RESEARCH ARTICLE   OPEN ACCESS

A Bibliometric Analysis on intuitionstic fuzzy set

ABSTRACT: Despite the fast growth of intuitionistic fuzzy publications, only a small part of these groundbreak- ing researches have significantly impacted the field. The main purpose of this paper was to identify and investigate the 100 most cited publications in the intuitionistic fuzzy field. Topic search based on the keyword "intuitionistic fuzzy" in the Science Citation Index and Social Sciences Citation Index databases was con- ducted to identify the 100 most cited articles. Bibliometric analysis methods were employed to describe these articles from different angles, such as the citation amount and rate, distribution among journals, institutions and countries/regions, author frequency, and citation distribution over time. This paper provides an insight on the characteristics of the highly cited intuitionistic fuzzy publications. The achievements of this study may provide useful information for researchers in the fields related to intuitionistic fuzzy.
Keywords: Intuitionistic fuzzy, bibliometrics, Web of science, citation.

I. INTRODUCTION

With the increase in the complexity and uncertainty of the socio-economic environment, the difficulty of decision makers in dealing with decision-making problems is also significantly enhanced [117, 118]. It is diffi- cult for decision makers to describe the decision-making object accurately and then make accurate decisions [31, 32]. Intuitionistic fuzzy set (IFS), introduced by Atanassov [1, 2], is an effective technique to deal with the decision maker's subjective uncertainty and fuzziness of knowledge [110]. As an extension of the traditional fuzzy set [127], IFS has been widely used in various fields, such as computer science [113], mathematics, oper- ations research and management science, engineering, and automation and control systems [111, 112, 114]. At present, IFS has become an important branch of fuzzy mathematics and it has been extended to hesitant fuzzy sets (HFSs) [116, 132], dual HFSs [123, 122, 133], and so on. The research on IFS has evolved rapidly over the last few decades. A lot of achievements of the research on its theory and application have been made by scholars around the world [125, 126].

Given the extensive application of IFS and the thousands of academic achievements that have been made, it is necessary to make a comprehensive overview of the current research status. In previous related studies, Yu and Shi [119] investigated the developmental track of IFS based on bibliometric analysis methods. The positions of crucial literatures are also determined via analyzing the citation network. Yu et al. [120] presented a scientometric review on IFS studies. Visualization technologies are also employed to show the influential authors and influential journals. It should be noted that the research

object of these two studies are all the publications related to IFS included in Web of Science. Although each article contributes to the development of this discipline, only a small part of those groundbreaking researches have significantly impacted the field. Therefore, identifying and analyzing the critical researches are very helpful to understand the developmental track and trend of this discipline

Some research has been conducted on the highly cited articles in various disciplines. For example, Garousi and Fernandes [28] identified the top 100 papers in the field of software engineering based on two indicators: total citations and citation rate. Ellul et al. [27] presented a bibliometric analysis and identified the top 100 highly cited papers in the field of emergency abdominal surgery. The formation and development of the key research topics in this field are well investigated. Tahim et al. [70] studied the evolutional trends and characteristics of the top 100 highly cited papers in facial trauma surgery. Recently, several bibliometric analyses-based publications appeared focused on the 100 highly cited papers in the field of spine [17, 22, 35] or radiology, nuclear medicine, and medical imaging [10, 38, 57, 58]. To the best of our knowledge, however, there has been no research focused on the most cited papers in the field of IFS.

The structure of this paper is organized as follows. Section 2 illustrates the bibliometric analysis methods and the document data. Section 3 presents the research findings and discussions. Section 4 concludes this paper.

Data Sources and Methods

IFS is a very popular research topic in the past decades. Tens of thousands of research publications appear in a Google Scholar search. In order to ensure the standardization and quality of research data, Web of Science is used to search related documents. The search strategy of this paper for retrieving IFS-related publications was defined as follows:

– TC □ (intuitionistic fuzzy);
– Timespan □ all years. Databases □ (SCI □ EXPANDED, SSCI). The retrieval time was April 7, 2017;
– TC was referred to as the topic search.

A total of 1903 records are found based on the above search strategy. Furthermore, these records are ranked according to their citations. The top 100 records are selected for further analysis. Bibliometric analysis methods [33, 115, 124] are used in this paper for the analysis of the top 100 most cited publications. The total citation and citation rate of these publications, features of the influential schol- ars, journals, institutions, and countries/regions are investigated.

Results and Analysis

The SCI (Science Citation Index) and SSCI (Social Sciences Citation Index) returned 1903 papers. The 100 most cited papers are shown in Table 1. The most frequent publication year was 2010 with 17

publications. The citation times ranged from 2564 for Atanassov [2] to 82 for Zhou and Wu [131]. The most cited publication in IFS was Atanassov's 1986 article [2] in Fuzzy Sets and Systems. In this pioneering achievement, the author defined the concept of IFS, which is a generalization of the traditional fuzzy set and proved various proper- ties of IFS. According to the statistical results from Web of Science, this paper was not cited since 3 years after its publication, and the citation rate is very low before 2000. However, this study has been widely cited in recent years, and the year with the most citations was 2016, with 539 citations. The second most highly cited publication was the 1989 paper by Atanassov and Gargov [6], which extended the IFS and introduced the notion of interval-valued IFS, inspired by the ordinary interval-valued fuzzy sets. Since its publication in 1989, it has received 826 citations and the most citations are generated in the past 10 years. Ranked the third place is a paper written by Xu and published in 2007 [90]. In this paper, the author presented a method for ranking the intuitionistic fuzzy values based on the score function and accuracy function. Furthermore, the author developed a series of intuitionistic fuzzy aggregation operators, such as intuitionistic fuzzy weighted averaging operator, intuitionistic fuzzy ordered weighted averaging operator, and intuitionistic fuzzy hybrid.

Atanassov [2]	2564	1	85.47	1	Saadati and Park [63]	135	51	13.50	76
Atanassov and Gargov [6]	826	2	30.59	16	Szmidt and Kacprzyk [68]	135	52	9.64	92
Xu [90]	562	3	62.44	4	Xu [95]	133	53	22.17	31
Xu and Yager [101]	546	4	54.60	5	Mitchell [55]	132	54	12.00	85
Torra [74]	511	5	85.17	2	Li [40]	129	55	21.50	35
Maji et al. [53]	481	6	37.00	10	Xu and Yager [103]	128	56	18.29	47
Szmidt and Kacprzyk [66]	467	7	29.19	19	Takeuti and Titani [71]	125	57	3.91	100
Bustince and Burillo [14]	434	8	21.70	34	Ye [106]	124	58	17.71	50
Maji et al. [52]	409	9	29.21	18	Zeng and Li [128]	124	59	12.40	82
Atanassov [3]	387	10	14.33	69	Wang and Xin [77]	124	60	11.27	89
Deschrijver and Kerre [23]	368	11	28.31	22	Ye [108]	123	61	20.50	41
Xia and Xu [87]	332	12	66.40	3	Xu [91]	123	62	13.67	75
Herrera et al. [34]	321	13	29.18	20	Chen and Li [16]	121	63	40.33	9
Boran et al. [9]	316	14	45.14	8	Xu [98]	119	64	14.88	67
Xu [92]	306	15	34.00	13	Beliakov et al. [8]	116	65	23.20	28
Szmidt and Kacprzyk [67]	295	16	19.67	44	Wei [80]	116	66	16.57	57
Wei [81]	287	17	47.83	6	Wei [79]	116	67	14.50	68
Liu and Wang [50]	278	18	30.89	15	Liu and Jin [51]	112	68	28.00	23
Li and Chuntian [44]	278	19	19.86	43	Wei [83]	112	69	22.40	29
Atanassov [4]	273	20	12.41	81	Xu and Wang [89]	112	70	12.44	80
Li [39]	264	21	24.00	26	Çoker [18]	112	71	5.89	97
De et al. [21]	263	22	17.53	52	Tan [72]	109	72	21.80	32
Atanassov [5]	253	23	11.50	86	Li [43]	107	73	21.40	36
Deschrijver et al. [25]	249	24	20.75	40	Xu and Yager [104]	107	74	21.40	37

Xu and Yager [102]	243	25	30.38	17	Park et al. [61]	106	75	21.20	39
Burillo and Bustince [11]	228	26	11.40	87	Ye [107]	105	76	17.50	53
Xu [96]	222	27	37.00	11	Li et al. [45]	102	77	11.33	88
Grzegorzewski [30]	216	28	18.00	48	Gerstenkorn and Mańko [29]	100	78	4.00	99
Zhao et al. [130]	208	29	34.67	12	Ye [109]	98	79	19.60	45
Liang and Shi [48]	195	30	15.00	66	Zeng and Li [129]	97	80	19.40	46
Dubois et al. [26]	190	31	17.27	54	Li [41]	97	81	16.17	58
Hung and Yang [37]	189	32	15.75	61	Yu et al. [121]	96	82	24.00	27
Cornelis et al. [19]	186	33	15.50	62	Bustince and Burillo [13]	94	83	4.70	98
Vlachos and Sergiadis [75]	182	34	20.22	42	Rodríguez et al. [62]	93	84	46.50	7
Wei [82]	170	35	28.33	21	Li et al. [47]	92	85	15.33	63
Atanassov et al. [7]	167	36	15.18	65	Xu et al. [105]	92	86	15.33	64
Mitchell [54]	161	37	12.38	83	Wang [76]	91	87	13.00	77
Xu [97]	160	38	32.00	14	Shabir and Naz [64]	90	88	18.00	49
Tan and Chen [73]	157	39	26.17	25	Wei and Zhao [84]	89	89	22.25	30
Lin et al. [49]	154	40	17.11	56	Park et al. [60]	89	90	12.71	78
Bustince and Burillo [12]	154	41	7.33	95	Li et al. [46]	88	91	12.57	79
De et al. [20]	153	42	9.56	93	Hung and Wu [36]	87	92	6.21	96
Wang et al. [78]	152	43	21.71	33	Xu and Chen [99]	86	93	17.20	55
Park [59]	146	44	12.17	84	Li [42]	86	94	14.33	70
Xu [88]	145	45	16.11	59	Wei and Zhao [85]	85	95	21.25	38
DeschrijverandKerre[24]	142	46	15.78	60	Xu [94]	84	96	14.00	71
Xu [93]	141	47	17.63	51	Montero et al. [56]	84	97	9.33	94
Xu and Xia [100]	138	48	27.60	24	Chen et al. [15]	83	98	13.83	72
Shu et al. [65]	138	49	13.80	74	Wei et al. [86]	83	99	13.83	73
Szmidt and Kacprzyk [69]	137	50	10.54	90	Zhou and Wu [131]	82	100	10.25	91

Table 2: Journals with the Top 100 Cited Intuitionistic Fuzzy Articles.

Journal title	Journal title (abbreviation)	IF (2015)	5-IF	TP	TC
Fuzzy Sets and Systems	FSS	2.098	2.376	20	7585
Information Sciences	INS	3.364	3.683	13	1800
Expert Systems with Applications	ESWA	2.981	2.879	9	1169
Knowledge-Based Systems	KBS	3.325	3.433	7	898
Pattern Recognition Letters	PRL	1.586	2.002	7	1232
Computers & Mathematics with Applications	CMWA	1.398	1.873	5	1169
Applied Soft Computing	ASCO	2.857	3.288	4	568
International Journal of Intelligent Systems	IJIS	2.05	2.483	4	856
European Journal of Operational Research	EJOR	2.679	3.109	3	722
IEEE Transactions on Fuzzy Systems	TFS	6.701	7.198	3	940
International Journal of Approximate Reasoning	IJAR	2.696	2.655	3	704
International Journal of Uncertainty Fuzziness and Knowledge-Based Systems	IJUFKBS	1.0	1.004	3	421
Applied Mathematical Modelling	AMM	2.291	2.4	2	211
Chaos, Solitons & Fractals	CSF	1.611	1.628	2	251
Fuzzy Optimization and Decision Making	FODM	2.569	2.57	2	273
International Journal of General Systems	IJGS	1.677	1.244	2	674
Journal of Computer and System Sciences	JCSS	1.583	1.598	2	387
Mathematical and Computer Modelling	MCM	1.366	1.602	2	252
Control and Cybernetics	CC	0.3	0.773	1	135
Group Decision and Negotiation	GDN	1.312	1.394	1	84
IEEE Transactions on Systems Man and	TSMC	6.22	6.184	1	107

Cybernetics Part B					
Cybernetics					
International Journal of Computational Intelligence Systems	IJCIS	0.391	0.639	1	83
International Journal of Systems Science	IJSS	1.947	1.837	1	167
Journal of Symbolic Logic	JSL	0.51	0.517	1	125
Microelectronics Reliability	MR	1.202	1.285	1	138

aggregation operator [90]. This publication has been consistently cited since 2008, and a total of 562 papers have cited this publication.

Takeuti and Titani [71] is the oldest publication in the top 100. The most recent publication was published by Rodríguez et al. [62], and looked at the state of the art and future directions of HFSs. The authors pointed out that special attention should paid to the coming HFS-based proposals. The second newest publication was the 2013 paper written by Chen and Li [16] In this paper, the authors first presented the interval-valued

Table 3: Countries/Regions of Origin of the 100 Most Cited IFS Articles.

Country/region	No.	Country/region	No.
China	56	Sweden	1
Spain	9	Saudi Arabia	1
USA	7	Pakistan	1
Poland	7	Italy	1
Bulgaria	6	Iran	1
Taiwan	5	Greece	1
India	5	Germany	1
South Korea	4	France	1
Belgium	4	Czech Republic	1
Turkey	2	Canada	1
Israel	2	Australia	1

hesitant preference relations based on the combination of hesitant fuzzy preference relations and interval- valued HFSs. Some aggregation operators for aggregating interval-valued hesitant fuzzy information are also presented in this study [16].
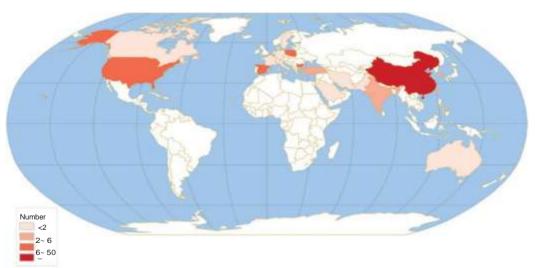

Figure 1: Global Geographic Distribution of the Highly Cited Publications in IFS.

Table 4: Institutions with the Top 100 Cited IFS Articles (n ☐ 2).

Institution	Country	No. of articles in top 100	No. of citations
Southeast University	China	9	1324
Chongqing University Arts and Sciences	China	8	1058
Tsinghua University	China	7	1913
PLA University of Science Technology	China	6	951
Polish Academy of Sciences	Poland	6	1440
Shanghai Jiao Tong University	China	6	1017
The Public University of Navarra	Spain	6	1110
Dalian Naval Academy	China	5	808
Fuzhou University	China	5	511
Iona College	USA	5	956
Bulgarian Academy of Sciences	Bulgaria	4	3944
Ghent University	Belgium	4	945
Indian Institute of Technology	India	4	1306
Pukyong National University	South Korea	4	476
Shaoxing University	China	4	450
Central South University	China	2	266
CSIC	Spain	2	604
Dalian University of Technology	China	2	432
Dong A University	South Korea	2	195
Elta Systems Ltd.	Israel	2	293
IPACT	Bulgaria	2	526
University of Jaen	Spain	2	414
University of Granada	Spain	2	414

Table 5: Authors Who Contributed ☐ 2 of the 100 Most Cited IFS Articles.

Author	Institutions	Country	No. of articles	Position on author list (no. of articles)
Xu	Sichuan University	China	20	First(16), second(3), third(0), fourth (1)
Wei	Sichuan Normal University	China	8	First (8)
Li	Fuzhou University	China	8	First (8)
Bustince	The Public University of Navarra	Spain	6	First(3), second(2), third(1)
Atanassov	Bulgarian Academy of Sciences	Bulgaria	6	First (6)
Kacprzyk	Warsaw University of Technology	Poland	5	Second (4), fourth (1)
Ye	Shaoxing College of Arts and Sciences	China	4	First (4)
Yager	Iona College	USA	4	Second (4)
Szmidt	Polish Academic of Sciences	Poland	4	First (4)
Roy	Indian Institute of Technology	India	4	Second (1), third (3)
Park	Pukyong National University	South Korea	4	First(1), second(1), fourth(1)
Kerre	Ghent University	Belgium	4	Second (2), third (2)
Deschrijver	Ghent University	Belgium	4	First (3), second (1)
Burillo	The Public University of Navarra	Spain	4	First (1), second (3)
Zhao	Chongqing University of Arts and Sciences	China	3	Second (3)
Xia	Beijing Jiao Tong University	China	3	First(1), second(1), third(1)

Biswas	Indian Institute of Technology	India	3	Second (3)
Torra	Institution of Investigation and Intelligence Artificial	Spain	2	First (1), third (1)
Tan	Central South University	China	2	First (2)
Park	Pukyong National University	South Korea	2	Second (1), fourth (1)
Mitchell	Elta Systems Ltd	Israel	2	First (2)
Martinez	University of Jaen	Spain	2	Second (2)
Maji	Indian Institute of Technology	India	2	First (2)
Kwun	Dong A University	South Korea	2	Second (1), third (1)
Hung	National Hsinchu Teachers College	Taiwan	2	First (2)
Herrera	University of Granada	Spain	2	First (1), fifth (1)
De	Midnapore College	India	2	First (2)
Cornelis	Ghent University	Belgium	2	First (1), second (2)

The average citations per year were also included to describe these highly cited documents. Another ranking list of these 100 articles based on citation rate is also shown in Table 1. Atanassov [2] was again in the first place, with an average of 85.47 citations per year. Following were the 2010 paper by Torra [74] (85.17 citations per year) on HFSs and the 2011 paper by Xia and Xu [87] (66.40 citations per year), which proposed a series of hesitant fuzzy information aggregation operators and discussed their applications in decision making.

These top 100 most cited articles were published in 25 different journals. The most number of publica- tions appeared in Fuzzy Sets and Systems (20), followed by Information Sciences (13), and Expert Syst. Appl. (9). The total ranking list according to the number of articles (TP) in the top 100 is shown in Table 2. Some other indicators such as the impact factor (IF) (2015), 5-year impact factor (5-IF), and citation numbers (TC) are also used to describe these journals. Fuzzy Sets and Systems did not only publish the most highly cited papers but also had the most citations (7585). IEEE Transactions on Fuzzy Systems had the highest IF (6.701) and 5-IF (7.198). The country/region that contributed the most papers in the top 100 was China, with 56 highly cited papers. Following was Spain with nine. Table 3 shows the ranking in IFS field by country/region. Figure 1 shows the global geographic distribution of the highly cited publications in IFS. The contributions of different institutions in IFS studies were investigated and the influential ones that have more than two highly cited papers are shown in Table 4. Southeast University in China contributed nine publications with 1324 citations, followed by Chongqing Univeristy Arts and Sciences in China with eight papers, Tsinghua University in

China with seven papers, and PLA University of Science Technology in China with six papers.Authors who contributed two or more of the 100 most cited IFS articles are shown in Table 5. Xu from Sichuan University, China, was the most productive author with 20 highly cited publications. As shown in Table 5, most of the authors work in China and Spain, although some scholars work in Bulgaria, Poland, India, South Korea, Belgium, and Israel.

II.   CONCLUSIONS

Although citation analysis is not the only way to evaluate the quality of a scientific publication, it is an effec- tive tool to help the scientific community determine the influential authors, journals, and articles. In this study, we identified and studied the 100 most cited IFS articles. Some important and interesting results were obtained. This analysis provided an insight into the historical developments in the intuitionistic fuzzy field.

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