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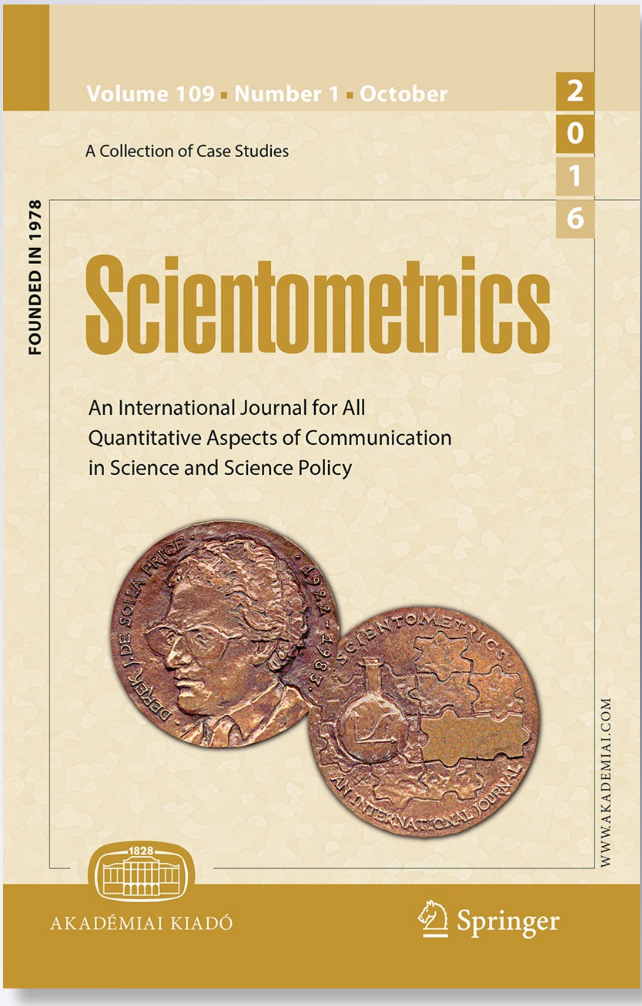

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Research trend of metal–organic frameworks: a bibliometric analysis

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Abstract A bibliometric analysis based on the related articles in the Science Citation Index Expanded database was conducted to gain insight into global trends and hot issues of metal–organic frameworks (MOFs). The word clusters of synthesis methods, MOFs' properties and potential applications and some representative MOFs with related supporting words in title, author keywords, abstract, along with *KeyWords Plus* were proposed to provide the clues to discover the current research emphases. *Y* index was introduced to assess the publication characteristics related to the number of first author and corresponding author highly cited articles. Top eight classic articles with total citations since publication to the end of 2014 more than 1000 times ($TC_{2014} > 1000$) and top eight classic articles with citations in 2014 more than 165 times ($C_{2014} > 165$) were selected and assessed regarding distribution of outputs in journals, publications of authors, institutions, as well as their citation life cycles. Solvothermal (including hydrothermal) method and diffusion (slow evaporation) were used mostly to prepare MOFs. Series representative MOFs, as well as the corresponding composites or film (membrane) arose the wide interests from researchers due to their excellent performances. Among the various properties and potential applications of MOFs, adsorption (gas adsorption and liquid adsorption) took the lead, followed by catalysis (including photocatalysis), as a result of their ultrahigh porosity and even their catalytic property. The results of *Y* index analysis revealed that most highly cited articles in MOFs field were contributed by Yaghi, O.M. as corresponding author, who published 27 articles with TC_{2014} (number of citations since its publication to the end of 2014) $\geq$100. Omar M. Yaghi, as corresponding author (reprint author), contributed most classic articles, which dealt with synthesis strategy of MOFs with high porosity and high capacity of gas storage. The remaining classic ones concerned to

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catalysis and drug delivery. These classic articles were published in four high impact journals. The analyses on citation life cycles of the classic articles with highest TC_{2014} and C_{2014} can help the researchers in MOFs related fields gain insight into their impact histories.

Keywords Web of science · SCI-EXPANDED · Scientometrics · Metal–organic frameworks

Introduction

Yaghi and Li (1995) firstly proposed the term of metal–organic framework, a group of coordination polymers which can be dated back to the 1960s (Janiak 2003). The terminology of metal–organic framework led to a hot discussion by an IUPAC task group (Batten et al. 2012). After discussions and consultations with hundreds of multinational scientists, the chemical community through IUPAC had agreed on the following definitions as "a metal–organic framework, abbreviated to MOF, is a Coordination Polymer (or alternatively Coordination Network) with an open framework containing potential voids" (Batten et al. 2013). Still, it should be noted that MOFs go by many names, such as porous coordination networks and porous coordination polymers (Zhou and Kitagawa 2014; Kuppler et al. 2009), which refer to similar if not the same general type of materials (Kuppler et al. 2009; Han et al. 2014). MOFs had attracted lots of significant research attentions in diverse areas during the last two decades due to their versatile architectures with ultrahigh surface areas, tunable pore sizes and topologies and their multiple active sites (Zhou and Kitagawa 2014; Stock and Biswas 2011; Xie et al. 2014). The unprecedented rapid development in MOFs research could also be ascribed to ever-expanding potential applications resulting from their unique properties and the feasible synthesis methods (Zhou and Kitagawa 2014).

The scientific production related to metal–organic frameworks was counted in reviews and books, in which the number of the paper published annually (Kuppler et al. 2009; Farrusseng 2011; Janiak and Vieth 2010) or the number of the MOFs structures reported annually (Long and Yaghi 2009) were summarized. A common research analysis tool based on bibliometric methods had been used to investigate scientific output and trends in material science (Rojas-Sola and Aguilera-Garcia 2014; Ho 2014a). The Science Citation Index Expanded (SCI-EXPANDED) from the Web of Science Core Collection of the Thomson Reuters is the most frequently used database to analyze scientific accomplishment in all research fields, for example medical science (Autier and Gandini 2007), material science (Li et al. 2008), chemistry (Fu et al. 2012b), environmental sciences ecology (Fu et al. 2013a), water resources (Wang et al. 2011), and engineering (Konur 2011). In last decade, using results of distributions of author keywords, words in title, and *KeyWords Plus* in different period to evaluate trends of research focuses in a field became a main issue (Xie et al. 2008; Ho et al. 2010). Based on results of word analysis, word cluster was further applied to trend studies (Fu et al. 2013a; Mao et al. 2010).

In this study, the analyses were performed on the basis of words in article titles, author keywords, and *KeyWords Plus* to track the global research focuses and their trends in MOFs field (Ho et al. 2010). Words clusters (Mao et al. 2010) were used to map the hot issues related to synthesis, properties and potential applications, and some representative ones of MOFs. *Y* index (Ho 2012, 2014a), as an indicator, was introduced to assess the author performances of the top-cited articles. Also, eight classic articles with $TC_{2014} > 1000$ and eight classic ones with $C_{2014} > 165$ were selected and analyzed with regard to authors, institutions, citation life, TC_{2014} and C_{2014}. These classic articles were reviewed to gain insight into the reason why they arose wide interest from the counterparts of MOFs research. The results of bibliometric analysis on MOFs dependent research during the past two decades can provide a basis for a better understanding of the global research situation, which can facilitate to establish the medium and long term strategies of MOFs researches.

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 (updated on 01 August 2015). 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" (Kuppler et al. 2009) were searched in terms of topic within the publication year limitation from 1991 to 2014. In total, 17,312 publications met the selection criteria. Another filter, the "front page" (Fu et al. 2012b), meant only the articles with the searching keywords in their front page including article title, abstract, and author keywords were preserved. *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 (Garfield 1990). The articles that can only be searched out by *KeyWords Plus* were excluded. Finally, 9083 articles were regarded as the metal–organic frameworks (MOFs) publications. $TC_{2014} \geq 1000$ and $C_{2014} > 165$ were used as a filter to extract the classic articles. Web of Science Core Collection full record and number of citations in each year for each article were downloaded into spreadsheet software, and additional coding was manually performed for the distribution of words in article title, abstract, author keywords, and *KeyWords Plus* using Microsoft Excel 2010 (Li and Ho 2008).

Results and discussion

Research trend

Keywords analysis

In last decade, Ho and co-workers presented the distribution of words in article titles, author keywords, and *KeyWords Plus* to evaluate trends in research topics (Fu et al. 2013a; Ho et al. 2010; Li and Ho 2008). Detection of certain words in the abstracts of articles has also been used as information to determine research trends (Zhang et al. 2009). It is accepted that the words in titles and author keywords supply reasonable details of the article subjects and include the information which author would like to express to their readers (Zhang et al. 2009). The examination of the author keywords revealed that 5880 author keywords were used from 1991 to 2014. These keywords were calculated and ranked by total 24-year study and 6 year-time periods, respectively. The 20 most frequently used author keywords with their rankings and corresponding percentages were listed in Table 1. Besides "metal–organic frameworks" (36 % of 3565 articles), "metal–organic framework" (19 %) as searching words, the two most frequently used keywords were "crystal structure" (9.3 %) and "adsorption" (8.9 %). The keywords "microporous materials" (4.4 %) and "porous materials" (2.3 %) presented the structure characteristic corresponding to the property of adsorption. Out of the top 20 keywords, there were five terms corresponding to MOFs' properties and found an increased trends, including "adsorption" (8.9 %, ranking 3rd place), "luminescence" (5.1 %, 5th), "heterogeneous catalysis" (4.2 %, 6th), "hydrogen storage" (3.6 %, 9th), and "magnetic properties"

Table 1 Top 20 mostly used author keywords in metal–organic framework articles in 1991–2014 periods

Author keywords	TP	1991–2014 *R* (%)	1991–1996 *R* (%)	1997–2002 *R* (%)	2003–2008 *R* (%)	2009–2014 *R* (%)
Metal–organic frameworks	1291	1 (36)	N/A	5 (17)	1 (30)	1 (38)
Metal–organic framework	695	2 (19)	N/A	2 (20)	2 (21)	2 (19)
Crystal structure	333	3 (9.3)	N/A	3 (18)	3 (14)	4 (8)
Adsorption	319	4 (8.9)	N/A	17 (3.3)	4 (10)	3 (8.9)
Coordination polymer	180	5 (5.0)	N/A	1 (23)	4 (10)	10 (3.5)
Luminescence	172	6 (4.8)	N/A	N/A	12 (4.0)	5 (5.1)
Coordination polymers	159	7 (4.5)	1 (100)	5 (17)	7 (7.9)	12 (3.3)
Microporous materials	157	8 (4.4)	N/A	N/A	6 (8.6)	11 (3.5)
Hydrothermal synthesis	149	9 (4.2)	N/A	3 (18)	8 (7.1)	13 (3.1)
Hydrogen storage	142	10 (4)	N/A	N/A	9 (5.7)	9 (3.6)
Heterogeneous catalysis	135	11 (3.8)	N/A	N/A	23 (2.3)	6 (4.2)
Metal organic framework	124	12 (3.5)	N/A	17 (3.3)	26 (2.0)	7 (3.9)
Metal organic frameworks	122	13 (3.4)	N/A	N/A	26 (2.0)	7 (3.9)
Zinc	108	14 (3.0)	N/A	10 (6.7)	11 (4.3)	15 (2.6)
Copper	105	15 (2.9)	N/A	7 (12)	13 (3.7)	17 (2.6)
Magnetic properties	98	16 (2.7)	N/A	10 (6.7)	14 (3.4)	18 (2.5)
MOF	95	17 (2.7)	N/A	33 (1.7)	32 (1.9)	14 (2.9)
Topology	86	18 (2.4)	N/A	N/A	32 (1.9)	16 (2.6)
MOFs	81	19 (2.3)	N/A	N/A	26 (2.0)	19 (2.4)
Porous materials	81	19 (2.3)	N/A	33 (1.7)	17 (3.0)	21 (2.1)

TP total articles, *R* rank, *N/A* not available

(2.5 %, 18th) in 2009–2014 period, implying that the recent studies focused on the potential applications of MOFs. The extremely high increasing rate in the ranking of the author keywords exhibited their importance and made them the new focus. However, it was noted that the analysis was based only on 3565 MOFs articles (45 % of 7937 articles) with author keywords records published in the 1991–2014 period. Therefore, the data in this study only provided an approximate reflection of the scientific attentions and focuses.

Word cluster analysis

Word cluster analysis with supporting words in title, abstract, author keywords, and *KeyWords Plus*, which can overcome the weak points of the separated types of keyword analysis, was also conducted to make inferences of the scientific literature or to identify the subjective focuses and emphases specified by the authors. After the integrated analysis of the four kinds of keywords, some valuable clues of the possible research focuses related to MOFs can be obtained. As depicted in Fig. 1, the word cluster analysis can be carried out following the procedure of (1) words in article titles and abstract, author keywords, and *KeyWords Plus*, were combined as the supporting words base; (2) word cluster, a serious synonymic single word and congeneric phrases, were summed up by researchers using their specialized knowledge, and could represent the possible research focuses of this field (Fu et al. 2013a). (3) the word cluster, which was composed of some supporting words, can be searched in the combined words' base from title, abstract, author keywords, and *Key-Words Plus* of the related publications; (4) the overview of the research trend or focuses can be obtained after analyzing the number of the publications containing the supporting words of word clusters (Mao et al. 2010). As to the research on MOFs, the synthesis

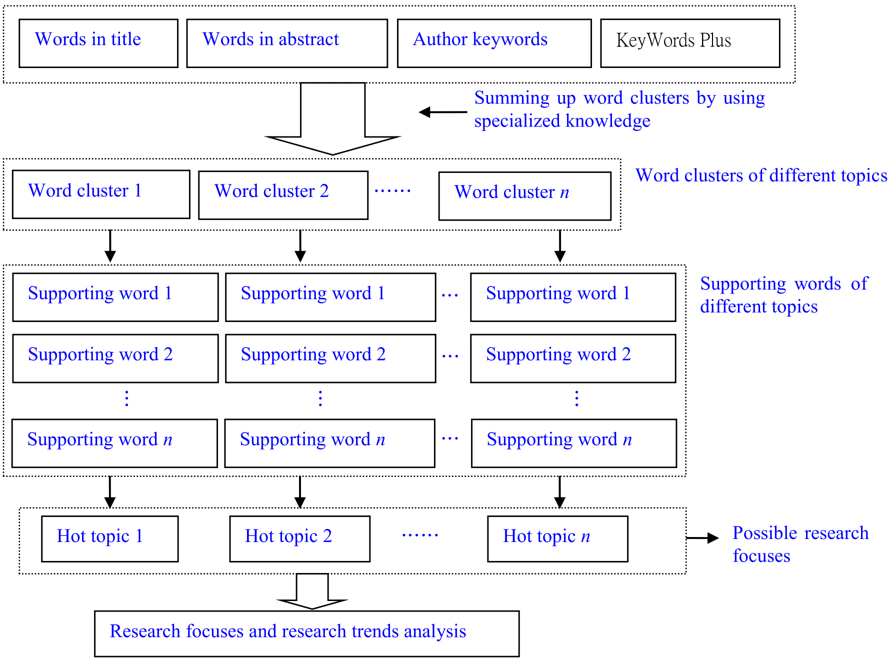

Fig. 1 Sketch map of the "Word Cluster Analysis" approach

methods (like solvothermal synthesis, diffusion, microwave-assisted synthesis, sonochemical synthesis, electrochemical synthesis and mechanochemical synthesis), versatile properties (including but not limited to luminescence, magnetism, gas storage, adsorption, separation, catalysis, and drug storage and delivery) and representative MOFs (like ZIF-8, MIL-53, MIL-101, MIL-125, HKUST-1, MOF-5, and UiO-66) arose the intense interests from the researchers. Hence, the MOFs synthesis methods, MOFs' properties, and several representative MOFs were selected to be carried out word cluster analysis.

Synthesis methods of MOFs

In order to clarify which synthesis method was mostly used to produce MOFs material, the word cluster analysis was conducted based on some selected methods including solvothermal (hydrothermal) synthesis, diffusion, microwave-assisted synthesis, sonochemical synthesis, electrochemical synthesis and mechanochemical synthesis. The corresponding supporting words of synthesis methods word cluster were listed in Table 2, and the trend analysis results were exhibited in Fig. 2. It can be concluded that the synthesis methods for the preparation of MOFs can be divided into three important stages as (Stock and Biswas 2011; Klinowski et al. 2011): (1) slow evaporation or diffusion of the solvents over time to harvest large single crystals in small yield, which was time-costly from several weeks to months; (2) solvothermal (including hydrothermal) synthesis methods, borrowed from conventional zeolite synthesis, was introduced, due to that they can precisely control over the size, shape distribution, and crystallinity of MOFs in a few days; and (3) in order to satisfy the demand of crystal engineers which require produce functional materials in large amounts within shorter reaction time, some new high-throughput methods including microwave-assisted synthesis, sonochemical synthesis, electrochemical synthesis and mechanochemical synthesis were used to prepare MOFs. The ABC information of microwave-assisted synthesis, sonochemical synthesis, electrochemical synthesis and mechanochemical synthesis were listed in Table 3. Based on the trend analysis on synthesis methods, it can be found that the conventional solvothermal synthesis (total article number being 783) and diffusion methods (331 articles) were used frequently, followed by microwave-assisted synthesis (109 articles). Due to their advantages of high throughput along with environment friendly characteristic, microwave-assisted synthesis,

Table 2 The supporting words of selected synthesis methods

Synthesis methods	Supporting words
Solvothermal synthesis	Hydrothermal, solvothermal, Solvothermal, solvo-thermal, solvothermally, Solvothermic, solvothermically, solvotherrnal, slovthermally
Diffusion	Evaporation, solvent-evaporation, gel diffusion technique, solvent-diffusion
Microwave-assisted synthesis	Microwave-synthesized, microwave-induced, microwave-enhanced, microwave-irradiation, microwave-nucleation, mw-assisted, microwave, micro-wave
Sonochemical synthesis	Sonochemical, sonochemistry
Electrochemical synthesis	Electrochemical synthesis, electrochemical syntheses
Mechanochemical synthesis	Mechanochemistry, mechanochemically, mechanochemical, mechanosynthesis

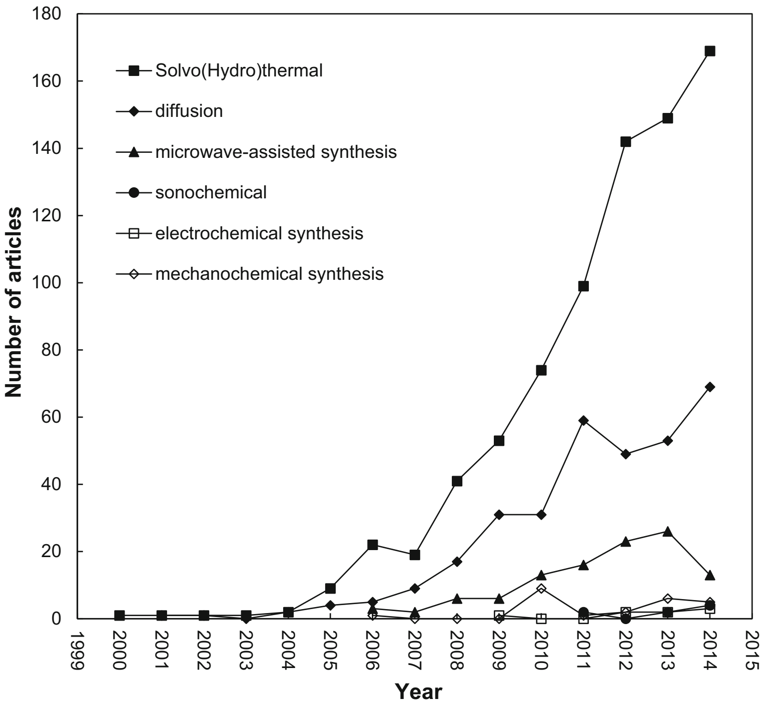

Fig. 2 Synthesis methods of MOFs in different periods

Table 3 The brief information of microwave-assisted synthesis, sonochemical synthesis, electrochemical synthesis and mechanochemical synthesis, adapted from reference (Stock and Biswas 2011)

Synthesis methods	Brief information
Microwave-assisted synthesis	(i) The reaction temperature and pressure can be monitored during the reaction to achieve more precise control of reaction conditions; (ii) Crystallization process can be accelerated; (iii) Some nanoscale products can be obtained; (iv) The product purity can be further improved and (v) The selective synthesis of polymorphs can be achieved
Sonochemical synthesis	(i) It is a fast, energy-efficient, environmentally friendly, room temperature method, which is of special interest for their future application, since fast reactions could allow the scaleup of MOFs; (ii) nanocrystalline particles of MOFs can be obtained
Electrochemical synthesis	(i) To exclude the influence of anions, like nitrate, perchlorate, or chloride, during the syntheses, in which the metal ions are continuously introduced through anodic dissolution to the reaction medium, rather than using metal salts. (ii) It was possible to run a continuous process and to obtain a higher solid content
Mechanochemical synthesis	(i) It is environment friendly as the reactions can be carried out at room temperature under solvent (especially organic solvents) free conditions; (ii) Quantitative yields of products in small particles can be obtained in short reaction times, normally in the range of 10–60 min; (iii) Some metal salts can be replaced by metal oxides as a starting material, resulting in the formation of water as the only side product

sonochemical synthesis (8 articles), electrochemical synthesis (8 articles) and mechanochemical synthesis (24 articles) arose much interest from the researchers in MOFs field, as illustrated in Fig. 2.

Properties and potential applications of MOFs

MOFs have exceptionally porosity, with uniform but tunable pore sizes and incredibly high internal surface areas, extending beyond a Langmuir surface area of 10,000 $m^2\ g^{-1}$ (Furukawa et al. 2010; Farha et al. 2010, 2012), which play a crucial role in such applications as gas storage (Li et al. 1999; Yaghi et al. 2003), adsorption (Yaghi et al. 1995; Park et al. 2006), separation (Li et al. 1999, 2009, 2013; Wang et al. 2014a; Zhao et al. 2014), and drug storage and delivery (Horcajada et al. 2006; Rieter et al. 2007). Additionally, versatile MOFs' functionalities beyond their ultrahigh porosity can be contributed to metal sites [e.g. magnetism (Liu et al. 2001; Uemura et al. 2005), catalysis (Lee et al. 2009; Wu et al. 2005)]; organic linkers [e.g. luminescence (Allendorf et al. 2009; Chen et al. 2007); or a combination of both (Zhu and Xu 2014). To understand the hot topics on MOFs' properties and corresponding potential applications, the words clusters analyses were carried out on some selected topics like luminescence, magnetism, gas storage, adsorption, separation, catalysis, and drug storage and delivery with corresponding supporting words as listed in Table 4. The article number growth trends of these seven different properties or applications of MOFs were illustrated in Fig. 3, in which all researches on the selected seven types of properties or applications possessed rapid increase. Studies on "adsorption" took the lead with total article number of 2776 in recent years, followed by catalysis (1178 articles), luminescence (1077), separation (953), magnetic property (768), gas storage (762), and drug storage and delivery (99).

Table 4 The supporting words of selected MOFs' properties and their potential applications

Properties and potential applications	Supporting words
Luminescence	Luminescence, luminescent, phosphorescence, phosphorescent, photoluminescent, photoluminescence
Magnetic property	Magnetic, magnetism, magnetoelectric, magnetoelectricity, magnetoelectrics, antiferromagnetic, paramagnetic, ferrimagnetism, antiferromagnetism, ferromagnetic, paramagnet, superparamagnetic
Gas storage	Store, storages
Adsorption	Adsorb, chemisorption, adsorptivity, adsorptivities, adsorptive, adsorption, adsorbing, adsorber, adsorbents, adsorbent, adsorbed, adsorbates, adsorbate, sorptivity, sorptive, physisorption, physisorbed, Coadsorbed, Coadsorption, co-adsorption
Separation	Separations, separating, separate, separable
Catalysis	Catalysis, catalyst, electrocatalytically, electro-catalytic, electrocatalytic, electrocatalysts, electrocatalyst, electrocatalysis, photo-catalysts, photo-catalytic, photocatalyzed, catalyzing, catalyzes, catalyzed, catalytically, catalytic, catalysts, catalyst-bridged, catalyst, catalysis, catalysing, catalysed, biocatalyst, biocatalysis, photocatalytic, photocatalyst
Drug storage and delivery	Drug-delivery, drug-loaded, drug-release, drug delivery, drug encapsulation, drug loading, drugs controlled delivery, drug sustained release

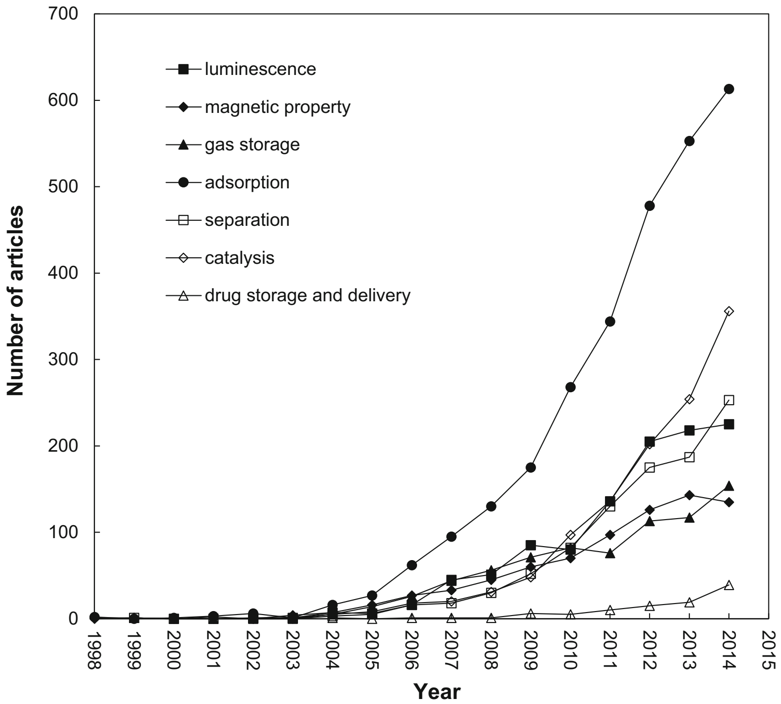

Fig. 3 Properties and applications of MOFs in different periods

Considering the MOFs' potential applications in environmental remediation field, some word clusters related to "adsorption in environmental remediation field" and "photocatalysis" are proposed as listed in Table 5. As shown in Fig. 4, the article number related to "adsorption in environmental remediation field" showed a sharp rise with the highest growth rate from 1 in 1995 to 482 in 2014. Recently, MOFs have been investigated extensively for the adsorptive removal of various hazardous pollutants (including toxic gases, organic pollutants and heavy metals) from the environment due to their ultra-huge porosity, pore geometry, and surface charge (Khan et al. 2013; Han et al. 2015). Also, the effects of central metal ions, open metal sites, linkers, porosity, functionalization/modification of MOFs in adsorption, along

Table 5 The supporting words of "adsorption in Environmental Remediation field" and "photocatalysis"

Potential applications	Supporting words
Adsorption in Environmental Remediation	Dye sorptions, dye sorption, dye removal, sulfur removal, sulfur removal, harmful gas removal, heavy metal removal, mercury removal, metal adsorption, NO_2 adsorption, ammonia adsorption, arsenic adsorbents, methylene-blue adsorption, SO_2 adsorption
Photocatalysis	Photocatalysis, photocatalytical, photo-catalytic, photocatalytic, photocatalysts, photocatalyst, photo-catalysts, photo-catalytic, photodegradation, photodecomposition

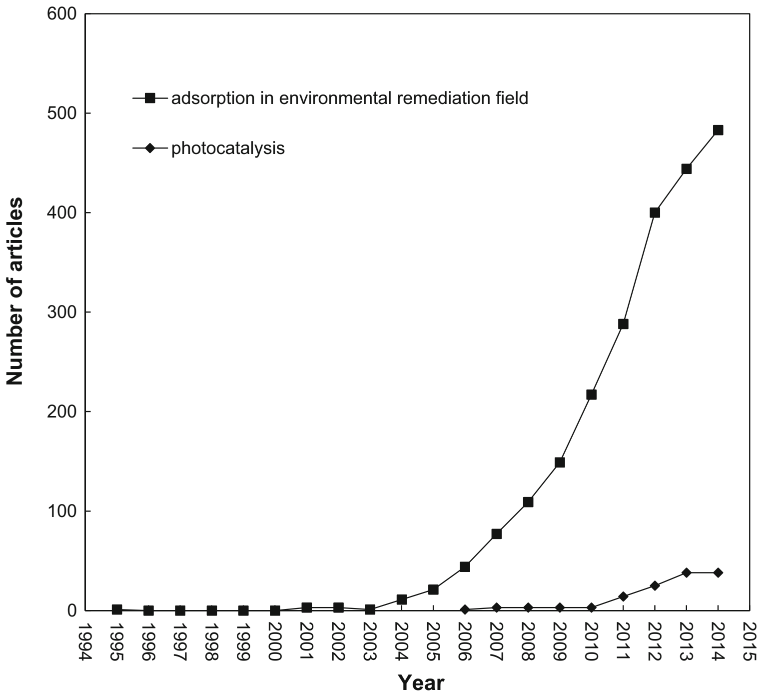

Fig. 4 The research trend of "adsorption in Environmental Remediation field" and "photocatalysis"

with the possible interactions between adsorbate and adsorbent were extensively discussed (Khan et al. 2013; Hasan and Jhung 2015; Zhang et al. 2015). The article number related to photocatalysis increased from one article in 2006 to 38 articles in 2014 with total article number of 128 from 2006 to 2014. Recent researches indeed not only demonstrated porous MOF materials to be a new class of photocatalyst, usable in photocatalytic degradation of organic pollutants under UV/visible/UV–visible irradiation (Mahata et al. 2006; Wang et al. 2014b), but also triggered an intense interest in exploring the application of MOFs as photocatalysts to achieve H_2 product via water split (Corma et al. 2010; Farrusseng et al. 2009; Wang et al. 2012), CO_2 reduction (Fu et al. 2012a; Zhang and Lin 2014; Wang et al. 2015), and Cr(VI) reduction (Shen et al. 2013a; Liang et al. 2015b; Wang et al. 2016).

The research trend of several representative MOFs

Some representative MOFs like ZIF-8, MIL-53, MIL-101, MIL-125, HKUST-1, MOF-5, and UiO-66 exhibited excellent properties and various potential applications, as listed in Table 6. In order to understand the trend of these representative MOFs, the word cluster analyses were performed with the supporting words as shown in Table 6. As demonstrated in Fig. 5, all the selected representative MOFs exhibited rapid increase in recent years, with total article number of 451 for KHUST-1, 353 for MOF-5, 280 for MIL-101, 257 for MIL-53, 204 for ZIF-8, 116 for UiO-66, and 25 for MIL-125 as a result of their outstanding properties and versatile applications.

Table 6 The basic information of some representative MOFs and corresponding supporting words for word cluster analysis

Representative MOFs (supporting words)	Characteristics, properties and applications
ZIF-8 (ZIF-8 and ZIF8)	ZIF-8 [Zn(2-methylimidazole)2·2H_2O], (Park et al. 2006) firstly synthesized by Chen and coworkers in 2006, is constructed from imidazolate organic ligands and Zn^{2+} center ions, which exhibits higher thermal and chemical stability than other MOFs (Cacho-Bailo et al. 2014). It is its high BET specific surface area (SSA) ($\approx$2000 m^2/g) (Gadipelli et al. 2014) and permanent porosity from its uniformly sized pore cavities (of $\approx$1.16 nm and pore volume of $\approx$0.60 cm^3/g) (Gadipelli et al. 2014) Applications: gas storage (Wu et al. 2007; Kumari et al. 2013; Zhang et al. 2011; Chen et al. 2011; Zhang et al. 2013; Amali et al. 2014), separation by membrane sieving (Kwon and Jeong 2013; Díaz et al. 2011; McCarthy et al. 2010; Venna and Carreon 2009; Liu et al. 2014), templating (Zhang et al. 2014b; He et al. 2014), catalysis (Tran et al. 2011; Li et al. 2012), and shape-selective distillation (First et al. 2013; Caro 2011; Kong et al. 2014), sensing (Pan et al. 2011; Lu and Hupp 2010; Liu et al. 2011; Lu and Hupp 2010), photocatalysis (Jing et al. 2014), and so on (Chuang and Ho 2014; Vasconcelos et al. 2012)
MIL-53 (MIL-53, MIL53)	MIL-53 (MIL = Material from Institut Lavoisier), nanoporous metal-benzenedicarboxylate M(OH)(O_2C–C_6H_4–CO_2) containing Cr^{3+}, (Millange et al. 2002) Al^{3+} or Fe^{3+}, labeled as MIL-53(Cr) (BET surface area $\approx$ 1100 m^2/g, Langmuir surface area was estimated to be over 1500 m^2/g)(Férey et al. 2003), MIL-53(Al) (with pores of 8.5 Å, BET surface area $\approx$ 1100 m^2/g, Langmuir surface area of 1590 m^2/g) and MIL-53(Fe) (BET surface area $\approx$ 1100 m^2/g), respectively Applications: adsorption (Hamon et al. 2009; Llewellyn et al. 2009; De Combarieu et al. 2009; Millange et al. 2010; Chen et al. 2012a; Bourrelly et al. 2010; Trung et al. 2008; Patil et al. 2011), catalysis (Ai et al. 2013), separation (Couck et al. 2009; Finsy et al. 2009), sensor (Jia et al. 2013) and photocatalysis (Du et al. 2011; Ai et al. 2014; Liang et al. 2015a)
MIL-101(MIL-101, MIL101)	MIL-101 is a chromium terephthalate-based mesoscopic metal–organic framework with BET surface area of 4230 m^2/g and Langmuir surface area 5900 m^2/g (Llewellyn et al. 2008) Applications: gas adsorption (Hamon et al. 2009; Llewellyn et al. 2008; Latroche et al. 2006; Jhung et al. 2007), liquid adsorption (Chen et al. 2012b; Huang et al. 2012; Haque et al. 2010), catalysis (Maksimchuk et al. 2008; Serra-Crespo et al. 2011), photocatalysis (Wen et al. 2014; Laurier et al. 2013)

Table 6 continued

Representative MOFs (supporting words)	Characteristics, properties and applications
MIL-125(MIL-125, MIL125)	MIL-125 is a TiO_2/1,4-benzenedicarboxylate (bdc) metal–organic framework, which is stable up to 360 °C under air atmosphere with BET surface area of 1550 m^2/g (Dan-Hardi et al. 2009) Applications: gas adsorption (Kim et al. 2013; Zlotea et al. 2011; Vermoortele et al. 2011; Moreira et al. 2012; Vaesen et al. 2013; Barea et al. 2014), liquid adsorption (Guo et al. 2015), catalysis (Martis et al. 2013) and photocatalysis (Fu et al. 2012a; Nasalevich et al. 2013, 2015)
HKUST-1(Cu-3(btc), Cu3btc2, Zn-3(btc)2)	HKUST-1, also known as copper benzene-1,3,5-tricarboxylate, with Langmuir surface area of 1958 m^2/g and BET surface area of 1154 m^2/g Applications: gas adsorption (carbon dioxide, nitrogen, oxygen, hydrogen gas, n-butane) (Bordiga et al. 2007; Liu et al. 2010; Moellmer et al. 2011; Klein et al. 2010; Lin et al. 2012), catalysis (Farrusseng et al. 2009; Sachse et al. 2012; Zhuang et al. 2011), separation (Münch and Mertens 2012; Peralta et al. 2012; Mao et al. 2013)
MOF-5 (MOF-5, MOF5, metal–organic framework-5, $Zn_4O_{13}C_{24}H_{12}$, $[Zn_4O(bdc)_3)$	MOF-5, is $Zn_4O(BDC)_3$ (BDC_{2-} = 1,4-benzenedicarboxylate) with Langmuir surface area of 4400 m^2/g (Phan et al. 2010; Kaye et al. 2007) and BET surface area of 3800 m^2/g (Kaye et al. 2007), and nitrogen adsorption isotherms measured at 77 K revealed an enhanced maximum N_2 uptake of 44.5 mmol/g and a BET surface area of 3800 m^2/g (Kaye et al. 2007) Applications: gas storage (Kaye et al. 2007; Saha et al. 2010; Mueller and Ceder 2005), adsorption (Zhao et al. 2009; Xie et al. 2015; Zhao et al. 2015), catalysis (Phan et al. 2010), photocatalysis (Alvaro et al. 2007; Das et al. 2011)
UiO-66 (UiO-66, UiO66)	UiO-66 is comprised of $Zr_6O_4(OH)_4$ octahedra that are 12-fold connected to adjacent octahedra through a 1,4-benzene-dicarboxylate (BDC) linker, which possessed with very high surface area (1147 m^2/g) and unprecedented stability (Cavka et al. 2008; Wu et al. 2013b; Wiersum et al. 2011; Valenzano et al. 2011) Applications: adsorption (Ragon et al. 2015; DeCoste et al. 2015; Kim et al. 2015; Žunkovič et al. 2015; Chen et al. 2015; Bárcia et al. 2011), gas storage (Chavan et al. 2012; Abid et al. 2012; Yang et al. 2012), separation, (Chang and Yan 2012; Fu et al. 2013b), catalysis (Kim et al. 2015; Vermoortele et al. 2013), and photocatalysis (Sun et al. 2013; Shen et al. 2013b, c; Gomes Silva et al. 2010; Long et al. 2012)

During the past two decades, many efforts were offered to preparing new MOF with novel structure and exploring their various properties and applications. MOFs still faced the some challenges like poor chemical stability, which inhibited the use of their full potential. MOF composites, which composed one MOF and one or more distinct constituent materials (including other MOFs), combined the advantages of both MOFs (like, high porosity with ordered crystalline pores) and various kinds of functional materials (like unique optical, electrical, magnetic and catalytic properties), to present new physical and

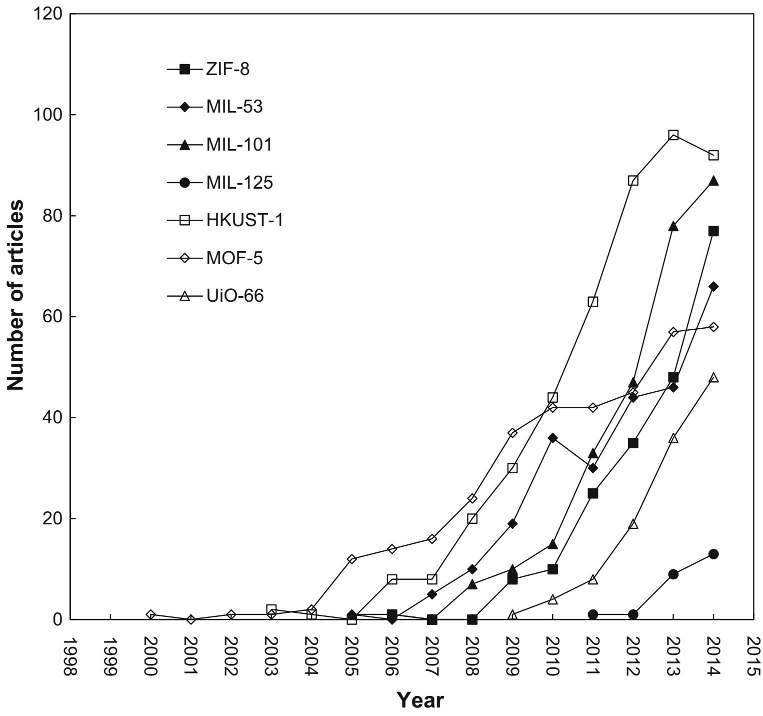

Fig. 5 The research trend of some representative MOFs

chemical properties and enhanced performance that are not attainable by the individual components. Consequently, the remarkable features of MOF composites resulting from the synergistic combination of both MOF and other active components made them suitable for a wide range of applications (Zhu and Xu 2014; Ahmed and Jhung 2014). Word cluster analyses based on MOF composite with supporting words as "composites, nanocomposites, nano-composite, nanocomposite, multi-composite" was conducted. 365 articles were published on MOF composites during 1999–2014, and the related research became a hot topic especially evidenced by the rapid increase of 11 articles in 2009 to 131 articles in 2014.

In addition, MOF film either supported on solid substrates or as free-standing membranes, provided possibilities not available for the typical MOF powders. Some main advantages of MOF thin films were discussed in related review type publications (Shekhah et al. 2011; Shah et al. 2012; Bétard and Fischer 2011; Zacher et al. 2009; Zhang et al. 2014a). Word cluster analyses based on MOF film with supporting words as "thin film, MOF-film, micro-film, thin-film, nanofilm, nanofilms, membrane, film-based, micromembranes, membranes, membrane-based, membrane-electrode" was also carried out to understand the research trend of MOF film. The results as illustrated in Fig. 6 revealed that the article number of MOF film exhibited enormous increase with total 409 articles distributed as 1 (2006), 4 (2007), 6 (2008), 19 (2009), 32 (2010), 58 (2011), 64 (2012), 89 (2013), and 136 (2014), which confirmed MOF film was a hot issue in MOF research.

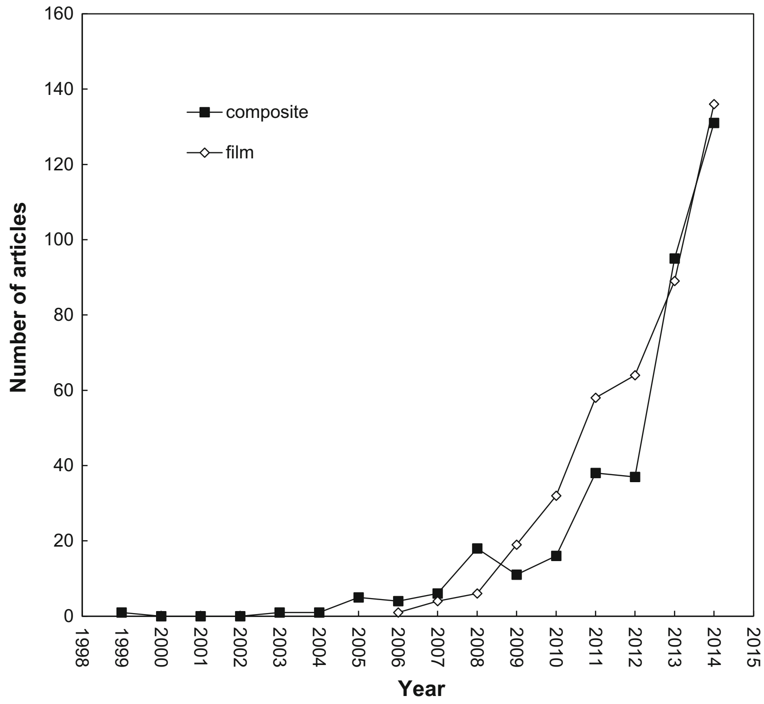

Fig. 6 The research trend of composite and film of MOFs

Author performance of highly cited articles

It is generally accepted that equal credit is not given to all authors. The first author who contributes most to the research work and writing of the article (Gaeta 1999), is regarded to be the most contribution, and should receive a greater proportion of the credit (Yank and Rennie 1999; Costas and Bordons 2011). While the corresponding author is responsible to supervise the planning and execution of the study, as well as preparation and subsequent publication of the paper (Burman 1982). *Y* index (*j*, *h*) was applied to compare authors' publication characteristics (Ho 2012, 2014). The *Y* index can provide information which cannot be obtained by other traditional indicators and identify the important characteristics related to both the number of first author and corresponding author (Ho 2012, 2014). The *Y* index can be defined as Eqs. (1) and (2):

$$j = \mathrm{FP} + \mathrm{RP} \tag{1}$$

$$h = \tan^{-1}\left(\frac{\mathrm{RP}}{\mathrm{FP}}\right) \tag{2}$$

where RP is the numbers of corresponding-authored articles and FP is the number of first-authored articles. In the index, j is the publication performance, which is a constant related to publication potential, and h refers to publication characteristics which describe the proportion of RP to FP. Different values of h indicate different proportions of corresponding-author articles to first-authored articles. h being >0.7854 implies that the author had more corresponding-authored articles; h being $= 0.7854$ indicates that the author had the same number of first-authored and corresponding-authored articles; and $0 < h < 0.7854$ implies that the author had more first-authored than corresponding-authored articles. When $h = 0$, j equals the number of first-authored articles, and $h = \pi/2$, j equals the number of corresponding-authored articles.

Y index has been applied to evaluate publication characteristics for highly cited articles (Ho 2014b; Chen and Ho 2015). In total, 523 articles with TC_{2014} (number of citations since its publication to the end of 2014) ≥100 were further analyzed for authors' publication characteristics by *Y* index. The top 16 authors with $j \geq 8$ are demonstrated in Fig. 7, in which *j*Cos*h* and *j*Sin*h* are chosen as the *x* and *y* coordinate axes. Each dot represents one value which could be one or more authors. In the metal–organic frameworks (MOFs) field, Yaghi, O.M. contributed the most highly cited articles with $j = 27$, followed by Chen, B.L. ($j = 24$), Kitagawa, S. ($j = 21$), Lieber, C.M ($j = 17$), Lin, W.B. ($j = 16$), Long, J.R. ($j = 13$), and Zhou, H.C. ($j = 13$). The publication characteristics constant, *h*, could provide the information about the different proportion of corresponding author articles to first author articles, which is very helpful to distinguish the different performance of the authors, especially when *j* value of authors is the same. For example, all the *j* values of Snurr, Eddaoudi, and Farria were the same of 10, but the *h* values of the authors mentioned above were π/2, 1.166, and 0.7854, respectively, implying these three authors possessed the identical publication performance with different publication characteristics. Snurr dedicated 10 highly cited articles only as corresponding author with *h* being π/2, while Farha ($j = 10$) published the same number of first author articles and corresponding author articles with *h* value of 0.7845. Among these 16 authors contributing the most

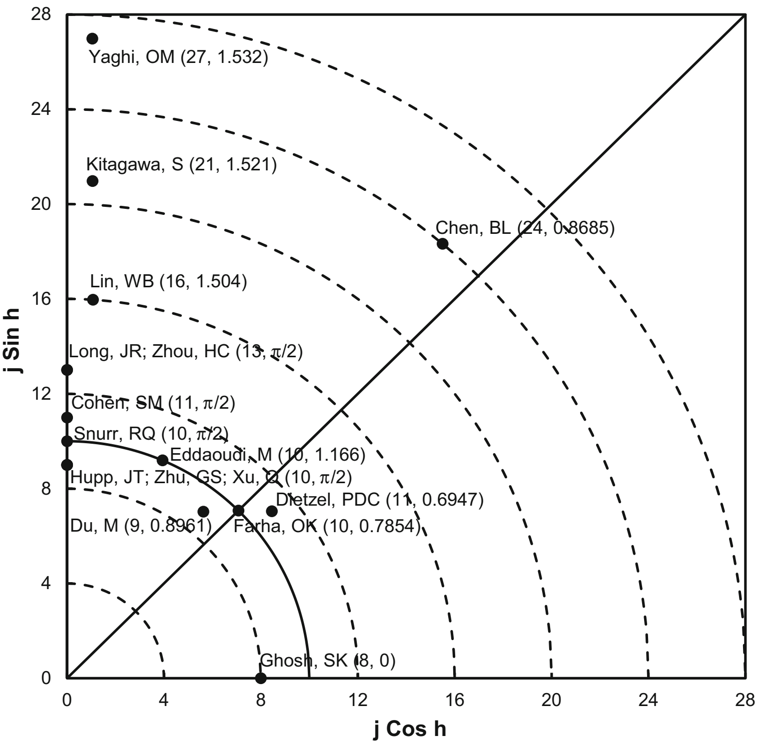

Fig. 7 Top 16 authors with *Y*-index ($j \geq 8$)

highly cited articles, Ghosh, S.K. ($j = 11$) contributed only first author articles with h being zero, Dietzel ($j = 11$) published more first author articles with the lowest h (0.6947). It was worthy to noting that Long ($j = 13$), Zhou ($j = 13$), Cohen ($j = 11$), Snurr ($j = 10$), Hupp ($j = 10$), Zhu ($j = 10$), and Xu ($j = 10$) published articles only as a role of corresponding author with the same h values of $\pi/2$. Thirteen authors in Fig. 7 possessed higher h values (>0.7845), implying that these 13 authors published more articles as corresponding author, which also demonstrated the fact of the emerging MOFs research originated by Yaghi and Li (1995).

Performance of classic articles

Classic articles with highest TC_{2014}

The trend of a publication's citations with time has long been a hot topic (Avramescu 1979). Considering that the information of total citations from Web of Science was updated weekly and applied widely in most studies, the total number of times an article that was cited from its publication to the end of 2014 (TC_{2014}) were utilized to investigate the life cycles of classic articles in metal–organic frameworks field. A total of eight so called classic articles published between 1995 and 2014 in four journals in metal–organic frameworks field, which possessed TC_{2014} being more than 1000 times, as illustrated in Fig. 8 and Table 7. Among them, two classic articles were published in *Science* and *Nature*

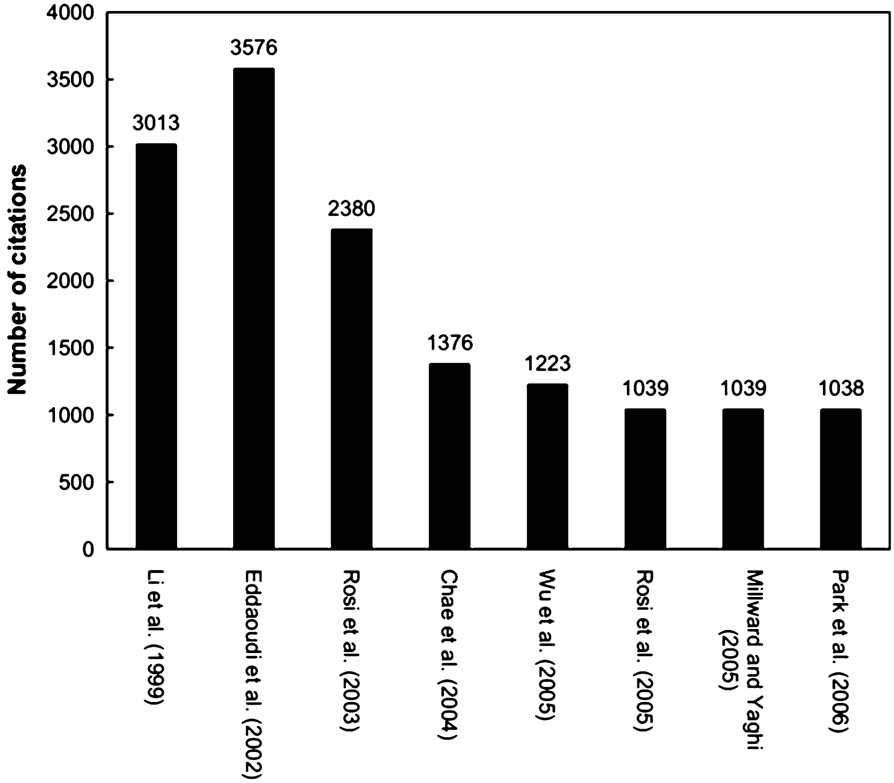

Fig. 8 TC_{2014} and authors of the classic articles according to the order of their publication years

Table 7 Eight most frequently cited articles with TC_{2014} > 1000 in the field of metal–organic frameworks

TC_{2014} (rank)	C_{2014}	C_0	References	Institution
3576 (1)	402	29	Eddaoudi, M.,[1] Kim, J.,[1] Rosi, N.,[1] Vodak,D.,[1] Wachter, J.,[1] O'Keeffe, M. [2] and Yaghi, O.M*[1] (2002), Systematic design of pore size and functionality in isoreticular MOFs and their application in methane storage. *Science*, **295** (5554), 469–472	[1]University of Michigan, USA [2]Arizona State University, USA
3013 (2)	356	1	Li, H.,[1] Eddaoudi, M.,[2] O'Keeffe, M.[1] and Yaghi, O.M*[2] (1999), Design and synthesis of an exceptionally stable and highly porous metal–organic framework. *Nature*, **402** (6759), 276–279	[1] Arizona State University, USA [2] University of Michigan, USA
2380 (3)	235	10	Rosi, N.L.,[1] Eckert, J.,[2,3] Eddaoudi, M.,[4] Vodak, D.T.,[1] Kim, J.,[1] OKeeffe, M.[5] and Yaghi, O.M[1*] (2003), Hydrogen storage in microporous metal–organic frameworks. *Science*, **300** (5622), 1127–1129	[1]University of Michigan, USA [2]University of California, USA [3]Los Alamos National Laboratory, USA [4]University of South Florida, USA [5]Arizona State University, USA
1376 (4)	163	20	Chae, H.K.,[1] Siberio-Perez, D.Y.,[1] Kim, J.,[1] Go, Y.,[1] Eddaoudi, M.,[1] Matzger, A.J.,[1] O'Keeffe, M.[2] and Yaghi, O.M[1]* (2004), A route to high surface area, porosity and inclusion of large molecules in crystals. *Nature*, **427** (6974), 523–527	[1]University of Michigan, USA [2]Arizona State University, USA
1223 (5)	135	6	Wu, C.D., Hu, A., Zhang, L. and Lin, W.B* (2005), Homochiral porous metal–organic framework for highly enantioselective heterogeneous asymmetric catalysis. *Journal of the American Chemical Society*, **127** (25), 8940–8941	University of North Carolina, USA
1039 (6)	145	17	Rosi, N.L.,[1] Kim, J.,[1] Eddaoudi, M.,[1] Chen, B.L.,[1] O'Keeffe, M.[2] and Yaghi, O.M[1]* (2005), Rod packings and metal–organic frameworks constructed from rod-shaped secondary building units. *Journal of the American Chemical Society*, **127** (5), 1504–1518	[1]University of Michigan, USA [2]Arizona State University, USA
1039 (7)	167	0	Millward, A.R. and Yaghi, O.M* (2005), Metal–organic frameworks with exceptionally high capacity for storage of carbon dioxide at room temperature. *Journal of the American Chemical Society*, **127** (51), 17998–17999	University of Michigan, USA
1038 (8)	288	3	Park, K.S.,[1] Ni, Z.,[1] Cote, A.P.,[1] Choi, J.Y.,[2] Huang, R.D.,[3] Uribe-Romo, F.J.[1], Chae, H.K.,[2] O'Keeffe, M.[4] and Yaghi, O.M[1,4*] (2006), Exceptional chemical and thermal stability of zeolitic imidazolate frameworks. *Proceedings of the National Academy of Sciences of the United States of America*, **103** (27), 10186–10191	[1]University of California Los Angeles, USA [2]Seoul National University, Korea [3]Beijing Institute of Technology, China [4]Arizona State University, USA

TC_{2014} = number of citation till 2014; C_{2014} = number of citation at the end of 2014; C_0 = number of citation in its publication year. * = corresponding author with impact factor in 2014 JCR (IF_{2014}) being 33.611 and 41.456, respectively, three classic ones were published in *Journal of the American Chemical Society* with $IF_{2014} = 12.113$, and one classic article was published in *Proceedings of the National Academy of Sciences of the United States of America* with $IF_{2014} = 9.674$. Seven of eight classic articles were published with Omar M. Yaghi as corresponding author (rank 1st–4th, 6th–8th in Table 7), in which Adam J. Matzger and Michael O'Keeffe acted reprint author of the classic one rank 4th and 7th in Table 7. The remaining one was published with Wen B. Lin (rank 5th in Table 7) from University of North Carolina as corresponding author and Chuan D. Wu as first author. Due to job-shifting, five and one out of classic articles contributed by Omar M. Yaghi were published with University of Michigan (rank 1st–4th and 6th–7th in Table 7) and University of California (rank 8th in Table 7) as first institution, respectively. M. Eddaoudi contributed the articles as first author (rank 1st in Table 7), second author (rank 2nd in Table 7), third author (rank 3rd and 6th in Table 7) and fifth author (rank 4th in Table 7). Nathaniel L. Rosi presented three classic articles with first author (rank 3rd and 6th in Table 7) and third author (rank 1st in Table 7). The first authors of the remaining classic articles were H. Li (rank 2rd in Table 7), Kee H. Chae (rank 4th in Table 7), Andrew R. Millward (rank 7th in Table 7) and Kyo S. Park (rank 8th in Table 7). Only two classic articles were institution independent ones, which were from University of North Carolina, USA (rank 5th in Table 7) and University of Michigan (rank 7th in Table 7). Three classic articles (rank 1st, 2nd and 6th In Table 7) were contributed by the cooperation of Omar M. Yaghi from University of Michigan (USA) and M. O'Keeffe from Arizona State University (USA). The article titled "Hydrogen storage in microporous metal–organic frameworks" was inter-institutionally collaborative article of University of Michigan (USA), University of California (USA), Los Alamos National Laboratory (USA), University of South Florida (USA), Arizona State University (USA). And the other inter-institution collaborative article titled "Exceptional chemical and thermal stability of zeolitic imidazolate frameworks" (rank 8th in Table 7) was offered by University of California (USA), Seoul National University (Korea), Beijing Institute of Technology (China) and Arizona State University (USA). In all, all eight classic articles with $TC_{2014} > 1000$ were from USA, only one article (rank 8th in Table 7) was dedicated jointly by USA, Korea and China institutions.

The indicator of total citations is often used to judge the performance of one publication (Rehn et al. 2007), but this indicator is too rough to get insight into the impact of the articles. Citation life cycles of classic articles were introduced to look further and deeper into their achievement (Aversa 1985; Levitt and Thelwall 2008). In recent years, the life cycles of the classic articles had been investigated in the subject category of water resource (Chuang et al. 2011), information science and library science (Ivanović and Ho 2016), biomass research (Chen and Ho 2015), thermodynamic research (Fu and Ho 2015), health care sciences and services field (Hsu and Ho 2014), pain research (Chuang and Ho 2014), social work (Zhou and Kitagawa 2014), chemical engineering (Ho 2012; Chuang et al. 2013), environmental sciences (Khan and Ho 2012), and adsorption research (Fu et al. 2012b). Generally, being compared to the articles published later, those published earlier attract more citations irrespective of their actual impact (Lefaivre et al. 2011). The citation life of the classic articles with $TC_{2014} > 1000$ was illustrated in Fig. 9. All the eight classic articles not only had the higher citation in recent year (C_{2014} being 402, 356, 235, 163, 135, 145, 167 and 288 for the articles from 1st to 8th listed in Table 7), but also had an extremely rapid increasing trend of citation.

The article contributed by Eddaoudi et al. (2002) possessed both highest C_{2014} (402) and C_0 (29). This article presented a strategy to design and construct a series of MOFs with

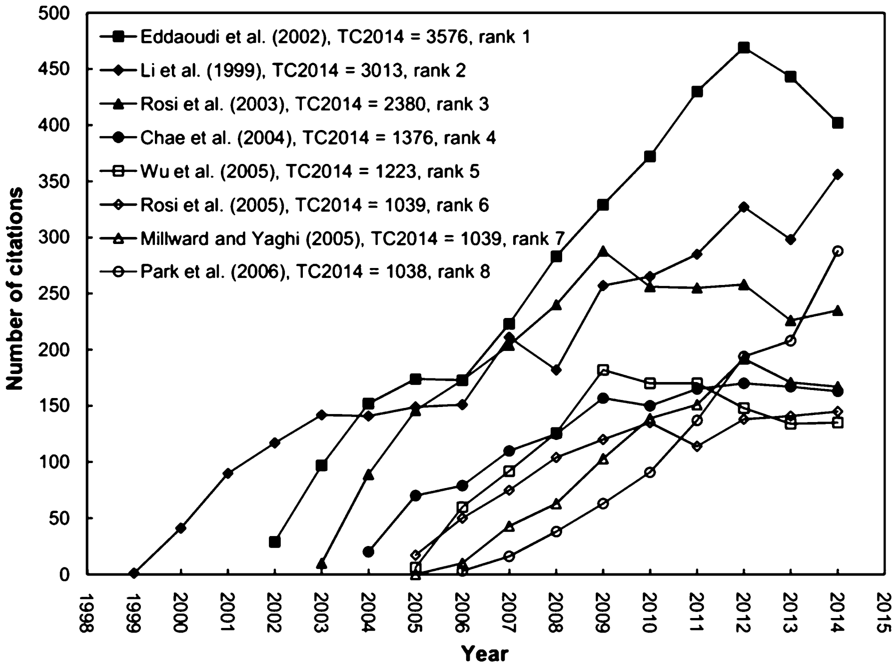

Fig. 9 Citation life cycles of the eight classic articles (TC_{2014} > 1000) in metal–organic frameworks field

structures based on the skeleton of MOF-5 ($[Zn_4O(1,4\text{-bdc})_3](DMF)_8(C_6H_5Cl)$, 1,4-bdc = 1,4-benzenedicarboxylate; DMF = dimethylformamide; C_6H_5Cl = chlorobenzene), in which the pore functionality and size can be expanded via introduction of the long molecular struts biphenyl, tetrahydropyrene, pyrene and terphenyl without changing the original cubic topology. Among this series, IRMOF-6 ($Zn_4O(R_6\text{-bdc})_3(CHCl_3)_7$) exhibited a high capacity for methane storage (240 cubic centimeters at standard temperature and pressure per gram at 36 atmospheres and ambient temperature). While Li et al. (1999) reported the synthesis of MOF-5 that remains crystalline, and is stable when fully desolvated and when heated up to 300 °C. This article provides a simple and potentially universal design strategy to produce a three-dimensional framework with higher apparent surface area and pore volume than most porous crystalline zeolites. The strategy is currently pursued in the synthesis of new phase/composites to perform gas-storage application, which made this article to be a classic article with TC_{2014} being 3013 (rank 2nd in the eight classic articles) and C_{2014} being 356.

The 3rd classic article with $TC_{2014} = 2380$ reported the hydrogen storage in microporous MOFs like MOF-5, IRMOF-6 and IRMOF-8, in which the uptake amount at room temperature and 10 bar is equivalent to 1.9, 4.2, 9.1 H_2 per formula unit, respectively. The capacity of these structures for hydrogen uptake at room temperature is comparable to the highest capacity achieved for carbon nanotubes at cryogenic temperature.

Just like the classic article ranked 1st based on TC_{2014}, the 4th article ($TC_{2014} = 1376$) also provided a route to design and synthesize chemical structures with exceptionally high surface areas, in which MOF-177, $Zn_4O(1,3,5\text{-benzenetribenzoate})_2$, with surface area estimated at 4500 m^2/g (Chae et al. 2004) was introduced. MOF-177 can uptake Astrazon

Orange R with amount over 40 wt%, corresponding to 16 dye molecules in each unit cell. Identically, the contribution with $TC_{2014} = 1039$ (Ranked 6th among the eight classic articles) outlined the principles to construct the structures from rod-like building blocks (Rosi et al. 2005). This approach was successful which was witnessed by the syntheses of fourteen new MOF structures with rigid and porous architectures based on four different rod packing nets.

Considering that MOFs offering some advantages for CO_2 storage like ordered structures, high thermal stability, adjustable chemical functionality and extra-high porosity, in the classic article with $TC_{2014} = 1309$, Millward and Yaghi (2005) selected nine MOFs with different framework characteristics to conduct CO_2 storage test. The results revealed that 1 g MOF-177 can store 33.5 mmol CO_2 at room temperature, which is far greater than that of any other porous materials reported at that time.

The 8th classic article with $TC_{2014} = 1038$ described the syntheses of twelve zeolitic imidazolate frameworks (ZIF) with exceptional chemical and thermal stability, which were constructed from Zn(II) (ZIF-1 to -4, -6 to -8, and -10 to -11) or Co(II) (ZIF-9 and -12) or Zn(II)/In(III) (ZIF-5) with imidazolate-type linkers. Among these twelve ZIFs, ZIF-8 and ZIF-11 possess their permanent porosity (Langmuir surface area = 1810 m^2/g), high thermal stability (up to 550 °C), and remarkable chemical resistance to boiling alkaline water and organic solvents (Park et al. 2006).

Different from the seven classic articles dealing with the synthesis strategy or gas storage/adsorption, the 5th one (Wu et al. 2005) with $TC_{2014} = 1223$ dealt with an strategy for creating catalytically active chiral porous MOFs, in which the chiral bridging ligands containing orthogonal functional groups were used. The primary functional groups in the ligand were linked by metal ions into extended networks, and the orthogonal secondary chiral groups can be utilized to form asymmetric catalytic sites. This strategy realized the synthesis of heterogeneous asymmetric catalysts with higher catalyst loading and more accessible catalytic centers, leading to achieving new chiral porous MOFs for practically useful heterogeneous asymmetric catalysis.

Classic articles with highest C_{2014}

Article life shows the characteristics of an article's impact after being published. Citations in recent year were investigated to gain more information about the top cited articles or classic articles (Zhou and Kitagawa 2014; Fu and Ho 2015; Long et al. 2014). TC_{2014}, as an accumulative citation indicator, may reach large values as long as the time span is long enough. But, an article impact might not be always high (Fu et al. 2012b). Also, some recently published articles within the past few years which had great potential citation perspective can't have a TC_{2014} in short time. Considering these situations, it would be interesting to investigate the publications with high citation number in 2014 (C_{2014}). The top eight highly cited articles (classic ones) with $C_{2014} > 165$ in metal–organic frameworks were examined, as illustrated in Table 8 and Fig. 3. All the eight articles showed rapid increase trends after their publications (Fig. 10). Among these eight classic articles with highest C_{2014}, five ones also possessed highest TC_{2014}, as listed in Tables 7 and 8.

The rank 4th highest citation article with C_{2014} being 237 and C_{2014} being 899 was contributed by Yaghi group, with paper title of "Ultrahigh porosity in metal–organic frameworks" published in *Nature materials* ($IF_{2014} = 36.503$). This classic article presented four different metal–organic frameworks like MOF-180, -200, -205 and -210, in which $Zn_4O(CO_2)_6$ units were linked with different carboxylate ligands (Furukawa et al. 2010). All these four MOFs exhibited exceptional porosities and gas (H_2, CH_4 and CO_2)

Table 8 Eight most frequently cited articles with $C_{2014} > 165$ in the field of metal–organic frameworks

C_{2014} (rank)	TC_{2014}	C_0	References	Institution
402 (1)	3576	29	Eddaoudi, M.,[1] Kim, J., [1] Rosi, N., [1] Vodak, D., [1] Wachter, J., [1] O'Keeffe, M. [2] and Yaghi, O.M*[1] (2002), Systematic design of pore size and functionality in isoreticular MOFs and their application in methane storage. *Science*, **295** (5554), 469–472	[1]University of Michigan, USA [2]Arizona State University, USA
356 (2)	3013	1	Li, H.,[1] Eddaoudi, M.,[2] O'Keeffe, M.[1] and Yaghi, O.M*[2] (1999), Design and synthesis of an exceptionally stable and highly porous metal–organic framework. *Nature*, **402** (6759), 276–279	[1] Arizona State University, USA [2] University of Michigan, USA
288 (3)	1038	3	Park, K.S.,[1] Ni, Z.,[1] Cote, A.P.,[1] Choi, J.Y.,[2] Huang, R.D.,[3] Uribe-Romo, F.J.[1], Chae, H.K.,[2] O'Keeffe, M.[4] and Yaghi, O.M[1,4*] (2006), Exceptional chemical and thermal stability of zeolitic imidazolate frameworks. *Proceedings of the National Academy of Sciences of the United States of America*, **103** (27), 10186–10191	[1]University of California Los Angeles, USA [2]Seoul National University, Korea [3]Beijing Institute of Technology, China [4]Arizona State University, USA
237 (4)	899	14	Furukawa, H.,[1] Ko, N.,[2] Go, Y.B.,[1] Aratani, N.,[1] Choi, S.B.,[2] Choi, E.,[2] Yazaydin, A.O.,[3] Snurr, R.Q.,[3] O'Keeffe, M.,[1] Kim, J.[2*] and Yaghi, O.M.[1*] (2010), Ultrahigh porosity in metal–organic frameworks. *Science*, **329** (5990), 424–428	[1]University of California Los Angeles, USA [2]Seoul National University, Korea [3]Northwest University, USA
235 (5)	2380	10	Rosi, N.L.,[1] Eckert, J.,[2,3] Eddaoudi, M.,[4] Vodak, D.T.,[1] Kim, J.,[1] OKeeffe, M.[5] and Yaghi, O.M[1*] (2003), Hydrogen storage in microporous metal–organic frameworks. *Science*, **300** (5622), 1127–1129	[1]University of Michigan, USA [2]University of California, USA [3]Los Alamos National Laboratory, USA [4]University of South Florida, USA [5]Arizona State University, USA
191 (6)	485	0	Cavka, J. H.,[1] Jakobsen, S.,[1] Olsbye, U.,[1] Guillou, N.,[2] Lamberti, C.,[3] Bordiga, S.,[3] and Lillerud, K. P.[1]* (2008), A new zirconium inorganic building brick forming metal organic frameworks with exceptional stability. *Journal of the American Chemical Society*, **130** (42), 13850–13851	[1]University of Oslo, Norway [2]Université de Versailles Saint Quentin en Yvelines, France [3]University of Torino, Italy

Table 8 continued

C_{2014} (rank)	TC_{2014}	C_0	References	Institution
176 (7)	609	30	Horcajada, P.,[1] Chalati, T., [2] Serre, C., [1] Gillet, B., [3] Sebrie, C., [3] Baati, T., [1] Eubank, J. F., [1] Heurtaux, D., [1] Clayette, P., [4] Kreuz, C. [4], Chang, J. S., [5] Hwang, Y. K., [5] Marsaud, V., [2] Bories, P.-N., [6] Cynober, L., [6] Gil, S., [3] Férey, G., [1] Couvreur, P., [2] Gref, R. [2*] (2010), Porous metal–organic-framework nanoscale carriers as a potential platform for drug delivery and imaging. *Nature Materials,* 9(2), 172–178	[1]Université de Versailles, France [2]Université Paris-Sud, Orsay, France [3]Université Paris-Sud, Châtenay-Malabry France [4]Laboratoire de Neurovirologie, France [5]Korea Research Institute of Chemical Technology, Korea [6]Laboratoire de Biochimie—Hôpital Hôtel-Dieu-AP-HP, France
167 (8)	1039	0	Millward, A.R. and Yaghi, O.M* (2005), Metal–organic frameworks with exceptionally high capacity for storage of carbon dioxide at room temperature. *Journal of the American Chemical Society*, **127** (51), 17998–17999	University of Michigan, USA

TC_{2014} = number of citation till 2014; C_{2014} = number of citation at the end of 2014; C_0 = number of citation in its publication year. * = corresponding author

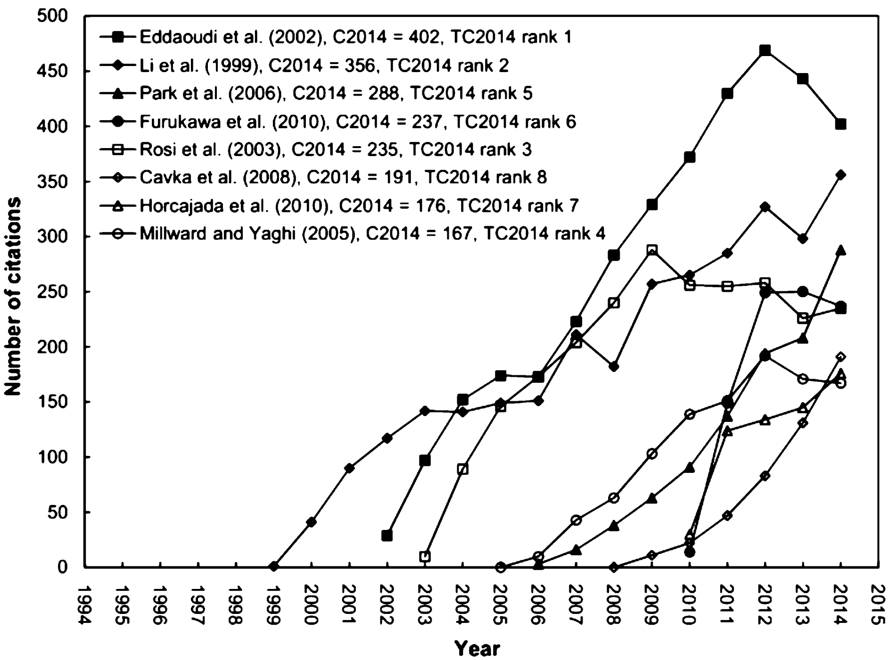

Fig. 10 Citation life cycles of the eight most frequently cited articles in 2014 ($C_{2014} > 165$) in metal–organic frameworks field

uptake capacities. Especially, MOF-210 has BET and Langmuir surface areas of 6240 and 10,400 m^2/g, respectively, achieving total carbon storage capacity of 2870 m^2/g. The volume-specific internal surface area of MOF-2010 is 2060 m^2/cm^3, which is near the ultimate adsorption limit for solid materials. Since this article was published, it got more and more attentions, which was cited 14 at its publication year (2010), then 149 in 2011, 249 in 2012, 250 in 2013 and 237 in 2014.

The rank 6th highest citation article with $C_{2014} = 191$ and $C_{2014} = 485$ was jointly presented by the researchers from university Oslo, Université de Versailles Saint Quentin en Yvelines and University of Torino. In this classic article, the researchers introduced zirconium-MOFs, naming UiO-66 and UiO-67 with exceptional stability, which is stable up to 540 °C. In fact, UiO-66 and UiO-67 is built up from $Zr_6O_4(OH)_4(CO_2)_{12}$ linked by bdc^{2-} (1,4-benzene-dicarboxylate) and $bpdc^{2-}$ (4,4′-biphenyl-dicarboxylate) linkers, respectively. This article proposed a strategy to synthesize MOFs with high surface area and unprecedented stability, overcoming one of the major disadvantages of MOFs, their weak stability. The impact of this article increased enormously at 2013 and 2014, with citation number of 131 and 191, respectively, maybe due to that Zr-MOFs and NH_2–Zr-MOFs were introduced to be photocatalysts to conduct gas adsorption (Wu et al. 2013a), photocatalytical degradation of organic pollutants (Wang et al. 2014b; Shen et al. 2013c; Nasalevich et al. 2014), reduction of CO_2 (Sun et al. 2013) and Cr(VI) (Shen et al. 2013a).

One important challenge in health field is the efficient drug delivery in body via non-toxic nanocarriers. Most of the exiting carrier can't overcome the disadvantages of poor drug loading and/or rapid release. Nineteen authors from seven institutions of France jointly published an article "Porous metal–organic-framework nanoscale carriers as a potential platform for drug delivery and imaging", whose C_0, C_{2014} and TC_{2014} were 30, 176 and 609, respectively. With this classic article ranked 7th based on its C_{2014}, some non-toxic porous iron(III)-based MOFs, like MIL-53, MIL-88A, MIL-88Bt, MIL-89, MIL-100 and NH_2-MIL-101 were prepared, and used to carry out efficient controlled delivery of antitumoural and retroviral drugs against cancer and AIDS, like busulfan, azidothymidine triphosphate, doxorubicin or cidofovir (Horcajada et al. 2010). Considering that these MOFs materials' high loading and their association to therapeutics and diagnostics, this work might widen the way for theranostics or personalized patient treatments, which made it arose wide attentions with citation number of 30 (C_0), 124, 134, 145, 176 (C_{2014}) in 2010, 2011, 2012, 2013 and 2014. More and more works on drug delivery in MOFs were conducted in recent years (Wang et al. 2013; Della Rocca et al. 2011; Zhuang et al. 2014).

Conclusion

An overview of the research in metal–organic frameworks (MOFs) was presented with the information related to keywords, word cluster and author performance of highly cited articles. The researches related to MOFs increased sharply in the last two decades, not only on MOFs' synthesis and preparation, but also their properties and potential applications. The analysis by word clusters with supporting words in title, author keywords, abstract, and *KeyWords Plus* provided the clues for research focuses as well as research trends. Among various synthesis methods, solvothermal (including hydrothermal) method was used mostly to synthesize MOFs, followed by diffusion (slow evaporation). As newly developing methods, microwave-assisted synthesis, electrochemical synthesis, sonochemical synthesis, mechnochemical synthesis were used widely in recent years due to their timesaving and high throughput. Besides preparing new MOFs with novel structures and versatile properties, a lot of attentions were paid to investigate the properties and applications of representative MOFs, such as HKUST-1, MIL-101, ZIF-8, MIL-53, MOF-5, UiO-66, and MIL-125. In order to make MOFs to be used more widely, increasing focuses were put on MOFs-based composite and film (or membrane). Among the properties and potential applications of MOFs, adsorption studies including gas adsorption (H_2, CO_2 etc.) and later liquid adsorption of organic pollutants took the lead in both total article number and increasing rate, followed by catalysis (including photocatalysis), separation, luminescence, gas storage, magnetic property, and drug storage and delivery. New approaches of utilizing MOFs to conduct environmental remediation were proposed, especially adsorption of organic pollutants and heavy metals, and photocatalytic degradation of organic pollutants and photocatalytic reduction of Cr(VI). The *Y* index identifies important characteristics related to the first author and corresponding author, and the characteristics of the top authors with $j \geq 8$ out of 523 articles with $TC_{2014} \geq 100$ were also analyzed. During the period from 1995 to 2015, there are five classic articles with both $TC_{2014} > 1000$ and $C_{2014} > 100$ (all with Omar M. Yaghi as corresponding author), three classic ones with $TC_{2014} > 1000$ (two with O.M. Yaghi as corresponding author and one with W.B. Lin as corresponding author) and another three classic ones with $C_{2014} > 100$. Among these eleven articles, nine ones dealt with the synthesis strategy of MOFs with high porosity and/or gas storage, and the remaining two articles were related to catalysis and drug delivery, respectively. A significant relation was observed between articles with TC_{2014} and C_{2014}. The method described in this paper had been proved to be an effective approach for mapping the global trend and research focuses of metal–organic frameworks, and could also be adapted in other fields for the characterization of a given research field. Information from citation life cycles of the classic articles with highest TC_{2014} and C_{2014} provides a clear overview of their impact histories.

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