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Feature article

Mapping of metal-organic frameworks publications: A bibliometric analysis

Yuh-Shan Ho [a,*], Hui-Zhen Fu [b]

[a] Trend Research Centre, Asia University, Taichung 41354, Taiwan
[b] Information Resources Management, School of Public Affairs, Zhejiang University, Hangzhou 310058, Zhejiang, China

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ABSTRACT

A bibliometric analysis based on the Science Citation Index Expanded from Web of Science was studied for research activities of the global metal-organic frameworks (MOFs) from 1995 to 2014. Study emphases included document types, languages, performance of publication covering annual outputs, journals, Web of Science categories, countries, and institutions. Six publication indicators including total, independent, collaborative, first authored, and corresponding authored, and single authored publications were used to evaluate publications of countries. China took a leading position of 75 countries while articles published by the USA had higher impact. An indicator SIN, a proportion of single institution articles:internationally collaborative articles:nationally collaborative articles (S:I:N) was applied to compare and describe institutions' publication characteristics. Based on number of citations since papers published to the end of the last year, citations per publication and h-index for highly cited articles were compared. In addition, Yaghi's group published the first article in the MOFs field and they contributed eight of the top ten leading articles in 2014.

Contents

1. Introduction

In 1995, Yaghi and co-workers in Arizona State University firstly named and published metal-organic frameworks (MOFs) in Web of Science [1,2]. MOFs are an identified class of porous polymeric material, consisting of metal ions linked together by organic bridging ligands, and are a development on the interface between molecular coordination chemistry and materials science [3]. Open metal-organic frameworks are widely regarded as promising materials for shape-selective catalysis [4], size-selective catalysis [5], adsorption based gas [6], capture of heavy metal ions [7], gas storage [8,9], drug delivery [10], and molecular recognition [11]. Furthermore, two isostructural coordination polymers with novel anionic metal-organic frameworks were synthesized under microwave conditions using an ionic liquid EMIm-Br as solvent and template [12].

In material science related fields, Spanish authors reported a series of bibliometric studies for countries, for example Latin American, Spanish, Portuguese [13]; journals [14]; and materials and ceramics subject

* Corresponding author.
E-mail address: ysho@asia.edu.tw (Y.-S. Ho).

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category [15]. More bibliometric studies were focused on nanoscience and nanotechnology [16,17]. The bibliometric analysis of highly cited articles in materials science was also presented in recent year [18]. In order to analyze the publication impact in a field, Ho and co-workers presented citation indicators such as the total number of citations of a paper in its publication year [19], the number of citation of a paper in the last year only [20], total citations from publication to the end of last year [21], and total citations per year [20]. Impact of an article [22] or a review paper [19] might not be always high. Most of the top articles did not have a high ranking of the citations of an article in its publication year [23]. A decreasing trend after about two years can be found in the top-10-most-cited reviews in their publication year [19]. In recent years, an indicator with two parameters, publication quantity and the characteristics of contribution to articles, was also presented [24] and applied to the highly cited articles in materials science [18].

Metal-organic frameworks related publications during the past two decades was analyzed to provide a basis for a better understanding of the global research situation, establishing medium and long term strategies of this field. The analyzed aspects covered not only the quantitative description of publications: annual outputs, mainstream journals, Web of Science categories, and leading countries, and institutions, but also the impact analyses using total citations and citations in recent year of publications.

2. Methodology

Data were obtained from the online version of Science Citation Index Expanded (SCI-EXPANDED) databases of the Thomson Reuters' Web of Science Core Collection. According to Journal Citation Reports (*JCR*) of 2014, it indexes 8618 journals with citation references across 176 Web of Science categories in science edition. "Metal-organic frameworks", "metal-organic framework", "porous coordination networks", "porous coordination network", "porous coordination polymers", and "porous coordination polymer" [25] were searched in terms of topic within the publication year limitation from 1900 to 2014. In total, 17,312 publications met the selection criteria. Another filter, the "front page", meant only the articles with the searching keywords in their front page including article title, abstract and author keywords were preserved [22]. *KeyWords Plus* supplied additional search terms extracted from the titles of articles cited by authors in their bibliographies and footnotes in the ISI (now Thomson Reuters, New York) database, and substantially augmented title-word and author-keyword indexing [26]. The articles that can only be searched out by *KeyWords Plus* were excluded. Finally, 9083 documents were regarded as the metal-organic frameworks (MOFs) publications. Downloaded information included names of authors, contact address, paper title, year of publication, document type, Web of Science categories of the article, names of journals publishing the articles, and citations in each year for each article. The records were downloaded into spreadsheet software, and additional coding was manually performed for the number of authors, country of origin of the collaborators, and impact factors of the publishing journals using Microsoft Excel 2010 [27]. Impact factors (IF_{2014}) were taken from the *JCR* published in 2014.

In the SCI-EXPANDED database, the corresponding author was designated as the "reprint" author; this study instead used the term "corresponding author" [20]. In a single author article where authorship was unspecified, the single author was both first author and corresponding author [20]. Similarly, for a single institution article, the institution was classified as the first author's institution and the corresponding author's institution [28]. Articles originating from England, Scotland, Northern Ireland, and Wales were reclassified as being from the United Kingdom (UK). Articles from Hong Kong were included under the heading of China. Contributions of different institutions and countries were estimated by the affiliation of at least one author to the publications. Collaboration type was determined by the addresses of the authors [29], where the term "single country article" was assigned if the researchers' addresses were from the same country. The term "internationally collaborative article" was designated to those articles that were coauthored by researchers from multiple countries. The term "single institution article" was assigned if the researchers' addresses were from the same institution. The term "inter-institutionally collaborative article" was assigned if authors were from different institutions [27].

3. Performance of publication

3.1. Document type and language of publication

The distribution of document types at the Web of Science has been analyzed in numerous research topics [30,31]. In recent years, Ho and co-workers presented idea of TC_{year} that is number of citations since papers published to the end of the last year [18,21,28,32]. This indicator makes total citations to be a constant as a scientific result which can be repeated and checked. In addition, citations per publication ($CPP = TC_{2014} / TP$) can be also a scientific result. Table 1 shows 11 document types and their total number of publications (*TP*), TC_{2014}, and *CPP*. As expected in science and engineering fields, journal article was the most frequently used document type [33,34] with 7937 articles, accounting for 87% of the total productions, followed by meeting abstracts (646; 7.1%) and reviews (412; 4.5%). The document type of note held the highest *CPP* of 603.

It was reported that a high percentage of non-article publications can be found in beginning period of a new research issue [30]. In metal-organic framework field, Yaghi and co-workers presented not only the first note "Hydrothermal synthesis of a metal-organic framework containing large rectangular channels" [1] published in *Journal of the American Chemical Society* ($IF_{2014} = 12.113$) with TC_{2014} of 603 but also the first article "Selective binding and removal of guests in a microporous metal-organic framework" [2] published in *Nature* ($IF_{2014} = 41.456$) with TC_{2014} of 969 in SCI-EXPANDED. Yaghi and Li [1] concluded that hydrothermal synthesis is a viable route to accessing zeolite-like materials in crystalline form and having components that are not generally observed otherwise. Articles were the dominant document type but with the 6th ranking of *CPP* (31). The following document type was meeting abstracts with four citations only. Furthermore, reviews had a high *CPP* of 172 which is 5.6 times of document type of articles. Only the document type of article was further analyzed, since they represented the majority of document types that also included whole research ideas and results [35].

Ninety-nine percent of 7840 articles were published in English. Several other languages also appeared: Chinese (85), German (4), Japanese (3), and one for each of Croatian, French, Portuguese, Slovak, and Turkish respectively. Such high percentage (99%) of English articles was also reported in wetland research [36]. Thirsty-3% of 97 non-English articles in MOFs field had no citations ($TC_{2014} = 0$), 19% articles had one citation ($TC_{2014} = 1$), and 10% articles had two citations ($TC_{2014} = 2$) while 14%, 7.2%, and 5.4% of 7840 English articles had $TC_{2014} = 0$, $TC_{2014} = 1$, and

Table 1
Document types of metal-organic frameworks publications in SCI-EXPANDED.

Document type	TP	%	TC_{2014}	CPP
Article	7937	87	245,334	31
Meeting abstract	646	7.1	4	0.0062
Review	412	4.5	70,892	172
Proceedings paper	102	1.1	3367	33
Editorial material	36	0.40	1791	50
Correction	26	0.29	42	1.6
Book chapter	21	0.23	446	21
News item	21	0.23	219	10
Letter	3	0.033	291	97
Note	1	0.011	603	603
Reprint	1	0.011	1	1.0

TP: total publications; TC_{2014}: total number of times cited since the paper was published to the end of 2014; *CPP*: citations per publication (TC_{2014}/TP).

$TC_{2014} = 2$ respectively. The most frequently cited non-English article entitled "Progress of research on hydrogen storage" [37] was published in Chinese with TC_{2014} of 19.

3.2. Publication outputs

To obtain an overview of metal-organic frameworks (MOFs) research, the annual number of articles during 1995–2014 was displayed in Fig. 1. The publication outputs of years increased during the last decade sharply. Metal-organic frameworks have received much attention in recent years especially as newly developed porous materials [25]. The mean number of *CPP* was 31. In 1999 with five articles and in 1995 with only one article had the much higher *CPP*s of 625 and 969, respectively, which can be attributed to the articles by Yaghi and Li with TC_{2014} of 969 in 1995 and Li et al. with TC_{2014} of 3010 in 1999. In 1995, the first article appeared with $TC_{2014} = 969$. Two articles were published in 1998. In the beginning years, Yaghi's group published the most parts of articles [2,8,38] when Yaghi was in Arizona State University and University of Michigan. At the same time Kurmoo from Institut de Physique et Chimie des Matériaux de Strasbourg in France and Kepert from University of Oxford in the UK published articles related to the dicyanamide bridges the metal ions to form infinite 3D metal-organic frameworks with a rutile-type structure [39,40].

Impact of papers in a research field has been compared with the number of times any paper is cited in other publications from Web of Science Core Collection [23,41]. In general, citation frequency is highly correlated with the length of time since publication and newly published papers require time to accumulate citations [42]. Indeed evidences can be found in articles published *Journal of Membrane Science* [43]; highly cited publications ($TC_{year} \geq 100$) in materials science field [18]; and classic articles ($TC_{year} \geq 1000$) in Science Citation Index Expanded [28]. Based on Fig. 1, it takes *CPP*s about a decade to reach a plateau. Similarly, classic articles ($TC_{year} \geq 1000$) in the top-cited research works in the SCI-EXPANDED [28]; highly cited publications ($TC_{year} \geq 100$) in materials science field [18]; highly cited articles in Taiwan [41]; independent research from China in the SCI-EXPANDED [44]; and articles published *Journal of Membrane Science* [43] took about one decade to reach a plateau, could also be found. It might be concluded that to evaluate impact of papers, citations accumulated at least one decade is needed. In order to verify this 10-year lag, Chuang and Ho [41] concluded that regardless of the year of data, they all showed approximately a 10-year period between the time of data collection and the peak output of highly cited papers. To emphasize this point, a total of 4442 MOFs articles (56% of 7937 articles) had no citations in the publication year ($C_0 = 0$). Although with an increasing number of journals in SCI-EXPANDED, articles have had higher citations in the publication year (C_0) in recent years [19]. Furthermore, among the top 100 C_0 articles, only 22% and 24% of them were among the top 100 TC_{2014} and C_{2014} articles respectively. In other words, using a 5-year time-span as the assessment period might not reflect the true impact of a paper [41].

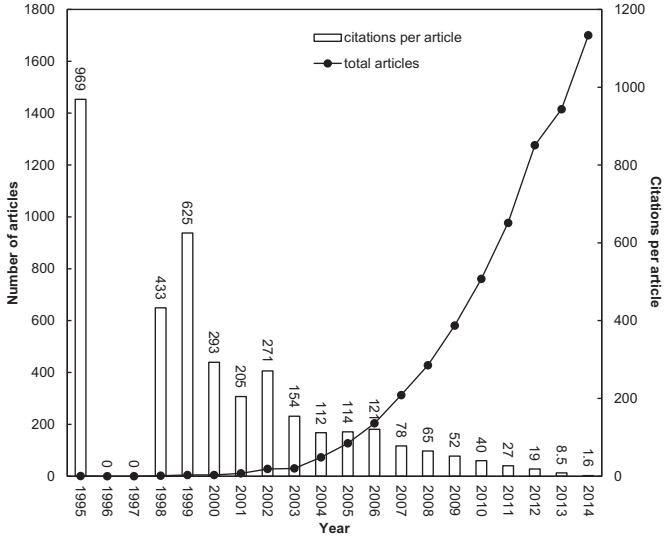

Fig. 1. Annual number of articles and citations per publication by year.

3.3. Web of science categories and journals

Articles published in SCI-EXPANDED journals which were distributed in 176 Web of Science subject categories. The distribution of the subject categories for research topics has been studied [30]. Based on the classification of categories in *JCR* science edition in 2014, the publication output data of MOFs research was distributed across 59 Web of Science categories. Multidisciplinary chemistry with 157 journals, contributed the most of 3387 articles (43% of 7937 articles), followed by physical chemistry with 139 journals (1982 articles; 25%), inorganic and nuclear chemistry with 44 journals (1809; 23%), multidisciplinary materials science with 259 journals (1793; 23%), and crystallography with 23 journals (1144; 14%).

In total, 7937 articles were published in a wide range of 426 journals. Among these journals, 364 (85% of 426 journals) journals contained <20 articles in the last two decades. Top 28 journals were listed in chemistry related categories. Table 2 shows the top 16 productive journals ($TP > 100$) which accounted for 58% of the articles. *Journal of the American Chemical Society* published the most articles with 511 articles (6.4% of 7937 articles), followed by *Chemical Communications* (505; 6.4%). *Crystengcomm* (462; 5.8%) and *Crystal Growth & Design* (449; 5.7%) ranked on top one and two in the category of crystallography with IF_{2014} of 4.891 and 4.034 respectively. It was reported that *Chemistry of Materials* ranked 4th most productive journal in highly cited articles ($TC_{2011} \geq 100$) in materials science [18] and *Journal of the American Chemical Society* ranked 18th most productive journal in articles with $TC_{2010} \geq 1000$ in SCI-EXPANDED [28]. The percentage of the top productive journal was not high (6.4%), which indicates the breadth of article distribution as well as the broad interest in MOFs from various research angles [45] of chemistry, physics, and materials fields. This phenomenon also appears in other research areas, such as *British Medical Journal* (4.3%) on homeopathy research [31], *Human and Ecological Risk Assessment* (3.0%) in articles related to risk assessment [46] and *Water Research* (4.2%) in papers concerning drinking water [47]. The journals with the highest IF_{2014} was *Nature* with seven articles ($IF_{2014} = 41.456$), followed by *Nature Materials* with 14 articles ($IF_{2014} = 36.503$), and *Science* with 18 articles ($IF_{2014} = 33.611$). In addition, the top four most frequently cited articles in MOFs were published in *Science* ($IF_{2014} = 33.611$) and *Nature* ($IF_{2014} = 41.456$).

3.4. Country and institution

In last decade, Ho and co-workers presented six indicators such as total publications (*TP*), independent publications (*IP*), collaborative publications (*CP*), first authored publications (*FP*), corresponding authored publications (*RP*), and single authored publications (*SP*) to compare publications of countries and institutions respectively [19,31,35]. It is generally accepted that the first author is the person who contributes most to the work and writing of the article [48]. The corresponding author responsibilities include supervision of the planning and execution of the study, along with writing the paper [49]. At the institutional level, the determined institution of the corresponding author might be a home base of the study or origin of the paper [20].

There were only seven articles without affiliations in Web of Science. Of 7930 articles with author affiliations from 75 countries, 6188 (78%) were single country articles from 52 countries and 1742 (22%) were internationally collaborative articles from 73 countries. The top 16 countries published >100 articles, taking 94% of 7930 articles, are listed in Table 3 with six indicators [19]. Seven European countries, six Asian

Table 2
The 16 most productive journals with the number of articles, impact factor, and category of journals in its position during the period of 1995 to 2014.

Journal	*TP* (%)	IF_{2014}	Web of Science category	Position
Journal of the American Chemical Society	511 (6.4)	12.113	Multidisciplinary Chemistry	10/157
Chemical Communications	505 (6.4)	6.834	Multidisciplinary Chemistry	20/157
Crystengcomm	462 (5.8)	4.034	Multidisciplinary Chemistry	32/157
			Crystallography	2/23
Crystal Growth & Design	449 (5.7)	4.891	Multidisciplinary Chemistry	24/157
			Crystallography	1/23
			Multidisciplinary Materials Science	31/259
Inorganic Chemistry	415 (5.2)	4.762	Inorganic and Nuclear Chemistry	4/44
Inorganic Chemistry Communications	310 (3.9)	1.777	Inorganic and Nuclear Chemistry	22/44
Angewandte Chemie-International Edition	292 (3.7)	11.261	Multidisciplinary Chemistry	13/157
Journal of Physical Chemistry C	276 (3.5)	4.772	Physical Chemistry	29/139
			Nanoscience and Nanotechnology	21/79
			Multidisciplinary Materials Science	32/259
Dalton Transactions	269 (3.4)	4.197	Inorganic and Nuclear Chemistry	5/44
Chemistry-A European Journal	259 (3.3)	5.731	Multidisciplinary Chemistry	22/157
Microporous and Mesoporous Materials	225 (2.8)	3.453	Applied Chemistry	7/70
			Physical Chemistry	40/139
			Nanoscience and Nanotechnology	26/79
			Multidisciplinary Materials Science	44/259
European Journal of Inorganic Chemistry	168 (2.1)	2.942	Inorganic and Nuclear Chemistry	8/44
Journal of Materials Chemistry A	116 (1.5)	7.443	Physical Chemistry	18/139
			Energy and Fuels	5/88
			Multidisciplinary Materials Science	20/259
Chemistry of Materials	114 (1.4)	8.354	Physical Chemistry	15/139
			Multidisciplinary Materials Science	17/259
Inorganica Chimica Acta	113 (1.4)	2.046	Inorganic and Nuclear Chemistry	16/44
Journal of Materials Chemistry	104 (1.3)	6.626*	Physical Chemistry	N/A
			Multidisciplinary Materials Science	

TP: total number of articles; %: the percentage of articles of journals in total articles; IF_{2014}: impact factor in 2014; *: IF_{2013}; N/A: not available.

countries, two American countries, and one Oceania country, were ranked on the top 16 of publications. There were no African countries in the top 16. The most productive African country was South Africa ranked 30th. China published 40% of the total articles followed by the USA (21%), Germany (7.5%), and Japan (6.2%). It is not usual that the USA ranked second in total publications but it still has more collaborative work and ranked top on internationally collaborative articles. The same phenomenon was found in adsorption technologies for dye containing wastewaters [50]. Based on top 1% and 10% TC_{2014} articles as well as top 10% TC_{2014} single country articles in each country, the USA had the highest citations per articles, $CPP_1 = 1294$, $CPP_{10} = 354$, and $CPP_{10S} = 419$. The USA also had highest h-index of 145 obtained from idea of TC_{2014} and lower percentage of articles counted for h-index of 8.7% = 145/1671. It is clear that China published the most articles but the USA was dominant by publication impact in MOFs research. Fig. 2 shows the top seven countries which have published >400 articles on MOFs. China has the fastest growing trend since 2005 and followed by the USA. Only 28 articles from China were published in 2005 but the number increased sharply to 253 by 2010. After 2010, China has higher growing trend again to reach 757 articles by 2014. This rapid increase might be attributed to the large-scale initiatives on basic research in China, such as the "211 Project", "973 Plan" and "985 Project" initiated in 1995, 1997 and 1998 respectively [51]. The 211 Project was entitled "High-level Universities and Key Disciplinary Fields" project and 985 Project was entitled "World Class Universities" [52]. "New materials" were highlighted as the seven priority industries in the "China's 12th Five-Year Plan (2011–2015)" [53]. Indeed, China published 3154 articles in which 2637 articles (84% of 3154 articles) had funding information in SCI-EXPANDED. In total, 2190 articles (83% of 2637 articles) supported by National Natural Science Foundation of China, 438 articles

Table 3
The top 16 most productive countries with *TP* > 100.

Country	TP	*TP R* (%)	*IP R* (%)	*CP R* (%)	*FP R* (%)	*RP R* (%)	*SP R* (%)	h-index (%)	CPP_1	CPP_{10}	CPP_{10S}
China	3154	1 (40)	1 (42)	2 (31)	1 (38)	1 (38)	1 (21)	106 (3.4)	302	112	90
USA	1671	2 (21)	2 (17)	1 (37)	2 (17)	2 (17)	2 (16)	145 (8.7)	1294	354	409
Germany	598	3 (7.5)	3 (5.7)	5 (14)	3 (5.6)	3 (5.6)	4 (7.8)	65 (11)	427	146	163
Japan	491	4 (6.2)	4 (5.4)	7 (8.8)	4 (4.8)	4 (4.9)	8 (4.3)	75 (15)	513	204	233
France	466	5 (5.9)	8 (2.6)	3 (17)	8 (3.5)	8 (3.6)	5 (6.1)	66 (14)	529	190	106
UK	452	6 (5.7)	7 (3.3)	4 (14)	7 (3.8)	7 (3.8)	3 (15)	66 (15)	574	215	213
South Korea	413	7 (5.2)	5 (4.2)	7 (8.8)	6 (3.9)	5 (3.9)	9 (3.5)	54 (13)	980	254	104
India	339	8 (4.3)	6 (3.9)	12 (5.5)	5 (3.9)	6 (3.8)	5 (6.1)	42 (12)	187	90	95
Spain	329	9 (4.1)	9 (2.0)	6 (12)	9 (2.9)	9 (2.9)	15 (0.87)	51 (16)	438	131	107
Australia	203	10 (2.6)	13 (1.1)	10 (7.6)	10 (1.5)	10 (1.5)	15 (0.87)	44 (22)	877	234	185
Italy	178	11 (2.2)	19 (0.60)	9 (8.1)	15 (1.1)	16 (1.0)	11 (2.6)	47 (26)	412	171	62
Belgium	156	12 (2.0)	12 (1.2)	14 (4.7)	11 (1.5)	11 (1.5)	N/A	37 (24)	422	167	133
Netherlands	155	13 (2.0)	16 (0.66)	11 (6.5)	17 (1.0)	15 (1.1)	15 (0.87)	43 (28)	321	151	154
Singapore	132	14 (1.7)	15 (1.0)	15 (4.2)	13 (1.2)	13 (1.2)	13 (1.7)	31 (23)	331	132	105
Canada	121	15 (1.5)	10 (1.3)	20 (2.2)	12 (1.2)	12 (1.2)	9 (3.5)	31 (26)	287	139	170
Russia	113	16 (1.4)	17 (0.65)	15 (4.2)	17 (1.0)	17 (1.0)	11 (2.6)	27 (24)	610	176	75

TP: total number of articles; *TP R* (%): rank and the percentage of total articles; *IP R* (%): rank and the percentage of independent articles; *CP R* (%): rank and the percentage of international collaborative articles; *FP R* (%): rank and the percentage of first authored articles; *RP R* (%): rank and the percentage of the corresponding authored articles; *SP R*: rank and the percentage of the single authored articles; CPP_1: citations per articles (top 1% articles only); CPP_{10}: citations per articles (top 10% articles); CPP_{10S}: citations per articles (top 10% single country articles); N/A: not available.

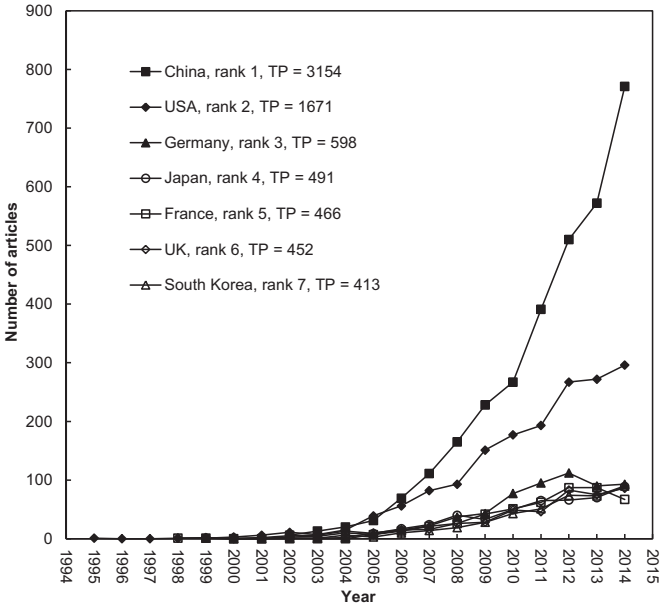

Fig. 2. Publications of the seven most productive countries during 1991–2014.

(17%) supported by 973 Program, and 423 articles (16%) supported by others. In addition, 414 articles were supported by both National Natural Science Foundation of China and 973 Program. The average number of funds for these 2637 articles was 2.9 with 11 as the largest number of funds. Times cited for a paper has been used as an indicator to compare research of countries. Usually an article will gain little attention during the first year after its publication, while the citing number accumulates gradually after several years for a classic article [54]. Due to China published much more articles in recent years (Fig. 2) and considered a bias of time. Thus, only articles published from 1995 to 2012 were analyzed. Fig. 3 shows the results of the top five productive countries. It is clear that China published articles with lower citations (35% articles < 10 citations). Eighty-three articles (4.6% of 1805 articles published from 1995 to 2012) without any citation and 30% with $0 < TC_{2014} < 10$. The USA published the most articles with $TC_{2014} > 40$.

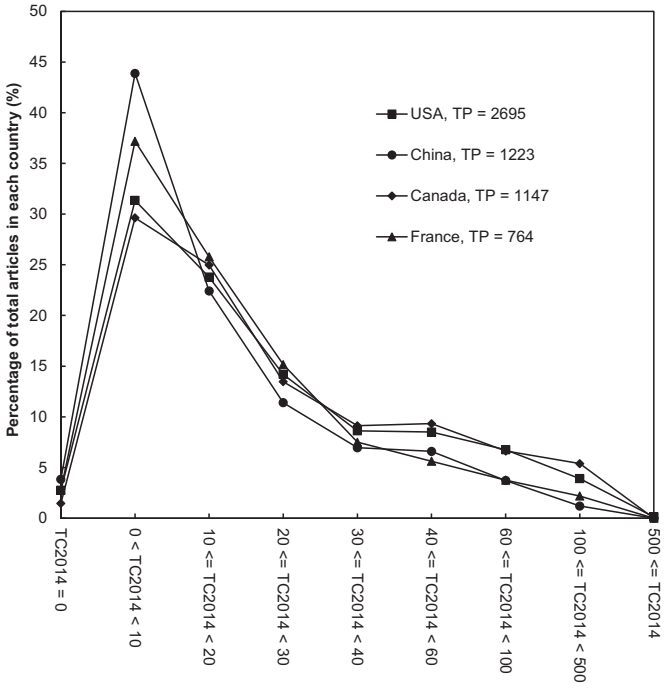

Fig. 3. Comparison of citation percentage in each country.

The top 20 institutions were ranked by the number of articles in Table 4. Among these institutions, 10 were in China, six in the USA, and one in each of the Belgium, Germany, Japan, and Singapore, respectively. The Chinese Academy of Sciences with 516 articles including 184 (36% of 516 articles) single institution articles, 78 (15%) internationally collaborative articles, and 253 (49%) national collaborative articles, ranked top on six indicators in Table 4. The Chinese Academy of Sciences had a large disparity with the others, and whose number of articles was more than double to that of Nanjing University in China with 237 articles. However, a bias appeared in Web of Science Core Collection because the Chinese Academy of Sciences has over 100 branches in different cities [55]. The publications of the institute were pooled as one heading. Except of the Chinese Academy of Sciences, Nanjing University in China published the most first authored articles and corresponding authored articles. Kyoto University in Japan published most national collaborative articles. Nankai University in China shows independent with the most single institution articles. University of Texas, San Antonio in the USA had the greatest number of international collaborations. Results in Table 4, also shows publication patterns of the institutions. Three universities in China such as Nankai University (63% of 183 articles), Beijing University of Chemical Technology (58% of 89 articles), and Northeast Normal University (56% of 170 articles), published >50% of articles as single institution publications in the universities. University of Texas, San Antonio in the USA (89% of 79 articles) and National University of Singapore (52% of 83 articles) published >50% of internationally collaborative articles in the universities. Kyoto University in Japan (65% of 220 articles) published >50% of nationally collaborative articles in the university.

Furthermore, the proportion of institutional independent articles:nationally collaborative articles:internationally collaborative articles has been developed to compare different institutions' publication characteristics. A proportion of single institution articles:internationally collaborative articles:nationally collaborative articles (S:I:N) might be used to describe institutions characteristics [56]. In metal-organic frameworks research field, the proportion of S:I:N was 47:22:31. Kyoto University's proportion of S:I:N was 15:20:65. It indicated that Kyoto University's research in MOFs field had more national teamwork or collaboration among different institutions than international collaborations among different countries. The Nankai University was more inclined or able to conduct research independently with S:I:N = 63:8.2:28. In Table 4, only three universities in China such as Nankai University (S:I:N = 63:8.2:28), Beijing University of Chemical Technology (S:I:N = 58:22:19), and Northeast Normal University (S:I:N = 56:9.4:35) had at >50% institutional independent articles of their total publications. University of Texas San Antonio in USA (S:I:N = 2.5:89:8.9) and National University Singapore (43:52:4.8) were the only two that had >50% of internationally collaborative articles of their total publications. This proportion indicator could show three important rates related with institution collaboration, which was more comprehensively and visually than just one traditional collaboration rate at a time for measurement and comparison.

3.5. Leading articles in 2014

Highly cited articles are particular importance because a high citation count is an indication of high impact or visibility in the research community [57]. Highly cited articles also provide an interesting and useful insight into which authors and topics are influencing a research discipline over time [58]. Highly cited articles play an important role in teaching students [59] and developing presentation skills [60]. However, an article impact might not be always high since it publication [20]. Even the top articles on total citations can be low impact in recent years, for example in pluripotent stem cell research [61], thermodynamic research [62], and articles in materials science field [18]. Thus number of

Table 4
The top 20 most productive institutions.

Institution	TP	*TPR* (%)	*SPR* (%)	*ICPR* (%)	*NCPR* (%)	*FPR* (%)	*RPR* (%)	*SP* (%)	*ICP* (%)	*NCP* (%)
Chinese Academy of Science, China	516	1 (6.5)	1 (5.0)	1 (4.5)	1 (10)	1 (4.4)	1 (4.4)	184 (36)	78 (15)	253 (49)
Nanjing University, China	237	2 (3.0)	4 (2.2)	6 (3.0)	3 (3.9)	2 (2.2)	2 (2.2)	83 (35)	53 (22)	97 (41)
Kyoto University, Japan	220	3 (2.8)	17 (0.89)	13 (2.5)	2 (5.7)	6 (1.8)	4 (1.8)	33 (15)	43 (20)	142 (65)
Jilin University, China	188	4 (2.4)	4 (2.2)	11 (2.6)	4 (2.4)	7 (1.7)	7 (1.7)	83 (44)	46 (24)	59 (31)
Nankai University, China	183	5 (2.3)	2 (3.1)	75 (0.86)	7 (2.1)	3 (2.0)	3 (2.0)	116 (63)	15 (8.2)	52 (28)
Northwestern University, USA	182	6 (2.3)	6 (1.8)	3 (4.0)	9 (1.9)	4 (1.8)	5 (1.8)	67 (37)	69 (38)	46 (25)
Northeast Normal University, China	170	7 (2.1)	3 (2.6)	70 (0.92)	4 (2.4)	5 (1.8)	6 (1.8)	95 (56)	16 (9.4)	59 (35)
University of California, Berkeley, USA	135	8 (1.7)	24 (0.76)	4 (3.9)	11 (1.6)	11 (0.87)	9 (1.0)	28 (21)	68 (50)	39 (29)
Sun Yat Sen University, China	120	9 (1.5)	7 (1.5)	81 (0.80)	8 (1.9)	8 (1.2)	8 (1.2)	57 (48)	14 (12)	48 (40)
Zhejiang University, China	99	10 (1.2)	19 (0.84)	8 (2.8)	47 (0.76)	9 (0.93)	11 (0.86)	31 (31)	49 (49)	19 (19)
Ruhr University Bochum, Germany	89	11 (1.1)	13 (1.1)	39 (1.4)	31 (1.0)	15 (0.78)	15 (0.77)	39 (44)	25 (28)	25 (28)
Beijing University of Chemical Technology, China	89	11 (1.1)	8 (1.4)	51 (1.1)	59 (0.68)	10 (0.92)	10 (0.95)	52 (58)	20 (22)	17 (19)
Texas A&M University, USA	88	13 (1.1)	11 (1.2)	31 (1.6)	65 (0.64)	12 (0.86)	12 (0.83)	43 (49)	28 (32)	16 (18)
Rutgers State University, USA	87	14 (1.1)	62 (0.35)	19 (2.0)	13 (1.5)	35 (0.45)	35 (0.48)	13 (15)	35 (40)	38 (44)
University of Michigan, USA	87	14 (1.1)	12 (1.1)	47 (1.1)	35 (1.0)	13 (0.81)	13 (0.82)	42 (48)	20 (23)	24 (28)
National University Singapore, Singapore	83	16 (1.0)	15 (1.0)	12 (2.5)	297 (0.16)	19 (0.69)	18 (0.69)	36 (43)	43 (52)	4 (4.8)
South China University of Technology, China	80	17 (1.)	21 (0.81)	50 (1.1)	20 (1.2)	16 (0.73)	16 (0.74)	30 (38)	20 (25)	29 (36)
Katholieke University of Leuven, Belgium	80	17 (1.0)	26 (0.65)	27 (1.8)	31 (1.0)	17 (0.71)	20 (0.67)	24 (30)	31 (39)	25 (31)
Zhengzhou University, China	79	19 (1.0)	16 (0.92)	187 (0.34)	13 (1.5)	13 (0.81)	13 (0.82)	34 (43)	6 (7.6)	38 (48)
University of Texas, San Antonio, USA	79	19 (1.0)	277 (0.054)	2 (4.0)	182 (0.28)	71 (0.3)	55 (0.35)	2 (2.5)	70 (89)	7 (8.9)

TP: total number of articles; *TPR* (%): rank and the percentage of total articles; *SPR* (%): rank of and the percentage of single institution articles; *CPR* (%): rank and the percentage of articles international collaborative articles; *FPR* (%): rank and the percentage of first author articles; *RPR* (%): rank and the percentage of the corresponding authored articles; *SP* (%): the number of single institution articles and the percentage of single institution articles in total articles of each institution; *ICP* (%): the number of internationally collaborative articles and the percentage of internationally collaborative articles in total articles of each institution; *NCP* (%): the number of nationally collaborative articles and the percentage of nationally collaborative articles in total articles of each institution.

citations in last year (C_{year}) of an article was concerned for top articles [20]. It was found that the top articles on TC_{year} and C_{year} were never be the same [20,24,63]. In addition, the rapid increase in the volume of scientific activity has made it nearly impossible to identify research "stars" using the standard bibliometric tools [64]. The top articles on number of citations in last year (C_{2014}) might be a new indicator to help researchers to understand recent research field. The 21 articles ($C_{2014} \geq 100$) with high impact in last year are shown in Table 5. Among the 21 articles, seven were published in the *Journal of the American Chemical Society* (impact factor $IF_{2014} = 12.113$), six in *Science* ($IF_{2014} = 33.611$), two in *Nature* ($IF_{2014} = 41.456$), two in *Nature Chemistry* ($IF_{2014} = 25.325$), and one each in the *Angewandte Chemie-International Edition* ($IF_{2014} = 11.261$), *Chemical Communications* ($IF_{2014} = 6.834$), *Nature Materials* ($IF_{2014} = 36.503$), and *Proceedings of the National Academy of Sciences of the United States of America* ($IF_{2012} = 9.674$). It was expected that papers published in journals with a high *IF* would probably have high citations. Three authors published the highly cited articles as first author such as N.L. Rosi with affiliations of Arizona State University in 2009 and University of Michigan in 2012; H.X. Deng with affiliation of University of California, Los Angeles; and P. Horcajada with affiliation of University of Versailles in France in 2004 and University of Complutense Madrid in Spain in 2005. Thirteen authors published only one highly cited article as corresponding author. O.M. Yaghi had eight corresponding authored highly cited articles with affiliations of University of California, Los Angeles (two articles in 2002 and 2006), University of Michigan (five articles in 2008, 2010, 2011, and 2012), University of California, Berkeley (one article in 2010). Due to Yaghi's group, University of Michigan (six *FP*, six *RP*) and University of California, Los Angeles (three *FP*, two *RP*) ranked top two in *FP* and *RP* respectively. This fact that the distribution of institutions hinged on certain scientists with high impact has been previously found in adsorption field [22]. It is noticeable that the third ranking institution of Nanyang Technological University in Singapore has two articles, and both of them were first author articles.

In Tables 5, 11 articles were published in the 2000s, nine in the 2010s, and only one in the 1990s. The 21 articles showed wide variations in C_{2014}, C_0, TC_{2014}, and *TCPY* values, with no particular pattern. Six articles (29 of 21 articles) on C_0, ten articles (48%) on TC_{2014}, and 16 articles (76%) on *TCPY* can be found in top 21 articles on C_{2014}. The earliest article with $C_{2014} \geq 100$ published in 1999 "Design and synthesis of an exceptionally stable and highly porous metal-organic framework" [8] and article entitled "Effects of functionalization, catenation, and variation of the metal oxide and organic linking units on the low-pressure hydrogen adsorption properties of metal-organic frameworks" [65] published by Yaghi's group in University of Michigan in the USA were the only two articles ranked on top 20 of the four indicators, C_{2014}, C_0, TC_{2014}, and *TCPY*. Furthermore, Yaghi's group published 11 articles (52% of 21 articles) in Table 5 including the earliest and the latest articles as well as the top one articles on C_{2014}, TC_{2014}, and *TCPY*, respectively.

A historical perspective on the highly cited articles in the Web of Science Core Collection that are still influential in MOFs was examined (Fig. 4). Ten articles had >140 citations in 2014 ($C_{2014} > 140$). Again Yaghi's group published eight leading articles in 2014 (80% of 10 articles) in Fig. 4. The article entitled "Systematic design of pore size and functionality in isoreticular MOFs and their application in methane storage" by Eddaoudi et al. [66] had the highest C_{2014}, TC_{2014}, and *TCPY*; and was the only one article had $C_{year} \geq 400$ times from 2011 to 2014. However, a decreasing trend of annual citations was found in last two years. This article has ranked top on C_{year} since 2004 in MOFs research field. The earliest article entitled "Design and synthesis of an exceptionally stable and highly porous metal-organic framework" by Li et al. [8] had the second highest number of citations in 2014 and still kept its annual number of citations increasing from the time of its publication. This article ranked top on C_{year} from 2001 to 2003. Articles entitled "Exceptional chemical and thermal stability of zeolitic imidazolate frameworks" [67] and "A new zirconium inorganic building brick forming metal organic frameworks with exceptional stability" Cavka et al. [68] were also keeping its annual number of citations increased from the time of its publication. Overall, it appeared to be going strong and showed no sign of leveling off. Article by Cavka et al. [68] had high citations in 2014 ($C_{2014} = 190$) but low total citations ($TC_{2014} = 484$; ranked 34). This latter article did not have enough time to accumulate citations, but it has continually increased in citations since its publication. In general, articles for example Rosi et al. [69], Chae et al. [70], Rosi et al. [71], Millward and Yaghi [72], and Furukawa et al. [73] had citation rates climbed initially to a plateau and then maintained steady for some years. In addition, Prof. Omar Yaghi was named to the shortlist of chemists predicted to win a Nobel Prize in 2010 by the Thomson Reuters (http://www1.cnsi.ucla.edu/news/item?item_id=1866790#).

Table 5
Twenty-one most frequently cited papers in 2014 ($C_{2014} \geq 100$).

Rank (C_{2014})	Rank (C_0)	Rank (TC_{2014})	Rank (*TCPY*)	Title	Reference
1 (400)	8 (29)	1 (3574)	1 (275)	Systematic design of pore size and functionality in isoreticular MOFs and their application in methane storage	Eddaoudi et al. (2002)
2 (353)	2150 (1)	2 (3010)	3 (188)	Design and synthesis of an exceptionally stable and highly porous metal-organic framework	Li et al. (1999) [8]
3 (288)	961 (3)	6 (1038)	8 (115)	Exceptional chemical and thermal stability of zeolitic imidazolate frameworks	Park et al. (2006) [74]
4 (235)	60 (14)	12 (896)	4 (179)	Ultrahigh porosity in metal-organic frameworks	Furukawa et al. (2010) [73]
5 (234)	123 (10)	3 (2378)	2 (198)	Hydrogen storage in microporous metal-organic frameworks	Rosi et al. (2003) [69]
6 (190)	3496 (0)	38 (484)	28 (69)	A new zirconium inorganic building brick forming metal organic frameworks with exceptional stability	Cavka et al. (2008) [68]
7 (176)	7 (30)	25 (609)	6 (122)	Porous metal-organic-framework nanoscale carriers as a potential platform for drug delivery and imaging	Horcajada et al. (2010) [75]
8 (166)	3496 (0)	6 (1038)	9 (104)	Metal-organic frameworks with exceptionally high capacity for storage of carbon dioxide at room temperature	Millward and Yaghi (2005) [76]
9 (163)	19 (20)	4 (1376)	5 (125)	A route to high surface area, porosity and inclusion of large molecules in crystals	Chae et a76l. (2004) [70]
10 (144)	33 (17)	6 (1038)	9 (104)	Rod packings and metal-organic frameworks constructed from rod-shaped secondary building units	Rosi et al. (2005) [71]
11 (135)	2150 (1)	49 (421)	16 (84)	De novo synthesis of a metal-organic framework material featuring ultrahigh surface area and gas storage capacities	Farha et al. (2010) [77]
12 (134)	359 (6)	5 (1222)	6 (122)	Homochiral porous metal-organic framework for highly enantioselective heterogeneous asymmetric catalysis	Wu et al. (2005) [78]
13 (133)	11 (25)	112 (256)	15 (85)	Hydrocarbon separations in a metal-organic framework with open iron(II) coordination sites	Bloch et al. (2012) [79]
14 (129)	33 (17)	123 (243)	18 (81)	Large-pore apertures in a series of metal-organic frameworks	Deng et al. (2012) [80]
15 (114)	9 (28)	61 (355)	13 (89)	Porous metal-organic frameworks as platforms for functional applications	Jiang and Xu (2011) [81]
16 (112)	23 (19)	15 (868)	12 (96)	Effects of functionalization, catenation, and variation of the metal oxide and organic linking units on the low-pressure hydrogen adsorption properties of metal-organic frameworks	Rowsell and Yaghi (2006) [65]
16 (112)	100 (11)	232 (171)	50 (57)	Imparting functionality to a metal-organic framework material by controlled nanoparticle encapsulation	Lu et al. (2012) [82]
18 (111)	11 (25)	43 (443)	13 (89)	Multiple functional groups of varying ratios in metal-organic frameworks	Deng et al. (2010) [83]
18 (111)	100 (11)	44 (434)	24 (72)	A luminescent microporous metal-organic framework for the fast and reversible detection of high explosives	Lan et al. (2009) [84]
20 (103)	359 (6)	33 (498)	25 (71)	Flexible porous metal-organic frameworks for a controlled drug delivery	Horcajada et al. (2008) [85]
21 (100)	3496 (0)	311 (138)	81 (46)	Formation of Fe_2O_3 microboxes with hierarchical shell structures from metal-organic frameworks and their lithium storage properties	Zhang et al. (2012) [86]

C_{2014}: number of citations in 2014; C_0: number of citations in the publication year; TC_{2014}: number of citations since its publication to the end of 2014; *TCPY*: TC_{2014} per year.

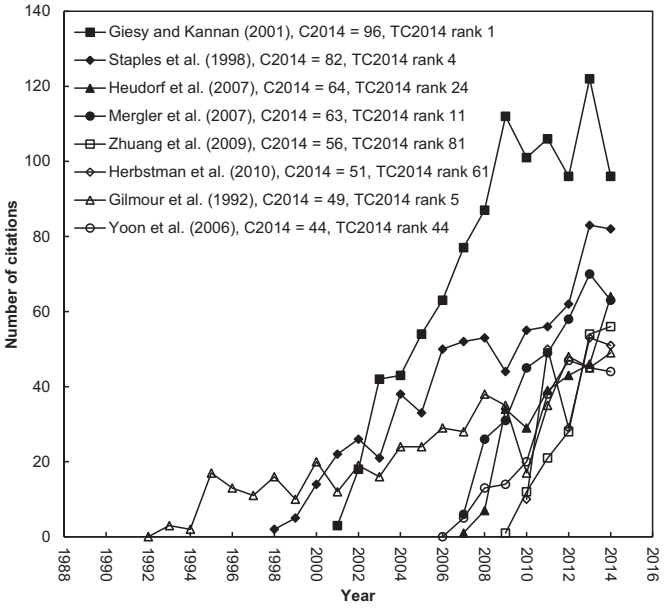

Fig. 4. Article lives of the top ten articles ($C_{2014} > 140$).

4. Conclusions

Eleven document types were used in metal-organic frameworks publications. Reviews had 5.6 times of citations per publication to that of articles. English was the dominant language. Non-English articles had low citations in metal-organic frameworks field. MOFs publications increased sharply after 2003. Articles published before 2003 had higher annual citations per publication. There were 7937 articles published in 426 journals listed in the 59 Web of Science subject categories. The highest number of articles was in *Journal of the American Chemical Society* and in the subject category of multidisciplinary chemistry. China published the most of articles while articles published by the USA had higher impact in the MOFs field. Nanjing University in China had the highest production as a research home base. Kyoto University in Japan was the most frequent national partner. Nankai University in China shows independent research. University of Texas, San Antonio in the USA was the most frequent research partner. In metal-organic frameworks research field, the proportion of single institution articles:internationally collaborative articles:nationally collaborative articles (S:I:N) was found to be 47:22:31. Yaghi's group published not only the first article but also most top leading articles in 2014.

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Yuh-Shan Ho received his Ph.D. in 1995 from the University of Birmingham, United Kingdom. He is currently Director of the Trend Research Centre at Asia University in Taiwan, where his main interests are in absorption processes for water treatment and bibliometric studies. Dr. Ho has had 39 papers cited more 100 times and one of these approximately 5000 times in the Web of Science Core Collection. Indeed, this particular paper has had >700 annual citations, and it has been ranked highest in this respect annual citations in the field of chemical engineering since 2008. Another of Dr. Ho's publications has been cited >1100 times. This particular paper has had >200 annual citations, and has been ranked top in this respect in the field of chemical engineering in 2015.

Hui-Zhen Fu received her Ph.D. in 2015 from the Peking University, China. She is currently worked in Department of Information Resources Management in Zhejiang University. Her main interests are bibliometric studies and evaluation. Dr. Fu has had published more than ten SCI or SSCI publications, receiving >200 citations in total.