram, M.	U Punjab	PAK	35	799	18	22.83	9	31
17	Guo, Y.	U Illinois Springfield	USA	34	1,759	23	51.74	21	33
18	Gulistan, M.	Hazar U	PAK	33	473	12	14.33	7	25
19	Salama, A.A.	Port Said U	EGY	32	452	13	14.13	5	20
20	Jun, Y.B.	Gyeongsang National U	KOR	32	394	11	12.31	5	17

Abbreviations: TRP = Total research papers; TC = Total citations; H = h–index; C/P = Cites per paper

The significant contributions are also made by Mohamed Abdel–Basset and P. Liu are ranked at positions 4 and 5 with 60 and 57 papers, respectively. The productivity position is evidence of interesting contributions by authors with institutional status in Asia, the Middle East, Africa, and North America. There are a lot of scholars affiliated with institutes in Saudi Arabia, India, Egypt, Iraq, Pakistan, and Thailand that appear on the list, meaning that NS research has largely been led by authors from these countries. The citation–per–paper (C/P) provides additional information on the distribution of impact. Authors such as Liu (109.61 C/P), Ye (46.51 C/P), and Abdel–Basset (80.43 C/P) tend to show their research outputs that have caused a significantly high impact with respect to their publications. Overall, the list of productive authors proves that research on NS has been driven by a relatively small number of highly productive and influential scholars, whose work has defined the methodological core of the field and its subsequent extension into multiple applied domains.

The most productive institutes in the field of NS are listed in Table 5, spanning from North America, Africa, Asia to Middle East. University of New Mexico (USA) leading the list with 314 papers, 8,524 citations, the C/P ratio of 27.15, and an h–index of 51. This suggests the long–term scholarly impact of this institution. Its worldwide position (QS 801–1000) signals that NS's high–impact results have been published irrespective of international top ranking. University Hassan II (Morocco) is the second leading institution with 186 papers, 2,151 citations, and 11.56 C/P ratio. At third position is

the University Regional Autonomous (Ecuador), with 165 publications, 975 citations, and a low C/P ratio of 5.91, indicating that its contributions have a lower impact, while productivities show some commitment of the institution to the dominant field. Shaoxing University (China) with 142 publications, Zagazig University (Egypt), with 109 papers, Central South University (China), with 88 publications, University of the Punjab (Pakistan) with 85 documents, University of Management and Technology (Pakistan) with 78 papers, Vellore Institute of Technology (India) with 76 publications, and King Abdulaziz University (Saudi Arabia) with 63 publications exhibits relatively modest but rising influence in the NS research network. Overall, the variety of contributing institutions from various continents indicates the worldwide acceptance and development of the NS theory.

Table 5
Top 10 contributing institutes in the neutrosophic set research

Rank	Institution	Country	TRP	Total citations	C/P	H	≥25	≥5	QS
1	U New Mexico	USA	314	8,524	27.15	51	98	229	801–1000
2	U Hassan II	MOR	186	2,151	11.56	25	25	100	1201–1400
3	U Regional Autónoma	ECU	165	975	5.91	16	6	64	–
4	Shaoxing U	CHN	142	7,210	50.77	41	67	118	–
5	Zagazig U	EGY	109	5,100	46.79	37	42	69	1201–1400
6	Central South U	CHN	88	5,122	58.2	41	47	79	452
7	U Punjab	PAK	85	1,966	23.13	25	25	74	741–750
8	U Management & Tech	PAK	78	1,204	15.44	20	20	50	1001–1200
9	Vellore Institute Tech	IND	76	1,188	15.63	20	16	43	851–900
10	King Abdulaziz U	KSA	63	944	14.98	20	14	40	143

The list of the top 10 contributing countries in terms of NS research productivity is presented in Table 6. India is the most productive country with 1,251 publications, 16,948 citations, h–index of 60, and a C/P of 13.55. Followed by China by number of publications (857), 25,403 citations, and h–index of 80. It suggests that research outputs from China have played a key role in the intellectual development of the field. The US has ranked third, with 449 articles and 12,963 citations. The C/P ratio is remarkable, and the h–index of 59 confirms that U.S. contributions are less compared to India and China. However, it demonstrate the lasting influence of American institutes in the development of the research field.

Table 6
Top 10 contributing countries in the neutrosophic set research

Rank	Country	TRP	Total citations	H	C/P	≥50	≥10
1	India	1,251	16,948	60	13.55	88	439
2	China	857	25,403	80	29.64	142	481
3	United States	449	12,953	59	28.85	78	263
4	Turkey	380	11,360	52	29.89	56	224
5	Pakistan	340	6,215	42	18.28	35	181
6	Saudi Arabia	334	3,943	33	11.81	10	127
7	Egypt	296	7,412	45	25.04	24	122
8	Ecuador	238	1,355	19	5.69	0	42
9	Morocco	195	2,404	25	12.33	2	66

Turkey ranked fourth with 380 articles, 11,360 citations, and a high C/P ratio of 29.89, demonstrates the wide visibility of Turkish contributions (Table 6). Pakistan with 340, Saudi Arabia with 334, Egypt with 296, Ecuador with 238, Morocco with 195, and Iraq with 161 papers exhibit

modest impact and strong presence in NS research. Overall, the results reveal that NS research is mainly focused on Asia, with significant contributions from the US, and North–Africa/Middle East.

4. Mapping the Neutrosophic Set Research with VOSviewer Software

This section provides a visual analysis of different bibliometric indicators to identify the patterns and research trends that are emerging in the NS field by using the VOSviewer software [35]. This method helps researchers to find out the structural trends and development of the topic under consideration. For this study, the data were extracted from the Scopus database and were analyzed through VOSviewer software. The visual exploration of the present study is divided into three subsections: subsection 1 presents a co–citation analysis, subsection 2 provides the bibliographic coupling of documents, and subsection 3: focuses on keywords and topical analysis. This structured approach provides a comprehensive visual representation of the key indicators within NS and helps scholars to identify influential works, collaboration networks, emerging research directions, and research gaps in the field.

4.1 Co–Citation Analysis

Co–citation analysis is a powerful bibliometric tool that helps identify the relationships between academic papers based on how frequently they are cited together [36]. It helps to map research trends and identify influential studies (Figure 3).

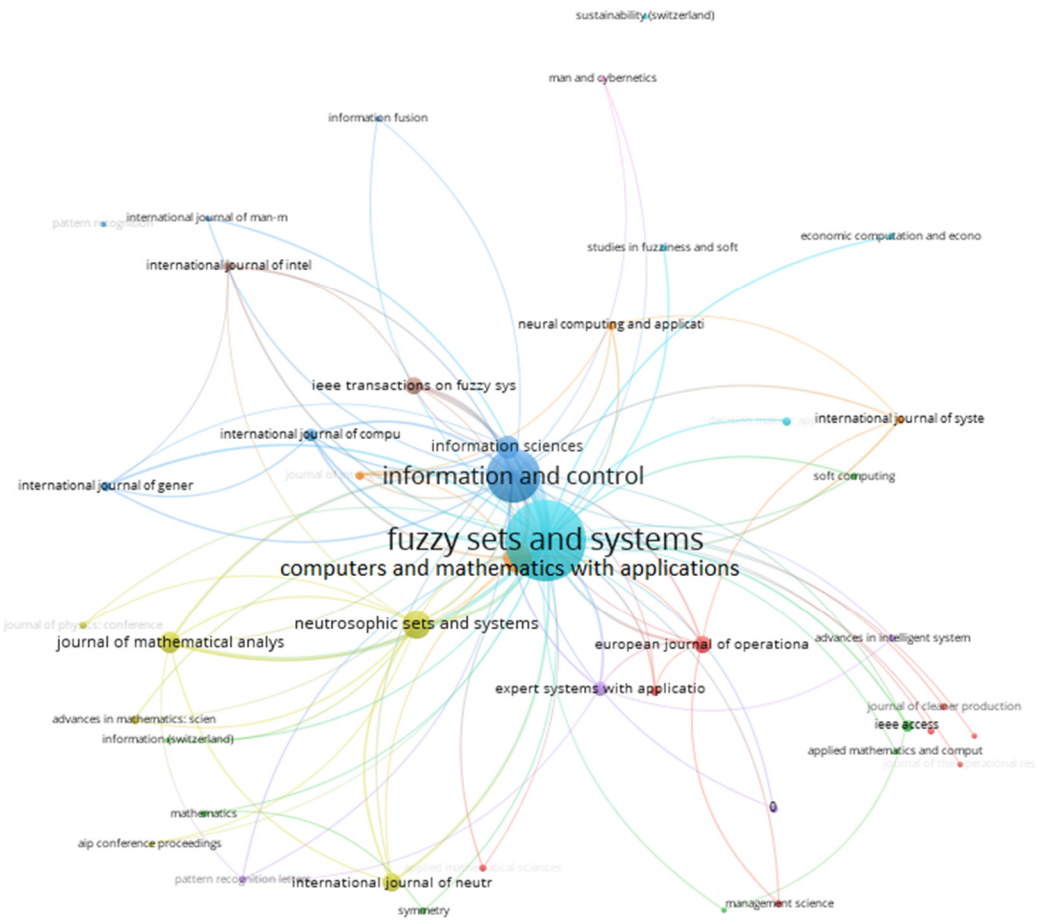

Fig. 3. Co–citation of journals (minimum 10 citations and 100 links)

Figure 3 shows the co–citation network of the sources (journals) citing the NS research. The visualization illustrates that journals are grouped by thematic closeness as well as node size representing citation density and thickness of link representing the weight of co–citation relationships. The prominent nodes represent the journals "Fuzzy Sets and Systems", "Information and Control", "Information Sciences", "Computers & Mathematics with Applications", and "Neutrosophic Sets and Systems". The interlinks between these journals illustrate the intellectual base of the NS research within the contexts of uncertainty modeling, soft computing, and decision–analytic methodologies.

Another group of journals representing "Soft Computing", "Neural Computing and Applications", "IEEE Transactions on Fuzzy Systems", "Expert Systems with Application" are highly connected to the core along with NS theories and linked with applied AI and computational intelligence literature. The interlinks also show the popularity of NS methods for classification, optimization, and prediction problems in complex decision–making environments. Small and disconnected nodes representing "Symmetry", "Sustainability", "Applied Mathematics and Computation", and "Journal of Cleaner Production" illustrate the wide scope of NS research to interdisciplinary and domain application fields. Their co–citation connections reveal that NS methods were employed in environmental studies, engineering optimization, management science, as well as operational research.

NS–specific themed journals such as "Neutrosophic Sets and Systems" and "International Journal of Neutrosophic Science" are separated but closely related nodes in the network. The connection of links on the map also confirms the interdisciplinary applications of the papers that come from mathematics, engineering, systems science, cybernetics, and information theory. The co–citation network analysis indicates that NS research is well embedded in an established scholarly landscape around fuzzy systems and computational intelligence publishing journals, extending its reach into new application realms. The finding of more than one interconnected cluster is evidence that NS publications have become an established and visible area of research, with strong cross-disciplinary connections and a growing presence at the international level.

4.2 Bibliographic Coupling

Bibliographic coupling is a fundamental bibliometric analysis technique to detect the similarities between research works through shared references. It highlights the relevant research topics, influential research papers and authors, and showcases the development of certain topics through time.

The bibliographic coupling of documents has been visualized in Figure 4, generated by considering 100 citations and 100 links. A large central node presents the seminal papers. These papers emerge as highly connected nodes with many coupling links (i.e., they share lots of referenced sources), and jointly, they have contributed to the foundational methodological landscape in NS research. The strong connection in this cluster indicates that these publications are the basis for similar measures, decision–making algorithms, and entropy–based expressions in a neutrosophic setting. Another important cluster is built around papers by Abdel–Basset as well as Nabeel, including some other co–authors. These papers demonstrate high–density of bibliographic coupling, and contribute to applied frameworks development mainly in optimization, MCDM, and computational intelligence.

Another prominent cluster appears around authors like Kutlu Gündoğdu, Biswas, Zhang, Wang, Ali, and others. Their work is highly interlinked with each other and with other high–impact publications, which implies that these papers have a shared methodological literature, and all contribute to the development of NS applications for clustering, decision analysis, and mathematical

operators. The overlap of this cluster and the Abdel–Basset group suggests some thematic convergence, especially in multicriteria models and uncertainty management approaches (Figure 4).

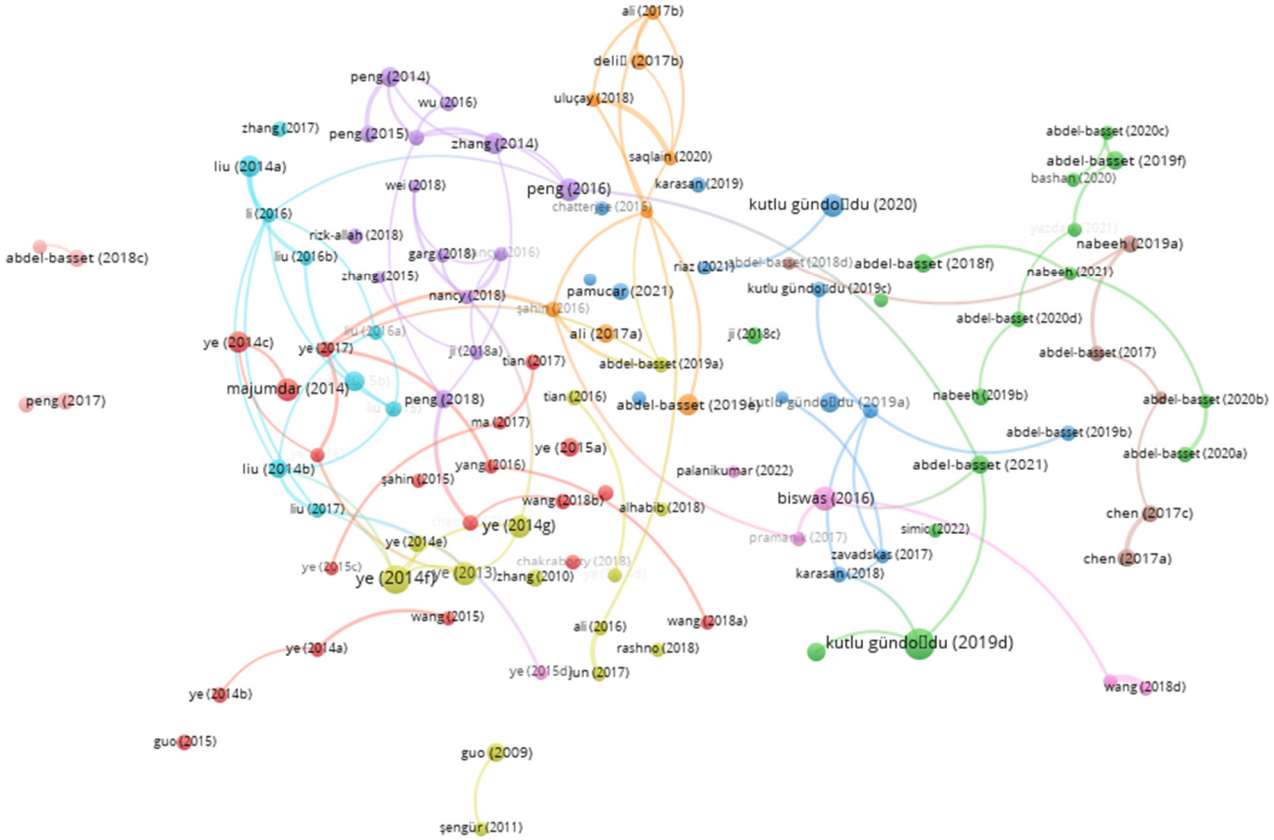

Fig. 4. Bibliographic coupling of documents (minimum 100 citations and 100 links)

On the edges and disconnected documents present the initial work of Guo [26], which emerged with fewer connections but still have ties to the central methodological literature, proving some early extensions of NS theory (image segmentation and uncertainty modeling) in previous decades. In general, the bibliographic coupling network indicates that NS research is a display of multiple well–connected clusters with rich intellectual foundations. The dense coupling of methodological papers indicates that the field has evolved around a common theoretical basis, and the existence of side clusters means thematic expansion in time. The existence of high-impact and highly coupled documents among these clusters proves the maturity of NS research as a rapidly growing, but composite scientific field with methodologically connected and extensive interdisciplinary applications. In conclusion, the early work of Guo [26] highlights the foundational development of NS theory. The bibliographic coupling network reveals a well–connected field evolving around a shared theoretical literature, and some high–impact documents within these clusters demonstrate the maturity and rapid growth of NS research.

The bibliographic coupling network of countries is shown in Figure 5, representing the global structure of scholarly influence in NS research, where several nations became central because of abundant shared reference patterns and strong citation interconnections. India is the most noticeable node in the network, with both size and interconnected links. The centrality of India might also imply that its research has an impact on international literature in NS, based on the major methodological theories that lead the field. Followed by China in the network is connected by dense,

multidirectional links with India, Turkey, the United States, and with some other active research countries.

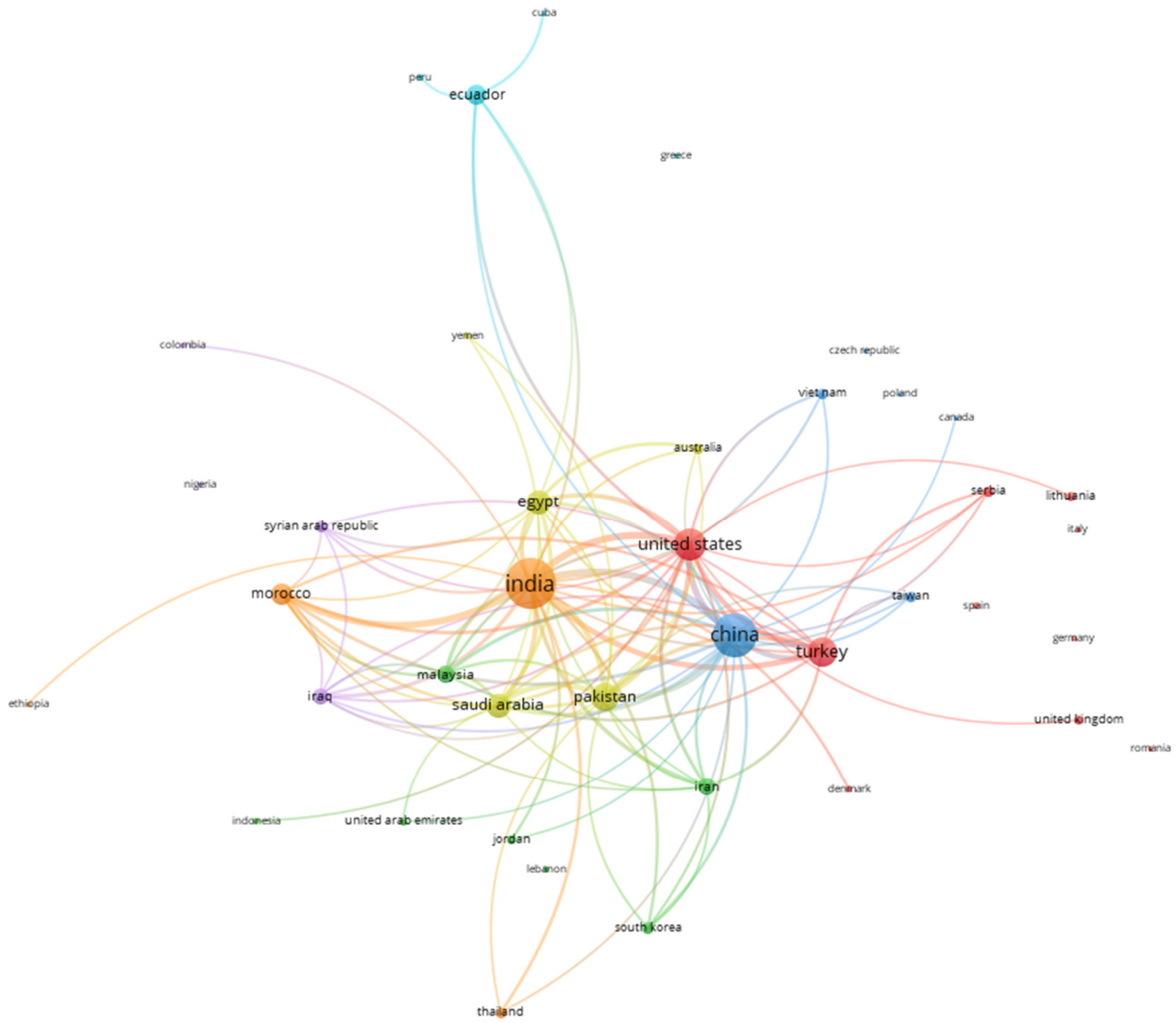

Fig. 5. Bibliographic coupling of countries (minimum 10 citations and 100 links)

The density of the Chinese node indicates that these publications are indeed thematically orientated towards a considerably high impact of NS literature, meaning that Chinese contributions have strong methodological foundation of the field. Turkey, Pakistan, and USA are also among major coupling nodes, and their ties between Asian and Middle East countries proves the foundational role in the development of the theory. A few Middle Eastern and North African countries (e.g., Egypt, Saudi Arabia, Iran and Morocco) act as intermediate nodes with strong linking to both India and China. The node of Ecuador, and its connection with other countries like Cuba and Peru is clearly shown indicating regional clusters in Latin America. While these nodes are less massive, the connecting suggest that there is a growing share of NS methodologies in South American research community.

Similarly, European countries like Spain, Poland, Lithuania, the Czech Republic, and the UK appear in the network with small nodes but having clear connecting links to China, Turkey, and the US. Other peripheral nodes such as Ethiopia, Colombia, Nigeria, and the Syrian Arab Republic are evidence of emerging NS adoption in these countries. Overall, the network coupling shows that the NS research

has been developed as a highly internationalized field closely related to India, China, Turkey, and the US. The links between countries indicate a common global knowledge of NS theory, but the presence of minor nodes shows continued propagation of NS techniques within new academic areas.

4.3 Co–Occurrence

Bibliometric analysis of the co–occurrence of author keywords is a useful tool to investigate the relationships among research topics in various papers. The co-occurrence of author keywords helps to determine the research gaps in the literature, leads to future research directions, and promotes collaboration among researchers who are working on similar or related research [46]. The thematic trends of NS research in author keywords are demonstrated by keyword analysis and are presented in Table 7.

Table 7
The most productive and influential keywords in the neutrosophic set research

Rank	Keyword	TRP	TC	H	C/P	≥100	≥10	D1 = 1998–2010	D2 = 2011–2020	D3 = 2021–2024
1	Neutrosophic Set	1,820	44,213	144	24.29	94	840	5	741	1074
2	Decision Making	1,507	40,233	147	26.7	82	773	1	569	937
3	Fuzzy Sets	432	12,819	57	29.67	26	222	5	169	258
4	MCDM	381	9,583	87	25.15	21	156	0	109	272
5	Uncertainty	365	5,719	61	15.67	9	140	2	59	304
6	Mathematical Operators	225	8,923	49	39.66	19	143	0	119	106
7	Neutrosophic Logic	214	2,364	25	11.05	3	71	2	66	146
8	Aggregation Operator	189	7,135	43	37.75	15	127	0	104	85
9	Similarity Measure	172	6,016	40	34.98	17	98	0	89	83
10	Set Theory	164	3,189	31	19.45	6	82	4	64	96
11	Soft Sets	157	2,808	30	17.89	4	73	0	53	104
12	Numerical Methods	151	2,749	27	18.21	6	63	0	42	109
13	Linguistics	151	4,180	38	27.68	9	84	0	87	64
14	Sensitivity Analysis	150	3,968	38	26.45	9	87	0	41	109
15	Uncertainty Analysis	145	2,902	31	20.01	5	67	0	37	108
16	Single–valued NS	142	4,107	35	28.92	8	69	0	55	87
17	Fuzzy Logic	136	3,375	28	24.82	9	71	6	56	74
18	Membership Functions	133	5,057	32	38.02	11	75	0	52	81
19	Topology	129	1,291	19	10.01	0	44	4	49	76
20	Interval–valued	120	2,298	24	19.15	5	56	0	35	85

The NS research is focused on decision sciences, uncertainty modelling, and mathematical operators. From the list, "neutrosophic set" is the frequently used keyword with 44,213 citations, and an h–index of 144. "Decision making" is the second most cited influential keyword, with 40,233 citations; its C/P ratio (26.7) and h–index value (147) indicate decision models as one of the major application fields for NS studies. "Fuzzy sets" and "MCDM (multi–criteria decision making)" with 12,819 and 9,583 citations, respectively, indicate that NS research has been strongly impacted by a long history in uncertainty modeling. The occurrence of such words emphasizes that neutrosophic theory is an extension of previous fuzzy/intuitionistic theories, even in multi–criteria evaluation.

Keywords "uncertainty", "mathematical operators", "aggregation operator", and "numerical methods" suggest that operator–driven advancements have been a key factor in the development of NS computational techniques, and their presence demonstrates a continuing expansion of NS

research into application–based mathematical and computational areas (Table 7). Keywords such as "set theory", "soft sets", "linguistics", "sensitivity analysis", and "uncertainty analysis" show the diversity of NS's applications in natural language representation, robustness, and probability analysis.

In general, the distribution of keywords proves that NS studies have been formed by coupling theoretical concepts (neutrosophic logic, similarity measures, mathematical operators, etc.) with the most popular application fields (decision making, MCDM, and uncertainty analysis). Temporal trend changes based on D1, D2, and D3 indicated a significant expansion of themes in the past decade, with an increase in research activities from 2021 to 2024.

The co–occurrence of frequently used author keywords is visualized in Figure 6. It reveals the thematic patterns inside NS research. The central node representing the word "neutrosophic set", demonstrate that it is regularly used with other methodological approaches within the field. Among other prominent keywords include "decision making", "neutrosophic logic", "uncertainty", "entropy", and "fuzzy set" that demonstrate the development of neutrosophic theory in solving the real–world problems. Another tightly connected clusters of decision–making representing "multi–criteria decision–making", "aggregation operator", "score function", "correlation coefficient", and "similarity measure". The close linkage between these keywords indicates that the problem–solving research of NS is heavily focused on decision–support aspects. This cluster also presents connections with "medical diagnosis", "COVID–19" and "group decision making", indicating that neutrosophic approaches are frequently used in complex decision–making situations as well as real–world problem–solving.

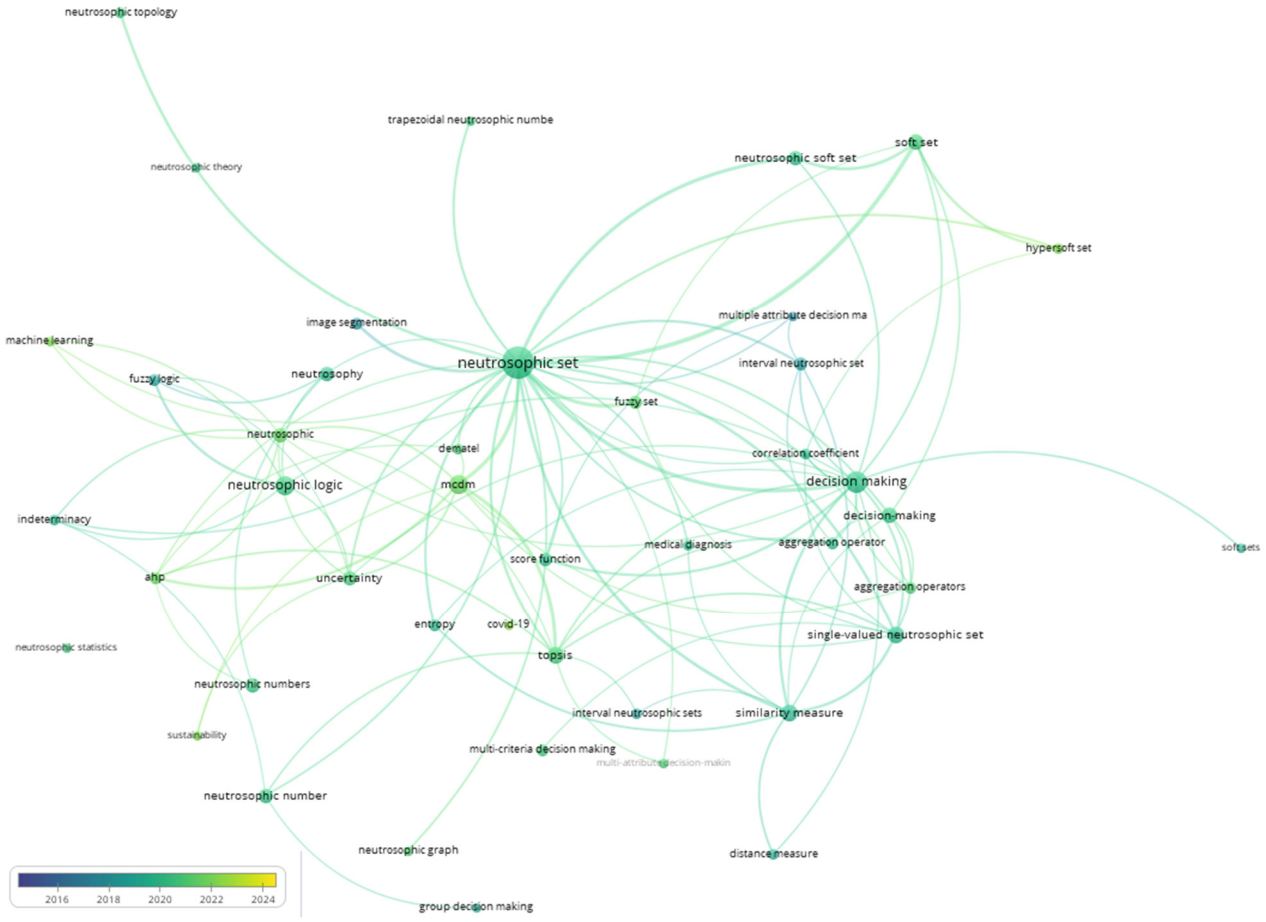

Fig. 6. Co–occurrence of author keywords (minimum 20 occurrences and 100 links)

Another significant thematic focal point is "neutrosophic logic", "indeterminacy", "neutrosophy", and "uncertainty" (Figure 6). This area is the superstructure of the field, with connections toward mathematical concepts like "entropy", "statistics", and "neutrosophic numbers". The interconnected nature of these thematics demonstrates that theoretical development is supporting applied research. A mathematical and set–theoretic cluster of keywords "single–valued neutrosophic set", "interval neutrosophic set", "soft set", "hybrid soft set", and "trapezoidal neutrosophic number". Their co–occurrence reveals that authors often define new set structures or extend the existing ones to handle more sophisticated types of uncertainty. This node is also linked to methodological expansions; e.g., "distance measure" and "multiple attribute decision making".

There is a cluster focused on computational and data–driven applications, such as "machine learning", "image segmentation", and "fuzzy logic". Smaller but significant nodes representing "sustainability" or "neutrosophic graph", "topology", or "neutrosophic theory" indicate newly emerging or special research directions (Figure 6). The colour spectrum, which is related to the average year of publication, shows that most keywords related to uncertainty modelling, decision–making and neutrosophic hybrid structures have been frequently used in the latest contributions (2021–2024). This time–lag might indicate that the field is actively developing and changing in terms of concepts and themes.

The co–occurrence network (Figure 6) shows that NS research is a decision-centric area of research based on theoretical and computational methodologies. The thick interconnection between keywords proves that the field has achieved thematic maturity and is emerging into new scientific and applied subfields.

A visual summary of the thematic prominence of the most frequently used author keywords among NS research is shown in Figure 7.

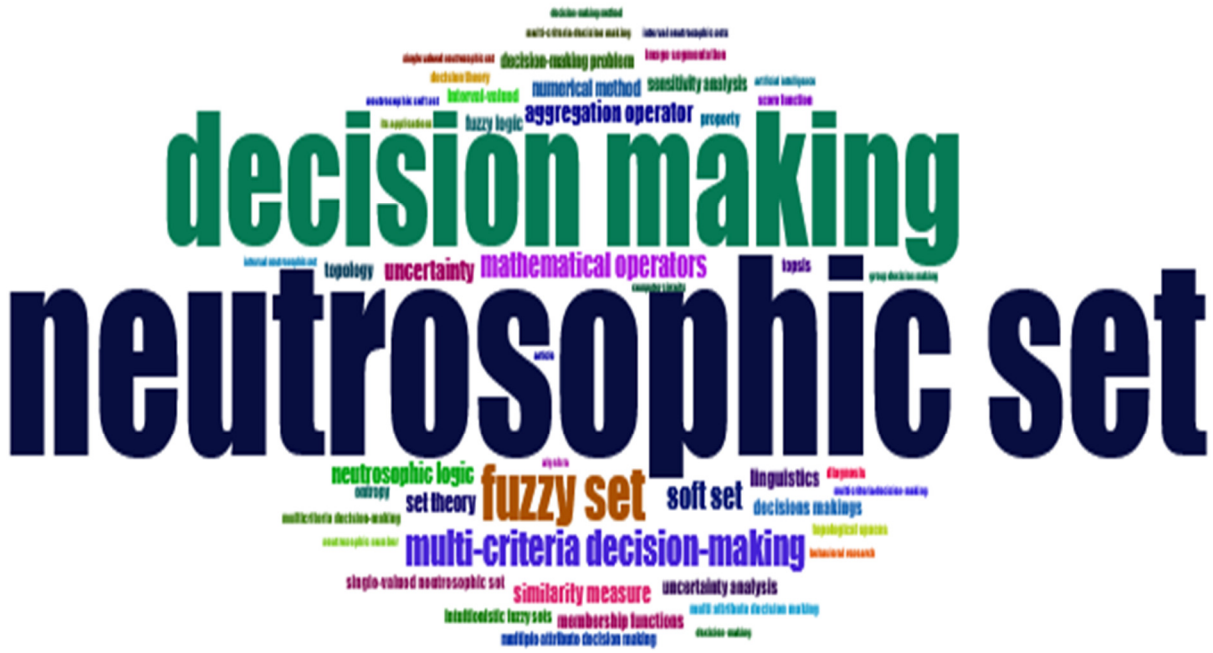

Fig. 7. Word cloud cluster of 50 most frequently used keywords in the neutrosophic set research

The keyword "neutrosophic set" has also come up as the leading keyword, which signifies its importance to the field and how commonly it is used in describing a research area (Figure 7). The second most frequent term (i.e., "decision making") shows that NS methods have been widely developed and employed for decision–support applications. This is due to the field oriented towards

solving problems in conditions of indeterminacy, incomplete information, and multi–criteria assessment. The term "multi–criteria (or multiple criteria) decision–making" can also be seen with a high significance, highlighting MCDM methods as a recurring application area.

The existence of "fuzzy set" as a major keyword reflects that conceptual continuity with the earlier theories, like the fuzzy sets or intuitionistic fuzzy sets (Figure 7). This implies that the neutrosophic models are generally formulated, compared, or hybridized with fuzzy theories. The terms "soft set", "neutrosophic logic", and "uncertainty" indicate that various theoretical notions involving indeterminacy are essential to the development of the NS research. Several related methodological concepts (e.g., similarity measure, aggregation operator, score function, as well as mathematical operators) are also prominent within the cloud. Their popularity underscores that most of the research in this field tries to improve the computational tools and propose new mathematical formulations, which improve decision-making power as well as information processing power. Terms involving applied contexts, such as "medical diagnosis", "numerical methods", and "sensitivity analysis", appear with those of moderate size, which suggest that NS approaches have been generalized to various fields of applications.

The presence of words like "linguistics", "image segmentation", and "COVID–19" also highlights the interdisciplinary implications of neutrosophic theory in emerging scientific and societal problems (Figure 7). Overall, it shows that the NS research is grounded in a conjunction of foundational theory and mathematical methods in decision–making problems.

5. Conclusion

In this paper, bibliometric analysis has proved that the NS research has grown from a small theoretical base to an active, interrelated theory around the world. The analysis of the publication and citation structures proves that an increase in publications between 2011 to 2024 indicates the development and implementation of NS methodologies across multiple disciplines.

Highly cited research papers show a significant methodological impact, evidencing main pioneering contributions related to similarity measures, decision–making algorithms, entropy formulations, and uncertainty modelling that influenced the evolution of the field. Institutional and country contributions were explored, and significant involvement from India, China, the USA, Turkey, and Egypt demonstrate a strong foundational role in the development of the research field. Journals that published NS studies show that specialized journals serve as the main publication platform, while high–impact journals in computational science and AI help to bring NS research into the broader scientific community.

Based on conceptual and thematic analysis, it was found that decision–making applications are dominant in the literature, with an extensive development of methods for mathematical operators, aggregation techniques, and similarity–based modelling. The keyword co–occurrence and the clustering of documents have revealed that NS research has spread in numerous applied fields, including medical diagnosis, image analysis, machine learning, sustainability, and complex systems engineering. These trends indicate that the field has not only strengthened its theoretical core but also broadened its scope to address a variety of interdisciplinary problems.

Compared with the earlier bibliometric study [67], the present conclusion reflects a more advanced stage of the NS research. While previous work primarily highlighted rapid growth, descriptive publication patterns, and concentration in a few leading countries, our analysis demonstrates clear methodological consolidation, broader international participation, and substantial interdisciplinary expansion. The results indicate that NSs have matured conceptually, with

strong impacts in decision–making methodologies and increasing diffusion into applied fields, while the continued diversification of themes confirms that the field remains in an active phase of growth.

5.1 Practical Implementations

Practical implementations of NSs will extend to data science, high–dynamic range problems. In AI, NS frameworks can be employed to establish model interpretability, enable uncertainty–aware machine learning, and build safety–critical decision–making systems, including autonomous vehicles and medical diagnostics. In healthcare, NS diagnostic, treatment–selection tools, or disease–risk prediction models can provide a more accurate assessment by accommodating ambiguous or partially known patient characteristics. In engineering, NS methods have potential applications such as fault detection, predictive maintenance, and reliability analysis in smart manufacturing and large–scale infrastructure. There is also substantial potential in areas of sustainability and environmental management where NS models can enhance climate risk assessment, strategies for resource allocation, and multicriteria policy planning. Moreover, NS–driven image analysis and signal processing can lead to more robust performance in biometrics, remote sensing, and cybersecurity. In the increasingly ambiguous and diverse data environment, neutrosophic models can be used in practical applications that incorporate actual decision systems across various domains.

5.2 Limitations and Future Directions

The study is conducted using the data from the Scopus database, but may exclude significant contributions from platforms such as WoS or Google Scholar. A limitation of this study is the inconsistency and incompleteness of the author keyword field in the database, particularly in older publications. Moreover, citation–based impact measures may not adequately capture the impact of recent publications because of the time lag of getting cited. The study is mainly based on universal quantitative indicators like the publication and citation numbers, and may not reflect qualitative factors, such as the theoretical significance of individual work.

Conflict of Interest

The authors declare no conflict of interest.

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