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Global Research Performance on the Design and Applications of Type-2 Fuzzy Logic Systems: A Bibliometric Analysis

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ABSTRACT: There has been a significant contribution to scientific literature in the design and applications of Type-2 fuzzy logic systems (T2FLS). The T2FLSs found applications in many aspects of our daily lives, such as engineering, pure science, medicine and social sciences. The online web of science was searched to identify the 100 most frequently cited papers published on the design and application of T2FLS from 1980 to 2016. The articles were analyzed based on authorship, source title, country of origin, institution, document type, web of science category, and year of publication. The correlation between the average citation per year (ACY) and the total citation (TC) was analyzed. It was found that there is a strong relationship between the ACY and TC ($r = 0.91643$, $P<0.01$), based on the papers consider in this research. The "Type -2 fuzzy sets made simple" authored by Mendel and John (2002), published in *IEEE Transactions on Fuzzy Systems* received the highest TC as well as the ACY. The future trend in this research domain was also analyzed. The present analysis may serve as a guide for selecting qualitative literature especially to the beginners in the field of T2FLS.

Key words: Type – 2 Fuzzy Logic System, Type – 2 Fuzzy Logic Controller, Type -2 Fuzzy Set, Bibliometrics, Citation.

1. INTRODUCTION

The available data in most real world problems are quite associated with uncertainties in nature [1]. These uncertaities are due to a deficiency in information that may be incomplete, imprecise, contradictory, unreliable, vague, fragmentary or deficient in some other ways. Uncertainty is an inherent characteristic of an information [2]. The introduction of fuzzy logic system (FLS) theory increased the ability of systems to cope with the uncertain problems [2, 3]. The primary feature of fuzzy reasoning allows for handling a different kind of uncertainties[3]. These include easy incorporation of expert knowledge into the control law, less model dependent, robust and can easily be used to model grammatical rules [4]. There are two types of FLS namely, type-1 fuzzy logic system (T1FLS) and Type-2 fuzzy logic system (T2FLS) [5]. In T1FLS, the uncertainty is represented by a precise number in a range of (0, 1) interpreted as a degree of membership function (MF). Given the fact that it 's hard to know a precise value for uncertainty, working with T1FLS model is more reasonable. However, some researchers argued that in cases where there is a high level of uncertainty, type-1 fuzzy has limited ability to handle it because its membership degree for each input is a crisp number [6, 7]. The T2FLS, which uses the type-2 fuzzy set (T2FS), was proposed to avoid the limitations of the T1FLS [6, 8, 9]. The main characteristic of T2FLS is that its MFs are fuzzy. Therefore, it has more degree of freedom (DOF) in designing verities of systems with uncertainties [10-12]. The T2FLS is of two types, namely, Interval type-2 fuzzy logic system (IT2FLS) that uses interval type-2 fuzzy sets (IT2FSs) and General type-2 fuzzy logic system (GT2FLS) that uses General type-2 fuzzy sets (GT2FS) [13]. It is argued that in the presence of uncertainty, T2FLS is preferred over T1FLS[14, 15]. Similarly, there are several records of evidence illustrating some significant improvements regarding accuracy of T2FLS over its counterpart, T1FLS [7, 15-18].

T2FLSs have been used in many types of applications such as intelligent control, pattern recognition, time series forecasting, decision making, classification, modeling, and system identification [19, 20]. This implies that T2FLS has found application in different study domain like Natural Science, Engineering, Medicine, Social Sciences etc [21, 22]. On the other hand, T2FLSs have been hybridized with other soft computing technique such as Bioinspired Optimization Algorithms (BOA), Artificial Neural Networks (ANN), Sliding Mode Control (SMC) [23, 24]. This is to simplify its designing method and to improve its performance by utilizing the futures of such soft computing methods. All the mentioned applications and design processes are considered in this study.

In bibliometric analysis contest, the citation indices trace the references in a published article. It shows the number of times a particular paper has been referring to in other articles [25]. In the past decades, the ways to assess citation tracing have been increased significantly [26]. The influence or impact of a particular article can be evaluated

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based on how recurrent that item is cited in another article. Though, the number of citations do not indicate the quality of the publication. Obviously, a number of citation alone is not enough to provide a comprehensive measure for judging the quality of scientific articles. Especially due to the existence of several ways to enhance the article citation. However, up to date citation continue to be the primary gauge of the significant of a research output [27].

Bibliometric analysis has been used extensively for evaluating scientific preferences of the research articles for the past decades [25]. In this contest, diverse aspects such as authors, annual publication outputs, language, journals, categories, contributing institutes, publishers, keywords and countries have been studied [26].

Despite the significant of the T2FLS, to the best of the author's knowledge, there is no bibliometric analysis carried out in the field of T2FLS. In this research, the trend of most often cited publications in the area of T2FLS design and applications have been investigated. The analysis of the author keyword and citation in the Institute for Scientific Information database were used to describe the trends of publications in this domain of research during 1980-2016. This study attempted to give insight into state-of-the-art publications in the area of T2FLS applications including author keyword, author analyses, distribution of the publication by country, publication trends, top-cited papers high-performing institutions and collaboration effects. The results offer a well understanding of the trends in T2FLS applications and show the direction for future research.

1.1 Essential Differences between T1FLS and IT2FLC

Both the T1FLS and the T2FLS consists of fuzzification and inference blocks, but they differ in the output processing block. In the T2FLC, the output processing block consist of type-reducer and defuzzification blocks, while only defuzzification block is present in T1FLS as shown in Figure 1 (a) and (b).

The are many experimental pieces of evidence that illustrate the superior performance of T2FLS over its T1FLSs counterparts, especially at the high level of uncertainties and nonlinearities [19]. However, the T2FLSs have relatively higher computational cost when compared with T1FLSs. The computational cost is due to the type reduction process, particularly when using the iterative Karnik and Mendel (KM) algorithms [28]. Many approaches have been proposed in the literature to reduce this computational cost [28].

There are many essential differences between T1FLS and T2FLS which are described in detailed by Wu [29]. The summary of some of the differences are as follows: The T2FLS can be thought of as a group of many diverse embedded T1FLS, and T2FLSs are more adaptive than T1FLSs [30]. Therefore, more complex input/output relationships, which cannot be realized by T1FLSs, can be achieved by IT2FLSs [31]. Also, it was shown that the representation of input/output of FLS with T2FSs resulted in a reduced rule base and increased robustness compared with the representation using T1FSs [29]. Moreover, some experimental evidence indicates that T2FLS can produce a smoother control surface, particularly around the steady state region compared to T1FLS [32-34]. In an IT2FLS, different membership grades from the same IT2FS can be used in various rules in an IT2FLS, whereas the same membership grade from the same T1FS is always employed in different rules in conventional T1FLS. This show that there is a novelty in a T2FLSs that does not exist in conventional T1 FLSs, and it indicated that a T2FLS cannot be implemented by a T1FLS using the same rule base and it is more complicated than a T1FLS [29].

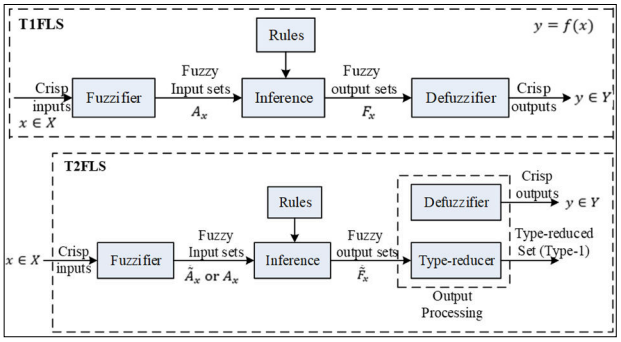

Fig. 1. Fuzzy logic system (a) Type-1, (b) Type-2 (adapted from [5])

2. MATERIALS AND METHODS

The data on the design and applications of type-2 fuzzy logic systems reported in this study were derived from the Web of Science (Thomson Reuters Web of Science database). This is based on the online version of the Science Citation Index Expanded on August 29th, 2016, for the period of 1980-2016. The key words used for the searching were: ("Type-2 Fuzzy Logic System*"), ("Type-2 Fuzzy Logic Controller*"), ("Interval Type-2 Fuzzy Logic System*"), ("Interval Type-2 Fuzzy Logic Controller*"), ("General Type-2 Fuzzy Logic System*"), ("General Type-2 Fuzzy Logic controller*"), ("Interval Type-2 Fuzzy Set*"), and ("General Type-2 Fuzzy Logic Set*"). A total of 1,258 documents were found to meet the criteria of selection.

The Microsoft Excel 2016 was used for analysis of the downloaded data. The manner adopted in selecting the top 100 cited papers is; The most cited articles per year are computed by dividing the total number of citations by the lifespan of the article [35]. To identify the top-cited articles, using the total number of citations per year is prepared scientifically and is more accurate than using the total number of citation only [36]. Abstracts of the top 100 cited papers were retrieved and reviewed to confirm that all the selected papers are within the domain of this study. All the chosen papers are verified to be within the scope of design and application of T2FLS with 92 technical journal article, five review articles, 2 Conference proceeding and one book chapter.

3. RESULTS AND DISCUSSION

3.1 Top 100 most cited papers in design and applications of T2FLS

Table 1 shows the ranking of the all the top 100 most cited papers in T2FLS design and application. This table indicates the ranking of the article based on their ACY. It also shows the reference, first author name and a total citation (TC) for each paper. The oldest article in the list was

Table 1 List of 100 Top most cited papers in design and applications of T2FLS

Rank	First Author	TC	ACY	Rank	First Author	TC	ACY	Rank	First Author	TC	ACY
1	Mendel [39]	820	54.67	34	Wang [40]	57	11.4	67	Castillo [41]	46	7.67
2	Mendel[42]	511	46.45	35	Wu [43]	45	11.25	68	Wu [44]	46	7.67
3	Liang[45]	661	38.88	36	Dereli [46]	65	10.83	69	Choi [47]	60	7.5
4	Hagras[48]	407	31.31	37	Wu [49]	52	10.4	70	Zarandi [50]	60	7.5
5	Karnik[51]	559	31.06	38	Chen [52]	41	10.25	71	Biglarbegian [53]	45	7.5
6	Mendel[54]	279	27.9	39	Liang [55]	173	10.18	72	Du [56]	52	7.43
7	Karnik[57]	424	26.5	40	Abiyev [58]	71	10.14	73	Karnik [37]	133	7.39
8	Mendel[59]	252	25.2	41	Mendel [60]	129	9.92	74	Wu [61]	44	7.33
9	Castillo[62]	117	23.4	42	John [63]	98	9.8	75	Hagras [64]	36	7.2
10	Li[38]	36	18	43	Melin [65]	39	9.75	76	Juang [66]	50	7.14
11	Hagras[67]	179	17.9	44	Lam [68]	87	9.67	77	Mendel [69]	71	7.1
12	Martinez[70]	142	17.75	45	Wu [71]	106	9.64	78	Zeng [72]	78	7.09
13	Wagner[73]	120	17.14	46	Wang [74]	123	9.46	79	Hosseini [75]	35	7
14	Karnik[76]	252	15.75	47	Zhai [77]	56	9.33	80	Melin [78]	41	6.83
15	Maldonado[79]	62	15.5	48	Khanesar [80]	46	9.2	81	Juang [81]	54	6.75
16	Liu [82]	134	14.89	49	Wu [83]	46	9.2	82	Mendel [84]	65	6.5
17	Biglarbegian [85]	100	14.29	50	Sepulveda [86]	46	9.2	83	Liang [87]	109	6.41
18	Mendel [88]	114	14.25	51	Aliev [89]	55	9.17	84	Sepulveda [90]	64	6.4
19	Castro [91]	112	14	52	Biglarbegian [92]	54	9	85	Oh [93]	38	6.33
20	Hwang[94]	138	13.8	53	Lin [95]	44	8.8	86	Zhai [96]	38	6.33
21	Wu [97]	206	13.73	54	Lin [98]	70	8.75	87	Hidalgo [99]	50	6.25
22	Castillo [100]	67	13.4	55	Castillo [101]	52	8.67	88	Uncu [102]	60	6
23	Cornelis [103]	170	13.08	56	Wu [104]	60	8.57	89	Greenfield [105]	30	6
24	Sepulveda [106]	128	12.8	57	Hsiao [107]	77	8.56	90	Leal-Ramirez [108]	35	5.83
25	Coupland[109]	127	12.7	58	Yeh [110]	51	8.5	91	Lin [111]	46	5.75
26	Castillo [112]	38	12.67	59	Melin [113]	59	8.43	92	Linda [114]	34	5.67
27	Lee[115]	86	12.29	60	Khosravi [116]	42	8.4	93	Abiyev [117]	34	5.67
28	Hidalgo[118]	61	12.2	61	Jammeh [33]	67	8.38	94	Juang [119]	45	5.62
29	Lam [120]	36	12	62	Linda [121]	50	8.33	95	Mendel [122]	94	5.53
30	Greenfield [123]	95	11.88	63	Zhang [124]	33	8.25	96	Coupland [125]	49	5.44
31	Juang [126]	106	11.78	64	Cazarez-Castro [127]	56	8	97	Castillo [128]	49	5.44
32	Gaxiola [129]	35	11.67	65	Mendel [130]	32	8	98	Liang [131]	86	5.38
33	Wu [132]	116	11.6	66	Cao [133]	55	7.86	99	Juang [134]	48	5.33
								100	Sudha [135]	32	5.33

published in the year 1999 by Karnik and Mendel [37] it was ranked 73 and was cited by 133 with 7.39 ACY. The latest paper in the list was published in the year 2015 by Li et al. [38] ranking 10 and cited by 36 with 18 average citations per year.

3.2 Comparisons between total citations and average-number of citations per year

The descriptive statistics and the scatter diagram for the ACY and TC are presented in Table 2 and Figure 2 respectively. The Pearson correlation coefficient (r) was employed to investigate the relationship between TC and the ACY in this domain of research. This is because the TC and ACY in the list of top 100 most cited papers in design and application of T2FLS are normally distributed. The results indicated a high and significant positive relation ($r = 0.91643$, $P<0.01$) between the TC and ACY in the list of top 100 most cited papers in design and application of T2FLS. Also, the linear regression was used for the perdition of ACY based on the TC. The significant and very high predictability result was obtained ($R^2 = 0.8382$ $F = 513.87$ and $\rho < 0.01$) for the linear. Thus, the equation for estimating the ACY based on the TC is:

$$ACY = 5.48057 + 0.05784 \times TC \quad (1)$$

Table 2 Descriptive statistics of ACY and TC

	N	Mean	Standard Deviation	Minimum	Median	Maximum
ACY	100	11.66	8.26	5.33	9.185	54.67
TC	100	106.84	130.79	30	60	820

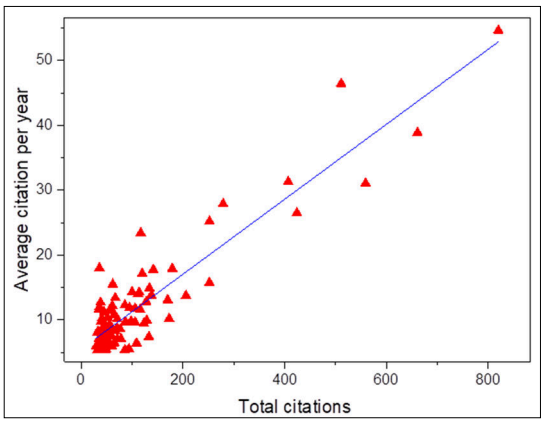

Fig. 2. Scatter diagram for the average citation per year and total citation

3.3 Most Cited Authors

The top 5 most cited authors are extracted from the list of all authors who have at least one article in the top 100 most cited papers in T2FLS design and application as a first or co-author. The top 5 authors were evaluated and selected based on the ranking in the top 100 most cited paper list. The presentation of these authors relies on four different indexes. Total number of publications in the top 100 cited list, total number of citations of all author's publications in the top 100 most cited list, summation of the average citation per year of the author's publication in the list, and finally average of Total ACY. Mendel, JM with has a higher number of publications, aggregate citation, and total average citation of 30, 5,581 and 452.82 respectively. However, he obtained the third rank in average citation per year per No of publications. The first rank average citation per year per number of publications was achieved by Karnik, NN with 17.42 from 5 articles. Table 3 shows the summary of the top 5 most cited authors in this domain of research.

Table 3 Summary of the top 5 most cited authors

Rank	Author	No of publications	Total TC	Total ACY	ACY per No of publications
1	Mendel, JM	30	5,581	452.82	15.10
2	Liang, QL	6	1,588	91.91	15.31
3	Hagras, HA	6	828	85.84	14.30
4	Karnik, NN	5	1,477	87.11	17.42
5	Castillo, O	21	1,299	215.26	10.25

3.4 Source Title

All of the top 100 most cited articles were published in 23 journals; the "IEEE Transactions on Fuzzy Systems" has a higher rank with 33 publications followed by "Information Sciences " with 21 articles. List of the contributing Journal, the number of papers published and the total citations for each journal are shown in Table 4.

Table 4 List of the contributing journals

Rank	Journal Name	Number Publication	Total citation
1	IEEE Transactions on Fuzzy Systems	33	5190
2	Information Sciences	21	2195
3	Expert Systems with Applications	6	313
4	IEEE Transactions on Systems Man and Cybernetics Part B-Cybernetics	6	443
5	Applied Soft Computing	5	320
6	IEEE Computational Intelligence Magazine	3	556
7	Engineering Applications of Artificial Intelligence	2	152
7	IEEE Transactions on Systems Man and Cybernetics Part C-Applications and Reviews	2	148
7	International Journal of General Systems	2	96
7	International Journal of Innovative Computing Information and Control	2	82
8	Analysis and Design of Intelligent Systems Using Soft Computing Techniques	1	64
8	Computers in Industry	1	65
8	Fuzzy Sets and Systems	1	252
8	IEE Proceedings-Electric Power Applications	1	50
8	IEEE Transactions on Circuits and Systems Ii-Analog and Digital Signal Processing	1	40
8	IEEE Transactions on Intelligent Transportation Systems	1	55
8	IEEE Transactions on Power Systems	1	42
8	IEEE Transactions on Systems Man and Cybernetics Part A-Systems and Humans	1	41
8	International Journal of Approximate Reasoning	1	170
8	Journal of Water Resources Planning and Management-ASCE	1	49
8	Knowledge-Based Systems	1	57
8	Signal Processing	1	94
8	Soft Computing	1	52

3.5 Institutes with more than one publications

The author's affiliations in the top 100 most cited papers are used to extract the data for evaluating the performances of the institutions. The number of organizations contributed in publishing the top most cited articles in T2FLS design and application was 68. Among which 47 organizations contribute with only 1 paper, 10 institutions have contributed with 2 articles each, and 11 institutions contributed with three or more papers. As indicated in Table 5. The "Univ So Calif" and the "Tijuana Inst Technol" obtained the higher number of publications of 32 and 18 respectively. Only the institutions with at least two records are presented in Table.

Table 5 List of the contributing institutions

Institution	No. Publication
Univ So Calif	32
Tijuana Inst Technol	18
De Montfort Univ	7
Univ Essex	7
Natl Chung Hsing Univ	5
Ge Global Res	4
Univ Alberta	3
Ipn	3
Natl Chiao Tung Univ	3
Univ Toronto	3
Univ Waterloo	3
Tobb Econ Technol Univ	2
Uabc Univ	2
Feng Chia Univ	2
Bogazici Univ	2
Chien Kuo	2
Technol Univ	2
Hanyang Univ	2
Ind Technol Res Inst	2
Natl Univ Singapore	2
Polish Acad Sci	2
Univ Georgia	2

3.6 Countries

The author's address in the database was used to extract the data for the countries that have contributed in the top most cited article in T2FLS design and application. The total of 15 countries contributed to the list. Among which four countries contributed with only one publication, three countries contributed with two publications while twelve countries contributed with three or more papers. Figure 3 shows that USA has the highs rank with 40 paper flowed by Mexico with 20 articles.

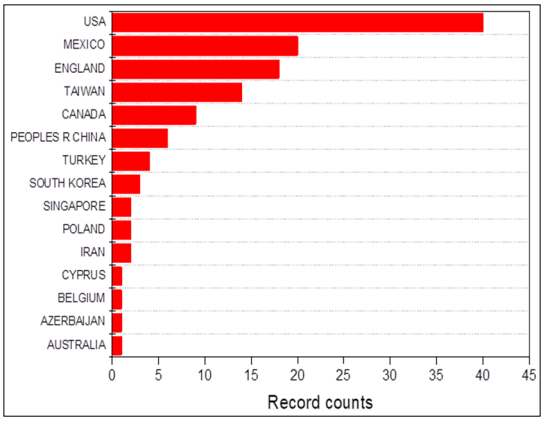

Fig. 3. Distribution of the 100 most cited publications by country

3.7 Web of Science categories

The web of science categories for the top 100 most cited papers in T2FLS design and application is shown in Table 6. As indicated from Table 7, the number of publications is higher than 100, this because some of the journals have more than one category, and the particular web of science category in which the paper is published is not indicated. This mean there is an overlapping. 17 different categories are found in our search, with 5 categories have only one publication; 3 categories with two publications and 9 categories with three or more publications.

Table 6 Web of science categories

Category	Record
Computer Science Artificial Intelligence	63
Engineering Electrical Electronic	50
Computer Science Information Systems	21
Automation Control Systems	15
Computer Science Interdisciplinary Applications	10
Computer Science Cybernetics	9
Operations Research Management Science	6
Computer Science Theory Methods	4
Instruments Instrumentation	4
Engineering Multidisciplinary	2
Ergonomics	2
Engineering Civil	2
Statistics Probability	1
Transportation Science Technology	1
Water Resources	1
Engineering Industrial	1
Mathematics Applied	1

4. FUTURE TREND

The pattern of a number of publications per year for the top 100 most cited articles in design and applications of T2FLS is shown in Figure 4. Based on this diagram, it can be seen that the number of publications is higher in the year 2007. Also, the total citation per year for the top 100 most cited articles in design and applications of T2FLS is shown in Figure 5. The citation per year is proved to be increasing. This is likely due to the high number of research in this area. Moreover, the line of best fit was drawn on the scatter diagram of the total citation per year to predict the future of the citation. The result of ($R^2 = 0.9126$ $\rho < 0.01$) was found, which means the citation will be increasing per year in future. By increasing the citation, it means the publication will be increasing. This shows that the arear of design and application of T2FLS is a hot are and has the promising future.

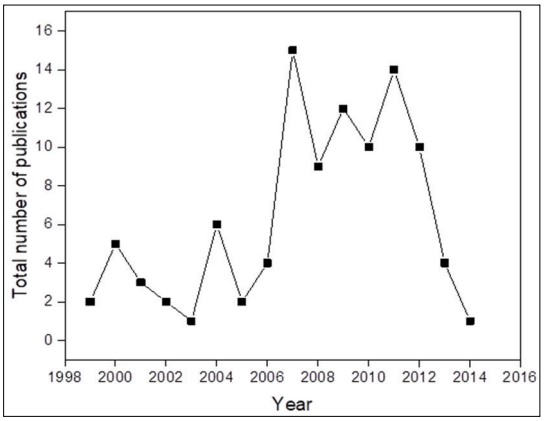

Fig. 4. Trend of number of publication per year

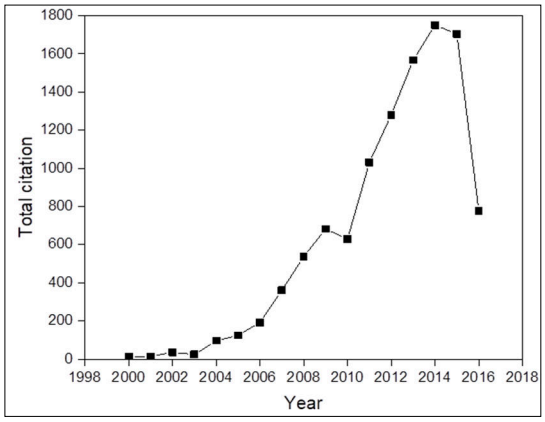

Fig. 5. Total citations per year

5. LIMITATIONS OF THE STUDY

It is worth mentioning that the present study cannot be entirely free of methodological deficiency. First, only the papers indexed by the ISI web of science are considered and those that are indexed by database other than ISI web science are omitted. Also, acceptance or rejection of manuscript for publication depend on upon the journal approach. Hence, stringent selection criteria by a journal may affect the quality of that journal. It is therefore not surprising that only 2 journals have contributed 54% of the top 100 most cited articles. Moreover, citation counts may be affected by other factors including self-citation, nature of the article such as review or open access, prominent authors, as well as the possibility for collaborative citations. Lastly, year of publication has an influence on the number of citations that a particular article can receive. Therefore, papers published recently may not have enough citations to get to the top cited list.

6. CONCLUSIONS

This analysis can be considered to be the report on the top most cited papers in T2FLS. The documents extracted from the web of science core collection and arranged according to the total number of citations received over the years. Notably, in this analysis, old papers were favored because longer time allows them to accumulate more citations compared to the recently published articles. Hence, the average number of citations per year was also considered in assessing the quality of this papers. Nevertheless, due to its significant contribution to the understanding of the fundamental concept in T2FLS, the article titled "Type -2 fuzzy sets made simple" by Mendel and John published in 2002, appeared on top of the pyramid with a total number of 820 citations, and receives an average of 54.67 citations every year.

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