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REVIEW ARTICLE

The research trends of metal-organic frameworks in environmental science: a review based on bibliometric analysis

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Abstract

Metal-organic frameworks, an emerging class of porous material, have developed rapidly in recent years. In order to clarify the application of metal-organic frameworks in the field of environmental science, 1386 articles over the last 20 years were obtained from Scopus and analysed by the bibliometric method. And the collaboration between countries, institutions and authors and the co-occurrence of keywords were also conducted using VOSviewer. The results indicated that this area of research has entered a fast-developing stage. The number of articles published has grown from 7 articles in 1999 to 378 articles in 2018. The most productive country was China with 626 articles published. The most productive institution was the Chinese Academy of Sciences, and the most productive author was Jhung SH from Kyungpook National University of South Korea. Although metal-organic frameworks have been widely used in adsorption and catalytic degradation of pollutants from the environment, the removal mechanism of pollutants by MOFs, the stability improvement and the cost reduction of metal-organic frameworks are still the main challenges for their practical applications.

Keywords Research trends · Metal-organic frameworks · Environmental science · Bibliometric

Introduction

Nowadays, serious environmental pollution has attracted worldwide attention (Awual et al. 2019). Over the last decades, a variety of materials with high surface area and large pore volume have been invented for removal of pollutants from environment, including carbonaceous material (Mauter and Elimelech 2008, Yang et al. 2019), zeolites (Siyal et al. 2020), mesoporous silica (Awual 2017, 2019; Shahat et al. 2015) and metal-organic frameworks (MOFs) (Dhaka et al. 2019; Rowsell and Yaghi 2004), and so on. Though these materials have shown excellent performance for their environmental applications, MOFs have attracted more and more attentions from researchers due to their ultrahigh porosity, high chemical and thermal stability, structural and functional tunability (Qiu et al. 2014, Van de Voorde et al. 2014, Zhu and Xu 2014). Till now, MOFs has been widely studied in adsorption of toxic gases (Saha et al. 2010, Zhi et al. 2015), adsorption of pollutants from water (Dhaka et al. 2019; Van de Voorde et al. 2014) and photocatalytic degradation of pollutants (Wang et al. 2014a; Zhang and Lin 2014), and so on. MOFs provide a new possibility for the removal of pollutants from the environment.

Metal-organic frameworks (MOFs), also known as porous coordination polymer or porous coordination network, emerged approximately two decades ago and developed quickly since then (Li et al. 2012). MOFs were first introduced by Yaghi et al. (1995) in 1995. They reported coordination compounds on *Nature* and named the material as the metal-organic framework. Since then, the concept of metal-organic framework has been formally proposed. And then, in 1999, the Yaghi group (Li et al. 1999) reported MOF-5 on *Nature*. In

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the same year, HKUST-1 was reported by the Williams group (Chui et al. 1999) on Science. The two achievements further promoted the development of MOFs because of their high porosity and stability. In 2006, the Yaghi group reported ZIF-1 to ZIF-12 (Park et al. 2006), which exhibited excellent thermal and chemical stability. From 2007 to 2008, the Yaghi group further reported a series of ZIFs on *Nature Materials* (Hayashi et al. 2007), Science (Banerjee et al. 2008) and Nature (Wang et al. 2008), which greatly expanded the ZIFs family. On the other hand, in 2004 and 2005, MIL-100(Cr) and MIL-101(Cr) with high surface area and super macropore were reported by the Férey group from France on *Angewandte Chemie* (Férey et al. 2004) and Sciences (Férey et al. 2005). In their study, they put forward a new strategy of synthesizing MOFs by combining target chemistry and computer simulation methods, which opened a new page for MOFs. In 2008, UiO-66, a new type of MOFs with exceptional stability, was reported by the group of Lillerud (Cavka et al. 2008). The representative MOFs are listed in Table 1.

Several review articles have been published to introduce the development, applications and future directions of MOFs (Dhaka et al. 2019; Li et al. 2012; Zhong et al. 2019). In order to clarify the current situation of MOFs' applications in environmental science, the bibliometric method was adapted to review the current progress. Bibliometric analysis is a method utilizing quantitative analysis and statistics to describe the characteristics of documents in a given field (Zhang et al. 2017c). It has recently played a much more important role in scientific study (Aleixandre-Benavent et al. 2017) because it can effectively reflect the hotspots and future trends of specific fields by analysing big data in research database (Zhi et al. 2015). It can be used to assess the scientific production of authors, institutions, countries and journals and to identify the cooperation between countries, institutions and authors (Li and Zhao 2015). Till now, the bibliometric method has been used in the research of environmental engineering and scientist, such as groundwater remediation (Zhang et al. 2017a), nanomaterials (Zhao et al. 2018) and climate change (Aleixandre-Benavent et al. 2017), and so on. MOFs, a new research hotspot in the field of environmental science, the researchers were eager to know its progress to determine their next studies. This requirement would be met by the report on the development of MOFs in environmental science through the bibliometric method.

The bibliometric method was used in this study to clarify the current state of MOFs in the field of environmental science (MOFs-ES). The analysis of the published articles included the annual number of articles; the productive journals, authors, institutions and countries; and the collaboration among authors, institutions and countries. In addition, to disclose the hot research topics in the MOFs-ES field, the co-occurrence analysis of keywords was conducted on the high-frequency keywords. Moreover, the relevant review articles and the newest studies on MOFs-ES research were also summarized. The results of this study cannot only clarify the overall development of MOFs and predict the future trends of MOFs in the field of environmental science but also could promote the cooperation between the groups in the related fields according to the information provided by this study.

Table 1 Representative MOFs during the development

Team	Year	Name of MOFs	Molecular formula	Journal	Citations	References
Omar M. Yaghi	1995	MOF	$CoC_6H_3(COOH_{1/3})_3(NC_5H_5)_2 \cdot 2/3NC_5H_5$	*Nature*	1284	(Yaghi et al. 1995)
Omar M. Yaghi	1999	MOF-5	$Zn_4O(BDC)_3 \cdot (DMF)_8(C_6H_5Cl)$	*Nature*	4614	(Li et al. 1999)
Omar M. Yaghi	2006	ZIF-8	$Zn(MeIM)_2 \cdot (DMF) \cdot (H_2O)_3$	*Proceedings of the National Academy of Sciences of the United States of America*	2835	(Park et al. 2006)
Omar M. Yaghi	2008	ZIF-67	$Co(mIM)_2$	*Science*	2168	(Banerjee et al. 2008)
Ian D. Williams	1999	HKUST-1	$[Cu_3(TMA)_2(H_2O)_3]_n$	*Science*	3790	(Chui et al. 1999)
Kimoon Kim	2000	POST-1	$[Zn_3(\mu_3\text{-}O)(1\text{-}H)_6] \cdot 2H_3O \cdot 12H_2O$	*Nature*	3440	(Seo et al., 2000)
Gérard Férey	2004	MIL-100(Cr)	$Cr_3F(H_2O)_3O[C_6H_3\text{-}(CO_2)_3]_2 \cdot nH_2O$ ($n \approx 28$)	*Angewandte Chemie*	534	(Férey et al. 2004)
Gérard Férey	2005	MIL-101(Cr)	$Cr_3F(H_2O)_2O[(O_2C)\text{-}C_6H_4\text{-}(CO_2)]_3 \cdot 25H_2O$	*Science*	2833	(G. Férey et al. 2005)
Gérard Férey	2007	MIL-100(Fe)	$Fe^{III}{}_3O(H_2O)_2F \cdot (C_6H_3(CO_2)_3)_2 \cdot nH_2O$ ($n \approx 14.5$)	*Chemical Communications*	652	(Horcajada et al., 2007)
Karl Petter Lillerud	2008	UiO-66	$[Zr_6O_4(OH)_4](BDC)_6$	*Journal of the American Chemical Society*	2122	(Cavka et al. 2008)

BDC: 1,4-benzenedicarboxylate; *DMF*: N,N′-dimethylformamide; *MeIM* and *mIM*: 2-methylimidazole; *TMA*: benzene-1,3,5-tricarboxylate

Data and method

Data source and treatment

The data was collected from the Scopus database on January 3, 2019. The following terms were searched in the topic field of article title, abstract, keywords in Scopus from 1999 to 2018: "MOF" OR "MOFs" OR "Metal organic framework" OR "Metal organic frameworks" OR "Metal-organic framework" OR "Metal-organic frameworks" OR "porous coordination polymer" OR "porous coordination polymers" OR "porous coordination network" OR "porous coordination networks". The publications were limited to the category of Environmental Science. In addition, the document type of "Articles", the source type of "Journals", and the language of "English" was limited. After regrouping the terms to avoid duplicates and remove irrelevant articles, a total of 1386 articles were obtained. In order to avoid ambiguation of authors, Scopus Author Identifier, which distributes a unique number to each author, was used in this study to obtain the accurate information of authors (Zhang and Yu 2019). This method can distinguish individuals sharing the same formatted name and thus avoid errors induced by homonyms. But some systematic errors may be produced, such as different persons may be mistakenly attributed to the same Scopus Author Identifier or articles published by the same author may be attributed to a different Scopus Author Identifier (Kolesnikov et al. 2018). To avoid these errors, manual disambiguation of Scopus author profiles according to the information of researchers was conducted in this study. Bibliometric data from the disambiguated profiles was then aggregated and recalculated for each individual. In order to observe the overall changes overtime clearly, the 20-year analysis was further divided into four periods: 1999 to 2003 (the first period), 2004 to 2008 (the second period), 2009 to 2013 (the third period) and 2014 to 2018 (the fourth period).

Methods

The methods used in this study mainly include bibliometric method and social network analysis. As an indicator of scientific production, the number of articles published annually and the contribution of articles for each of the authors, institutions, countries and journals were analysed. The articles published by Hongkong and Taiwan were included into China. As an indicator of scientific impact, the number of total citations, average citations per article, impact factor of journals and H-index for authors, institutions, countries and journals were included in this study. The H-index for an author (or institutions or countries or journals) is h of total articles of an author (or institutions or countries or journals) with at least h citations each (Hirsch 2005). The impact factor of journals was obtained from Journal Citation Reports in 2018. In addition, to assess the overall change of geographical distribution, the migration of centre of gravity for publications and citations were analysed according to the method reported by Zhang et al. (2017b). Moreover, the high-frequency keywords were analysed to find the hot topics in the analysed field.

R version 3.5.1 (Statistics Department of the University of Auckland, https://www.r-project.org/) was used to process the data mentioned above. The R packages which were used in these calculations and visualizations mainly included "bibliometrix", "stringr", "rgeos", "ggplot2" and "rworldmap" (Aria and Cuccurullo 2017). In addition, VOSviewer (Van Eck and Waltman 2010) was used in this study to visualize the collaboration of authors, institutions, countries and the co-occurrences of keywords. In order to obtain the correct visualization of the networks, a limitation of papers was applied which would be assigned when each Figure was mentioned.

Results and discussion

Trends of publications

A total of 1386 articles were published on MOFs-ES research from 1999 to 2018. As seen in Fig. 1, the number of articles grown from 7 articles in 1999 to 378 articles in 2018, which increased greatly from 2011. This indicates that the research on MOFs-ES is attracting increasing attention of researchers in recent years. During the first decade of the analysed period (1999–2008), only 7.0% of the total articles were published, whereas in the last 5 years from 2014 to 2018, 76.0% of the total works was published. The linear fitting was conducted by dividing the 20 years into three stages according to the growth trend. The results showed that the slope was 1.47 in the first stage from 1999 to 2010, then increased to 6.5 from 2011 to 2013 and finally increased to 68.3 in the third stage from 2014 to 2018. The markedly increased growth rate in the last 5 years indicated that the research on MOFs-ES has entered a fast development stage.

The annual number and annual total citations of articles on MOFs-ES research from 1999 to 2018 are listed in Table S1. The citations number of academic papers reflects the academic impact of the papers. Among the 1386 papers, 82 articles were cited more than 100 times and 218 articles were cited more than 50 times. As shown in Table S1, the annual total citations were much higher from 2011 to 2017 due to the increase of publications during that period. The maximal value of total citations was 5257 in 2015 with the average value of 37.8. While for the average citations per article, the maximum value was 83.0 in 2008. The average citations per article in 2016 to 2018 was much lower than those of other years because that time is necessary to accumulate citations.

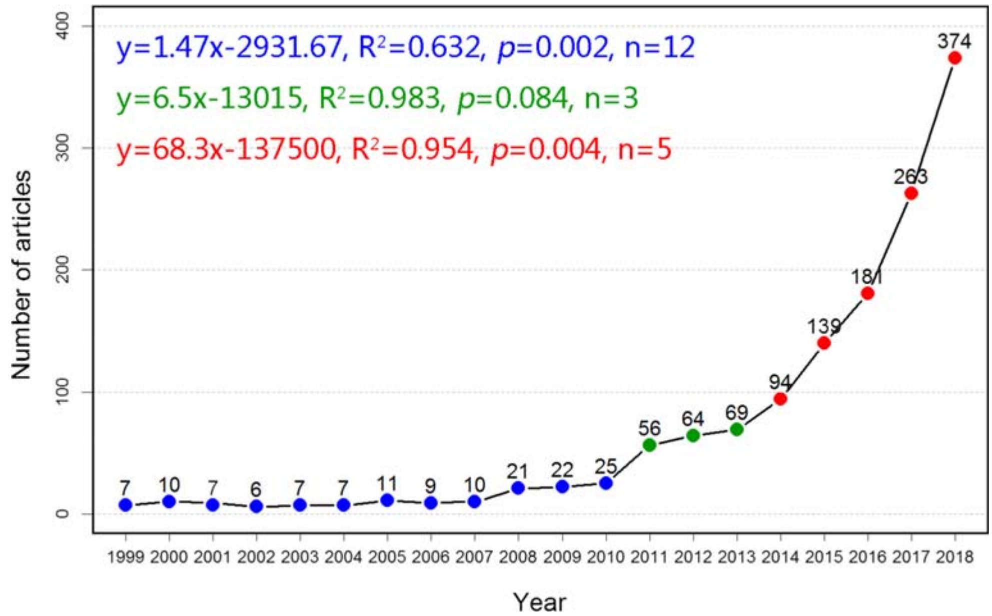

Fig. 1 The annual number of articles on the research of MOFs in the field of environmental science from 1999 to 2018

However, it is predictable that the total citations in recent years would increase further over time.

Table 2 lists the top 15 most-cited articles on the research of MOFs in the field of environmental science from 1999 to 2018. Among them, seven articles issued by China, six articles issued by the USA and four articles issued by South Korea, indicating that the extremely high academic influences in this field have been achieved by the researchers in these countries. In addition, 9 of the top 15 articles have been published in Energy & Environmental Science, indicating that this journal has an extremely high influence in this field. For the research contents of the 15 most-cited articles, eight articles focused on the adsorption or capture of CO_2 by MOFs, four articles studied the removal of pollutants from aqueous solution, and another three articles researched the role of MOFs for oxygen evolution reaction. This indicated that the environment application of MOFs still mainly focused on gas adsorption. The highest citation paper was published in 2011 in *Energy & Environmental Science* (Mason et al. 2011) with total citations of 511. This article evaluated the potential use of two representative MOFs in post-combustion CO_2 capture via temperature swing adsorption. The article with total citations of 431 was also published in 2011 (Haque et al. 2011), which used MOF-235 to remove harmful dyes from contaminated water. MOFs could be used as potential adsorbents for removing pollutants in solution based on their study.

Country analysis

The 1386 articles about the application of MOFs in the environment were published by 56 countries. The characteristics of the top 15 most productive countries are illustrated in Table 3. Nine of the top 15 most productive countries were developed countries. However, the country which published the highest number of papers was China with a total of 626 articles published from 1999 to 2018, accounting for 45.2% of the total articles, followed by the USA (215 articles, 15.5%) and South Korea (100 articles, 7.2%). During the period of 1999 to 2008, the USA had the highest number of published articles. However, China became the leading country in the last decade. China was also the country that had the highest total citations (15567), followed by the USA (9885) and South Korea (4135), which was consistent with the ranking of the number of articles and H-index. And the total citations of Iran, India and Saudi Arabia were much lower than those of other countries. For the average citations per article, Netherlands was the country with the highest value of 59.5, followed by the USA of 46.0, Singapore of 42.2 and South Korea of 41.4. Although China had the highest number of articles and the highest total citations, the average citations per article for China was much lower. The quality of articles published by China should be further improved while increasing the number of published articles.

The geographical distribution of articles for each of the countries and the regional migration of the centre of gravity over time were conducted, as shown in Fig. 2. Each circle represents one country, the bigger the circle, the more articles were published by the country. The different colors of the circles represent the total citations of the country which was shown in the color bar. The results for publications and total citations were corresponding to those shown in Table S1. The centre of gravity for both productions and citations migrated eastward obviously over the four periods. The centre of gravity for productions migrated from 35° N, 69° W in the1st period, to 35° N, 58° W in the 2nd period, to 37° N, 12° W in the 3rd period and finally to 37° N, 50° E in the 4th period,

Table 2 Top 15 most frequently cited articles on research of MOFs in field of environmental science from 1999 to 2018

Author	Year	Country	TC	Journal	Research highlights	References
Mason JA, Sumida K, Herm ZR, Krishna R, Long JR	2011	USA, Netherlands	511	*Energy & Environmental Science*	Post-combustion CO_2 capture	(Mason et al. 2011)
Haque E, Jun JW, Jhung SH	2011	South Korea	431	*Journal of Hazardous Materials*	Adsorption of harmful dyes from aqueous solution by MOF-235.	(Haque et al. 2011)
Saha D, Bao Z, Jia F, Deng S	2010	USA, China	375	*Environmental Science and Technology*	Adsorption of CO_2, CH_4, N_2O, and N_2 on MOF-5, MOF-177, and Zeolite 5A.	(Saha et al. 2010)
Zhao D, Yuan D, Zhou HC	2008	USA	320	*Energy & Environmental Science*	Hydrogen storage in MOFs.	(Zhao et al. 2008)
He Y, Krishna R, Chen B	2012	USA, Netherlands	309	*Energy & Environmental Science*	Adsorptive separation of light hydrocarbons by 19 different MOFs.	(He et al. 2012)
Haque E, Lee JE, Jang IT, Hwang YK, Chang JS, Jegal J, Jhung SH	2010	South Korea	289	*Journal of Hazardous Materials*	Adsorptive removal of methyl orange from aqueous solution.	(Haque et al. 2010)
Yu XY, Feng Y, Guan B, Lou XWD, Paik U	2016	South Korea, Singapore, China	288	*Energy & Environmental Science*	Electrocatalysis of oxygen evolution reaction by MOF-derived functional nanomaterials.	(Yu et al. 2016)
Sayari A, Belmabkhout Y, Serna-Guerrero R	2011	Canada	268	*Chemical Engineering Journal*	Post-combustion CO_2 capture by MOFs.	(Sayari et al. 2011)
Song J, Zhang Z, Hu S, Wu T, Jiang T, Han B	2009	China	258	*Green Chemistry*	The coupling reaction of CO_2 with propylene oxide catalyzed by MOF-5.	(Song et al. 2009)
Xia W, Zou R, An L, Xia D, Guo S	2015	China, USA	253	*Energy & Environmental Science*	Oxygen reduction by $Co@Co_3O_4@C$-CM derived from MOF.	(Xia et al. 2015)
Huo SH, Yan XP	2012	China	237	*Analyst*	Magnetic solid-phase extraction of polycyclic aromatic hydrocarbons from environmental water samples.	(Huo and Yan, 2012)
Simmons JM, Wu H, Zhou W, Yildirim T	2011	South Korea	234	*Energy & Environmental Science*	Carbon capture by MOFs	(Simmons et al. 2011)
Yang DA, Cho HY. Kim J, Yang ST, Ahn WS	2012	Singapore, China	220	*Energy & Environmental Science*	CO_2 capture and conversion by Mg-MOF-74.	(Yang et al. 2012)
Hu H, Han L, Yu M, Wang Z, Lou XW	2016	Singapore, China	216	*Energy & Environmental Science*	Oxygen reduction by MOF-engaged Co-C@Co_9S_8DSNCs	(Hu et al. 2016)
Wang H, Yuan X, Wu Y, Zeng G, Chen X, Leng L, Li H	2015	China	206	*Applied Catalysis B: Environmental*	Photocatalytic degradation of dyes by g-C_3N_4/MIL-125(Ti).	(Wang et al. 2015)

TC: total citations of this article

migrating eastward for 957 km, 4108 km and 5493 km, respectively. The centre of gravity for citations migrated from 45° N, 108° W in the 1st period, to 44° N, 80° W in the 2nd period, to 40° N, 17° W in the 3rd period, and finally to 37° N, 50° E in the 4th period, migrating eastward for 2226 km, 5060 km and 5684 km, respectively. Both the centre of gravity for productions and citations migrated from Europe and America to Asia gradually overtime.

It can be known that European and American countries started their research earlier in the field of MOFs-ES. Whereas Asian countries developed quickly in recent years though they started their research on MOFs-ES later. Therefore, the centre of gravity of publications and citations was located in the developed countries in Europe and America during the 1st and 2nd periods. While the centre of citations and publications migrated eastward to Asia during the 3rd and 4th periods due to the growing up of the countries in Asia such as China, South Korea and Iran. Another noteworthy phenomenon was that the centre of gravity of publications was far apart from that during the first and second periods, while the centre of publications and citations were close during the 3rd and 4th periods. This was because during the first period, 20 of the total 39 articles were published by the USA, accounting for 51.3%. However, the USA had total citations of 2472 at that period, accounting for 83.6% of the total citations of world. Thus, the centre of gravity of citations was located in the United States during that period, apart from the centre of gravity of publications. It was similar to that of the second

Table 3 Most productive countries on the research of MOFs in the field of environmental science from 1999 to 2018

Country	TP	TC	TC/TP	H-index	SCP	MCP	TP			
							1999–2003	2004–2008	2009–2013	2014–2018
China	646	15,633	24.2	62	491	155	1	3	49	572
United States	215	9885	46.0	56	108	107	18	17	46	134
South Korea	100	4135	41.4	34	72	28	–	–	16	84
United Kingdom	70	2278	32.5	26	28	42	2	7	12	49
France	68	2095	30.8	26	32	36	2	10	17	39
Spain	65	1598	24.6	25	28	37	1	4	14	46
Italy	47	1253	26.7	20	22	25	5	4	11	27
Iran	47	602	12.8	12	41	6	–	–	6	41
Germany	43	1121	26.1	19	16	27	2	3	11	27
Australia	37	920	24.9	15	16	21	2	–	10	25
India	37	425	11.5	11	20	17	–	–	5	32
Singapore	36	1518	42.2	18	23	13	–	1	5	30
Canada	36	899	24.9	15	18	18	2	1	12	21
Saudi Arabia	36	555	15.4	13	11	25	–	–	1	35
Netherlands	31	1846	59.5	18	11	20	1	4	16	10
World	1386	37,632	27.2	–	1056	330	37	58	236	1055

TP: total published articles; *TC*: total citations; *SCP*: single country publications; *MCP*: multiple country publications

period from 2004 to 2008, whereas with the rapid development from 2009 to 2018, the citations were accumulated from a large number of articles, and the centre of publications and citations became closer.

For international cooperation, 1056 (76.2%) of the total 1386 articles were from a single country and 330 (23.8%) were from multiple countries. This might be as the indicator of how wide of international cooperation conducted. A further analysis about the collaboration network between countries is shown in Fig. 3. The analysis collected the data of countries with more than 5 articles published. In Fig. 3, each circle represents one country and the size of the circle and line represent the number of articles of the country and the links between different countries, respectively. The bigger the circle, the more articles are published by the country. The thicker the line, the more links between the countries. The different

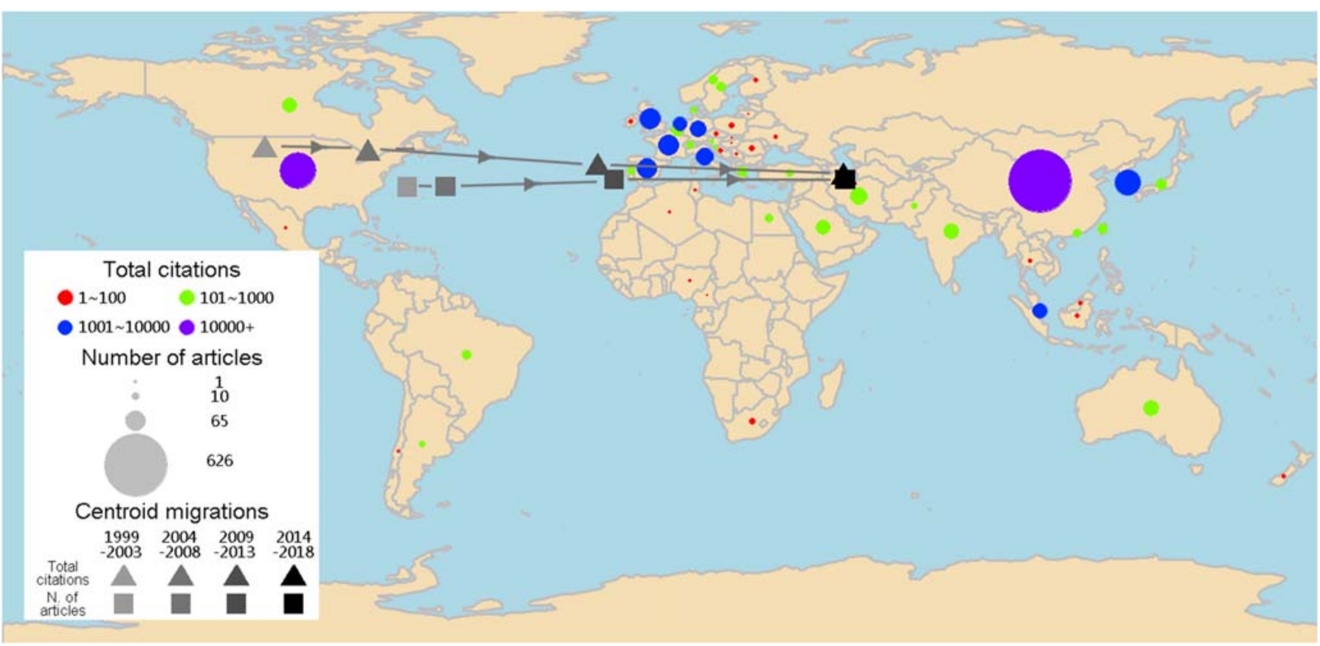

Fig. 2 Global geographic distribution and regional migration of research on MOFs in the field of environmental science from 1999 to 2018

colors correspond to clusters formed by different groups of countries. As seen in Fig. 3, five main clusters corresponding to five different colors can be distinguished, which were led by China, the United States, South Korea, France and Singapore, respectively. China had the most abundant links with other countries, followed by the USA. Moreover, the thickest line between China and the USA indicated that the two countries had the closest cooperation compared with other countries. The cooperation between Western countries and other countries was much more active than Asian countries. With the continuous development of this field, Asian countries should strengthen their international cooperation with other countries to further improve their influence and achievements.

Institution analysis

The most productive institutions (> 15) on MOFs-ES research are presented in Table 4. As seen, 11 of the top 16 institutions belong to China, which might be the reason for the large number of articles published by China. Besides, Kyungpook National University, South Korea, ranked second. University of California, USA, ranked fifth. National University of Singapore and Nanyang Technology University, Singapore, ranked ninth and fourteenth. And King Abdulaziz University, Saudi Arabia, ranked twelfth. Among the sixteen most productive institutions, the Chinese Academy of Sciences published the highest number of articles, while Tianjin University was the first institute in China to start the study in the field of MOFs-ES since their first paper was published on 2000.

For the total citations, the Chinese Academy of Sciences had the highest citations (2878), followed by Kyungpook National University (2237), South China University of Technology (1707) and University of California (1693). In respect to the average citations per article, the University of California listed as first (65.1), followed by Nanyang Technology University (64.8) and University of Science and Technology of China (59.2). Similarly, as an indicator of impact, the H-index of the Chinese Academy of Sciences was highest which was 28,

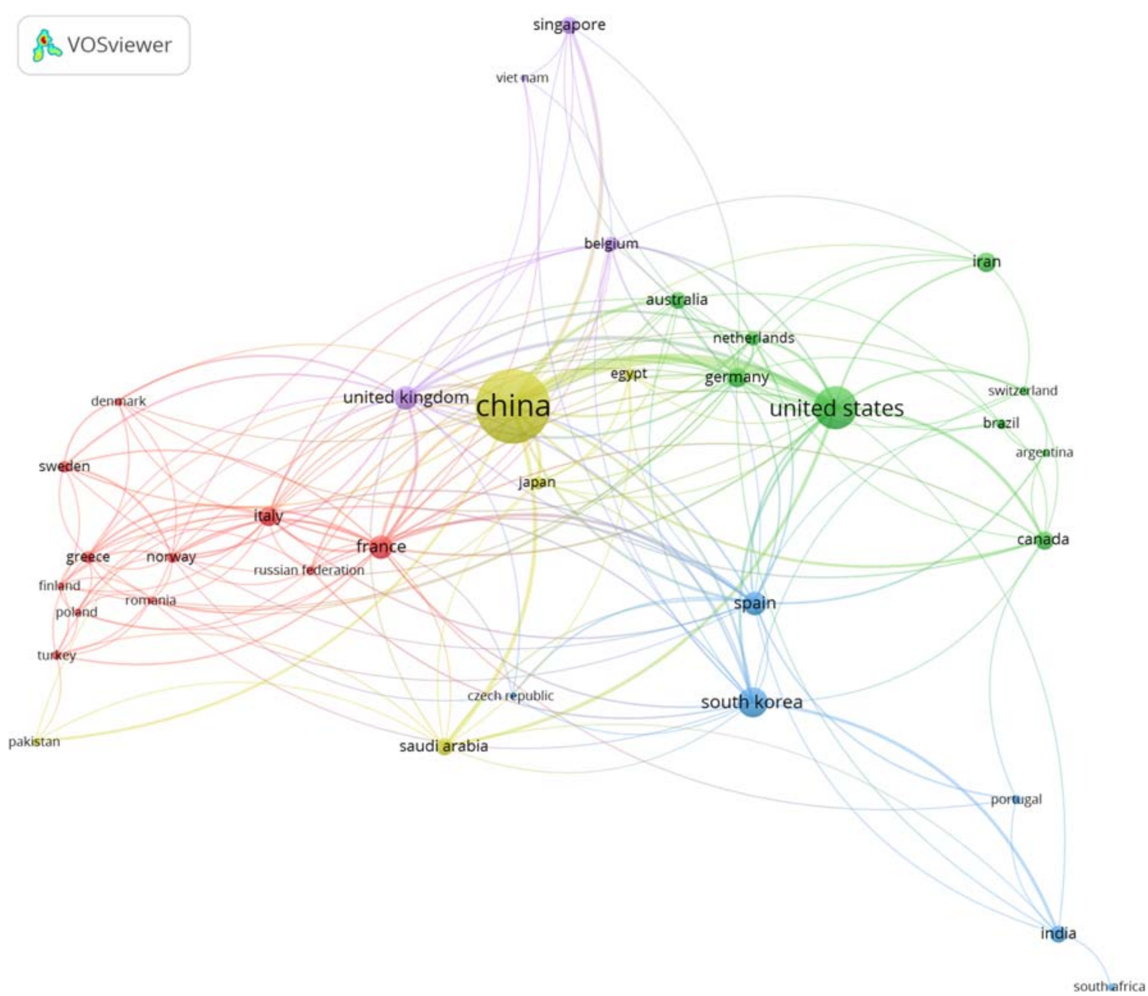

Fig. 3 Cooperation of countries and regions on the research of MOFs in the field of environmental science from 1999 to 2018

Table 4 Most productive institutions on research of MOFs in field of environmental science from1999 to 2018 (> 15 articles)

Institution	Country	TP	TC	TC/TP	SIP	MIP	H-index	TP			
								1999–2003	2004–2008	2009–2013	2014–2018
Chinese Academy of Sciences	China	86	2878	33.5	19	67	28	–	1	10	75
South China University of Technology	China	46	1707	37.1	13	33	24	–	–	4	42
Kyungpook National University	South Korea	40	2237	55.9	35	5	23	–	–	11	29
Beijing University of Chemical Technology	China	27	790	29.3	13	14	15	–	2	5	20
University of California	United States	26	1693	65.1	4	22	16	–	2	8	16
Fuzhou University	China	21	970	46.2	11	10	15	–	–	1	20
Nankai University	China	19	708	37.3	9	10	9	–	–	5	14
Tsinghua University	China	19	307	16.2	8	11	8	–	–	–	19
National University of Singapore	Singapore	19	459	24.2	13	6	8	–	1	4	14
Zhejiang University	China	18	723	40.2	7	11	12	–	1	4	20
King Abdulaziz University	Saudi Arabia	18	415	23.1	0	18	10	–	–	–	18
Sun Yat-Sen University	China	18	405	22.5	5	13	10	–	–	–	18
Tianjin University	China	17	404	23.8	3	14	10	1	–	2	19
Nanyang Technology University	Singapore	16	1037	64.8	7	9	11	–	–	1	15
University of Science and Technology of China	China	16	947	59.2	2	14	12	–	–	3	13
Soochow University	China	16	320	20.0	2	14	9	–	–	–	16
World	–	1386	37,632	27.2	599	787	–	37	58	236	1055

TP: total published articles; *TC*: total citations; *SIP*: single institution publications; *MIP*: multiple institution publications

followed by South China University of Technology with 24 and Kyungpook National University with 23.

It is worth noting that the South China University of Technology, which was founded in 2011, has published 46 articles on MOFs-ES. This indicated that the research on MOFs-ES was one of the main fields for this young university. Their research mainly focused on the removal of various pollutants such as congo red (Yang et al. 2017), methyl orange (Wu et al. 2017), and triclosan (Dou et al. 2017) by MOFs and the synthesis of new hybrid MOFs materials (Chen et al. 2017; Yu et al. 2018). The articles published by Kyungpook National University were mainly conducted by the team led by Jhung SH. They mainly focused on removal of dyes (Haque et al. 2010), denitrogenation from model fuels (Ahmed et al. 2013a; Ahmed et al. 2013b; Ahmed and Jhung 2014; Ahmed et al. 2017) and removal of pharmaceuticals from water (Bhadra et al. 2017; Hasan et al. 2012; Sarker et al. 2018; Song and Jhung 2017), and so on. Beijing University of Chemical Technology was mainly engaged in gas adsorption (Shao et al. 2011; Wu et al. 2012) and wastewater treatment (Han et al. 2015; Xie et al. 2014) using MOFs in their earlier years, while they have begun to develop the application of MOFs in electrode materials (Shi et al. 2017) and membrane materials (Ma et al. 2017) in recent years. Similarly, the National University of Singapore has also developed the application of MOFs in membrane materials for seawater desalination (Zhu et al. 2016) and vacuum membrane distillation (Zuo and Chung 2016), and as anode materials for batteries (Li et al. 2018b).

For the collaboration of institutions, multiple institution publications were slightly higher than single-institution publications, as shown in Table 4. Some of the institutions had much more multiple institution publications such as the Chinese Academy of Sciences, South China University of Technology and the University of California. It was interesting that all the articles published by King Abdulaziz University were completed through the cooperation with other institutions. While some institutions had more single-institution publications such as Kyungpook National University and the National University of Singapore. Figure 4 shows the collaboration network between institutions, where the size of the circle and the line also represent the number of publications per institution and the links between the institutions. The institutions published more than 5 articles which were collected as data. Twelve main clusters corresponding to twelve different colors can be differentiated. Chinese academy of sciences had the most abundant links to other institutions. However, Kyungpook National University, ranking third of the most productive institutions, had little cooperation with other institutions.

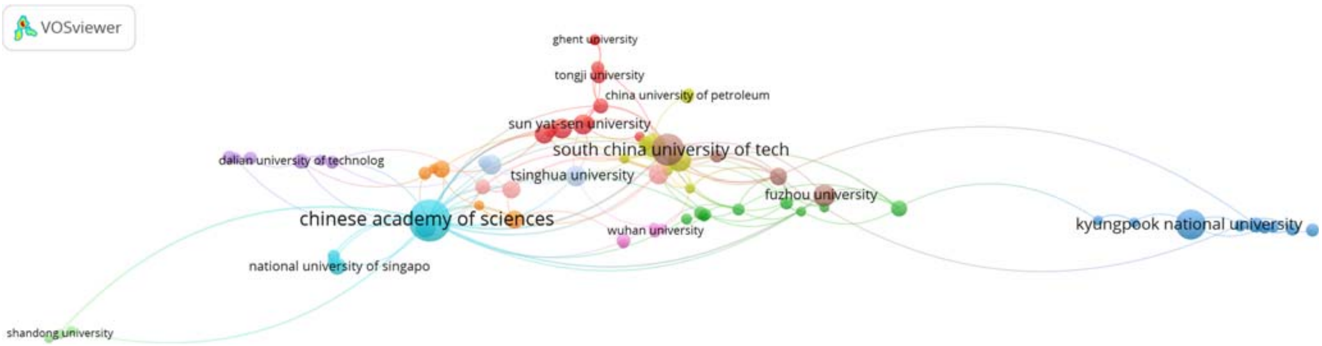

Fig. 4 Cooperation of institutions on the research of MOFs in the field of environmental science from 1999 to 2018

Authors analysis

The most productive authors (> 10 articles) in the field of MOFs-ES are shown in Table 5. Of the ten authors, five are Chinese and five are Korean. Three of them come from South China University of Technology, which is the most productive institution. And another three of them come from Kyungpook National University, which ranked second of the productive institutions. Jhung SH from Kyungpook National University was the most productive author, with 38 published articles, 2200 total citations accumulated from these studies, an H-index of 23 and an average citations per article of 57.9.

Figure 5 shows the collaboration network between authors who published more than 3 articles. The authors can be divided into12 main clusters represented by 12 different colors. Each cluster represented one collaboration team. Jhung SH comes from Kyungpook National University had the most abundant links with other authors. And the team of Jhung SH cooperated most with the team of Bae YS come from Yonsei University. Li Z, who comes from the South China University of Technology, also had much cooperation with other authors. His team cooperated closely with the team of Li Y come from the same university. It can be found that most authors collaborated more with native authors, while the cooperation with foreign authors was less.

Journals analysis

The 1386 articles were published in 185 different journals. The characteristics of the top 20 journals publishing most articles on MOFs-ES research from 1999 to 2018 are shown in Table 6. The journal published most articles in the field of MOFs-ES was Chemical Engineering Journal with a total of 234 articles. The first article about MOFs-ES research published on this journal was in 2010, whereas the number of published papers increased quickly from 2014 to 2018, with 212 articles published in these 5 years. In addition, as an important indicator of impact for the journal, this journal occupied the second position with respect to the H-index of 41. Energy & Environmental Science, which occupies the sixth position according to the number of published articles, accumulated the highest citations of 6741. What's more, as an indicator of impact, the average citations per article, impact factor and H-index of this journal were all the highest, with average citations per article of 102.1,

Table 5 Most productive authors on research of MOFs in field of environmental science from 1999 to 2018 (≥ 10 articles)

Author	ID	TP	TC	TC/TP	H-index	Country	Affiliation	First year	Last year
Jhung SH	56532168100	38	2200	57.9	23	South Korea	Kyungpook National University	2010	2018
Li Y	12040080600	16	667	41.7	12	China	South China University of Technology	2008	2017
Zhong C	7202121115	15	567	43.6	11	China	Beijing University of Chemical Technology	2007	2018
Li Z	35752191300	15	456	30.4	11	China	South China University of Technology	2011	2017
Khan NA	35170042700	13	634	48.8	10	South Korea	Kyungpook National University	2011	2018
Xia Q	8869056100	12	337	28.1	10	China	South China University of Technology	2014	2017
Chang JS	18933850100	10	461	46.1	10	South Korea	Korea Research Institute of Chemical Technology	2010	2018
Ahmed I	55377179600	10	409	40.9	9	South Korea	Kyungpook National University	2013	2017
Bae YS	7201465967	10	312	31.2	8	South Korea	Yonsei University	2012	2018
Zhu W	7404232544	10	242	24.2	7	China	Zhejiang Normal University	2014	2018

TP: total published articles; *TC*: total citations; *ID*: Scopus Author Identifier

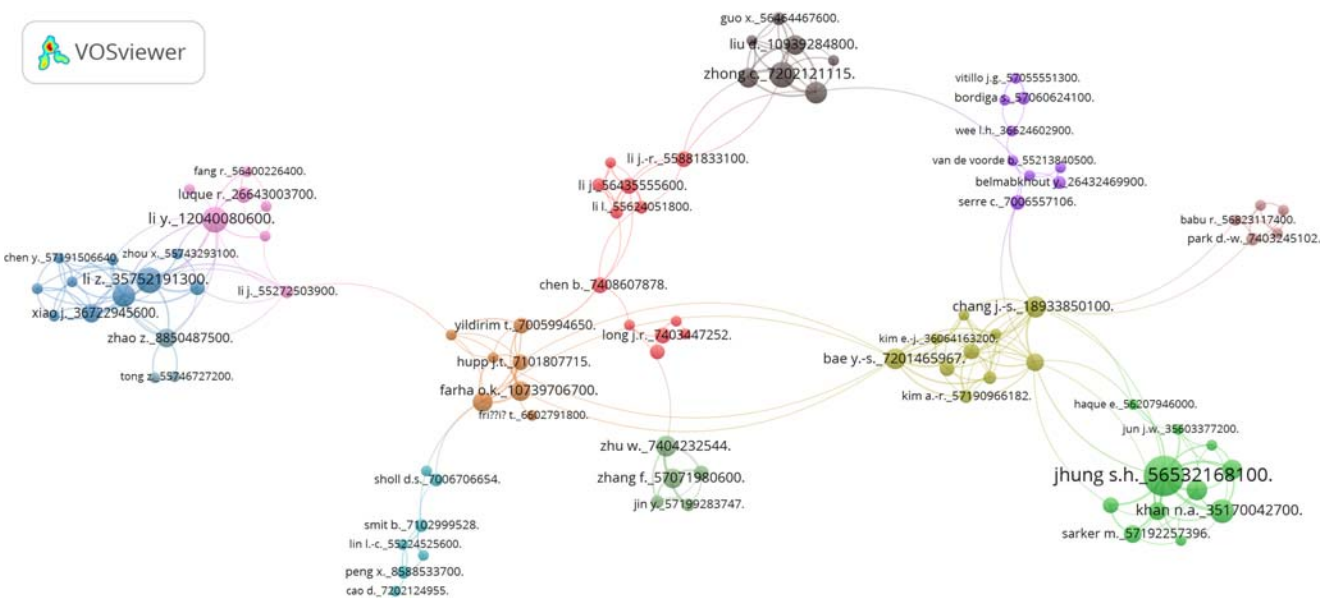

Fig. 5 Cooperation of authors on the research of MOFs in the field of environmental science from 1999 to 2018

impact factor of 30.067 and H-index of 42. This indicated that *Energy & Environmental Science* had the highest impact on MOFs-ES research. *Environmental Science and Technology* published its first article in MOFs-ES research in 1999, the first year of the period analysed. This journal had the number of citations per article with 55.2, ranking second position.

Table 6 Most productive journals on research of MOFs in field of environmental science from 1999 to 2018

Journal	IF	H-index	TP	TC	TC/TP	First year	TP			
							1999–2003	2004–2008	2009–2013	2014–2018
Chemical Engineering Journal	6.735	41	234	5245	22.4	2010	–	–	22	212
Applied Catalysis B: Environmental	11.698	33	87	3152	36.2	2000	1	2	3	81
ACS Sustainable Chemistry and Engineering	6.140	18	86	829	9.6	2013	–	–	1	85
ChemSusChem	7.411	23	76	1906	25.1	2008	–	1	11	64
Journal of Hazardous Materials	6.434	29	69	3201	46.4	2005	–	2	19	48
Energy & Environmental Science	30.067	42	66	6741	102.1	2008	–	3	24	39
Green Chemistry	8.586	28	52	2064	39.7	2009	–	–	8	44
Analytica Chimica Acta	5.123	15	46	718	15.6	2012	–	–	5	41
Aiche Journal	3.326	18	39	1295	33.2	2002	2	4	9	24
Environmental Science and Technology	6.653	22	37	2043	55.2	1999	4	1	12	20
Analyst	3.864	19	36	1180	32.8	2012	–	–	8	28
Science of the Total Environment	4.610	13	28	850	30.4	2003	2	3	3	20
Chemosphere	4.427	11	24	316	13.2	2008	–	1	7	16
Environmental Science and Pollution Research	2.800	6	23	102	4.4	2014	–	–	–	23
Journal of CO_2 Utilization	5.503	8	20	104	5.2	2016	–	–	–	20
Chem	14.104	9	18	310	17.2	2016	–	–	–	18
Desalination and Water Treatment	1.383	6	17	109	6.4	2011	–	–	1	16
Journal of Environmental Chemical Engineering	–	5	14	91	6.5	2013	–	–	1	13
Journal of Cleaner Production	5.651	5	13	98	7.5	2011	–	–	1	12
Chinese Journal of Chemical Engineering	1.712	6	13	98	7.5	2000	1	0	2	10

TP: total published articles; *TC*: total citations; *IF*: the impact factor of the journal. IF was obtained from the 2018 edition of the Journal Citation Reports

However, the number of publications in this journal on MOFs-ES research had not increased significantly in recent years, with a total number of 37 articles.

Figure 6 shows a 2 × 2 matrix where the *x*-axis represents the total citations of each journal accumulated from the related articles and *y*-axis represents the number of papers published by each journal in the field of MOFs-ES. By calculating the mean values of both variables of the top 20 journals, the journals could be divided into four groups (Fetscherin and Heinrich 2015). Quadrant A: high number of articles and high total citations; quadrant B: high number of articles and low total citations; quadrant C: low number of articles and low total citations; quadrant D: low number of articles and high total citations. Among the 20 most productive journals, 12 journals were located in quadrant C, which means that these journals had low number of articles and low total citations. And 6 journals located in quadrant A with higher number of articles and total citations, included Chemical Engineering Journal, Energy & Environmental Science, Applied Catalysis B: Environmental, Journal of Hazardous Materials, ChemSusChem, and Green Chemistry. The 6 journals with high number of articles and high total citations mainly belong to the WoS-category of chemistry and engineering & technology. The details for journals located in quadrant C are shown in Fig. S1 of supplementary material.

Keywords analysis

The analysis of high-frequency keywords is key to investigating hot topics of a field. A total of 3328 keywords were obtained from the 1386 articles analysed. By further grouping, the high-frequency keywords were classified into 4 categories, as shown in Table 7. It can be seen that "MOFs" was a category of keywords with the highest frequency. Besides MOFs and its synonym in this category, UIO-66, MIL-101, ZIF-8 and MIL-100(Fe) were also used as keywords frequently. MIL, ZIF and UIO were three typical types of MOFs, which has been widely used in recent years. The second category of keywords was adsorption, indicating that MOFs were widely used as adsorbents in the removal of pollutants, whereas from the keywords in the third category, we can know that the pollutants treated by MOFs mainly included heavy metals and carbon dioxide. The fourth category of keywords was catalysis, showing that MOFs

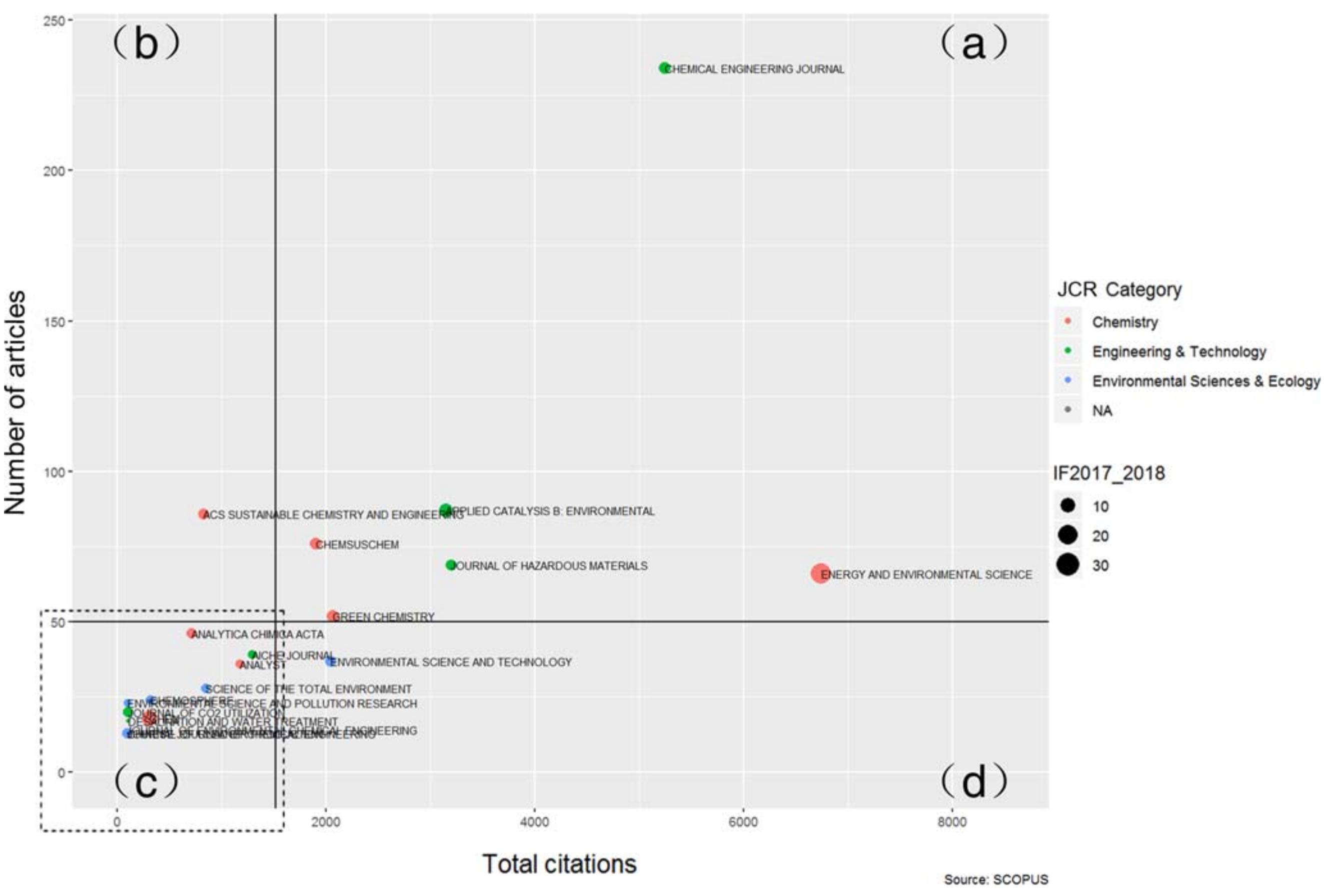

Fig. 6 The distribution of the journal in respect to the total citations and number of articles. The *x*-axis represents total citations and *y*-axis represents number of articles published by each journal

Table 7 Most frequently used keywords on research of MOFs in field of environmental science from 1999 to 2018

Category	Representative keywords	Frequency of keywords
MOFs	MOF/MOFs/Metal organic framework/Metal organic frameworks/ Metal - organic framework/ Metal - organic frameworks (499), UIO-66(18), MIL-101(17), ZIF-8(14), MIL-100(Fe) (12)	559
Adsorption	Adsorption (176), Separation (25), Removal (16)	217
Pollutants	Carbon dioxide Capture/ CO_2Capture (30), Carbon dioxide (19), CO_2Adsorption (11), Metals (21), Heavy metals (17), Methylene blue (15), Copper (14)	127
Catalysis	Photocatalysis/Photocatalyst (60), Heterogeneous catalysis/Heterogeneous catalyst (38)	98

were usually used in the catalysis reaction including photocatalysis and heterogeneous catalysis.

Here, high-frequency keywords which appeared more than 7 times were selected to conduct co-occurrence analysis. The keywords were regrouped in order to avoid duplicates due to pluralization. The keywords “MOF”, “MOFs”, “Metal organic framework”, “Metal organic frameworks”, “Metal-organic framework” and “Metal-organic frameworks” were all named as metal-organic framework in the co-occurrence map. The co-occurrence map of keywords in the field studied is shown in Fig. 7. The size of the circle represents the frequency of the keyword. The size of the line represents the links between the keyword to the other. The thicker the line between two keywords, the more frequently that the two keywords appear together. As shown in Fig. 7, metal-organic framework had the closest links with other keywords because that the field we studied was the application of MOFs in environmental science. Thus, most of the articles should include metal-organic framework in its keywords. Other keywords with relatively large size, such as adsorption, photocatalysis, heterogeneous catalysis, separation and carbon dioxide capture, also occupied an important position. Moreover, the lines between metal-organic framework and adsorption, photocatalysis, heterogeneous catalysis were thicker than other keywords, which indicated that adsorption and catalysis were the hotspots for MOFs-ES research.

The different colors of keywords in Fig. 7 represent the average publication year of keywords, as shown in the color bar. The change of color could reflect the change of hot topics in the field studied. In the purple color which represents

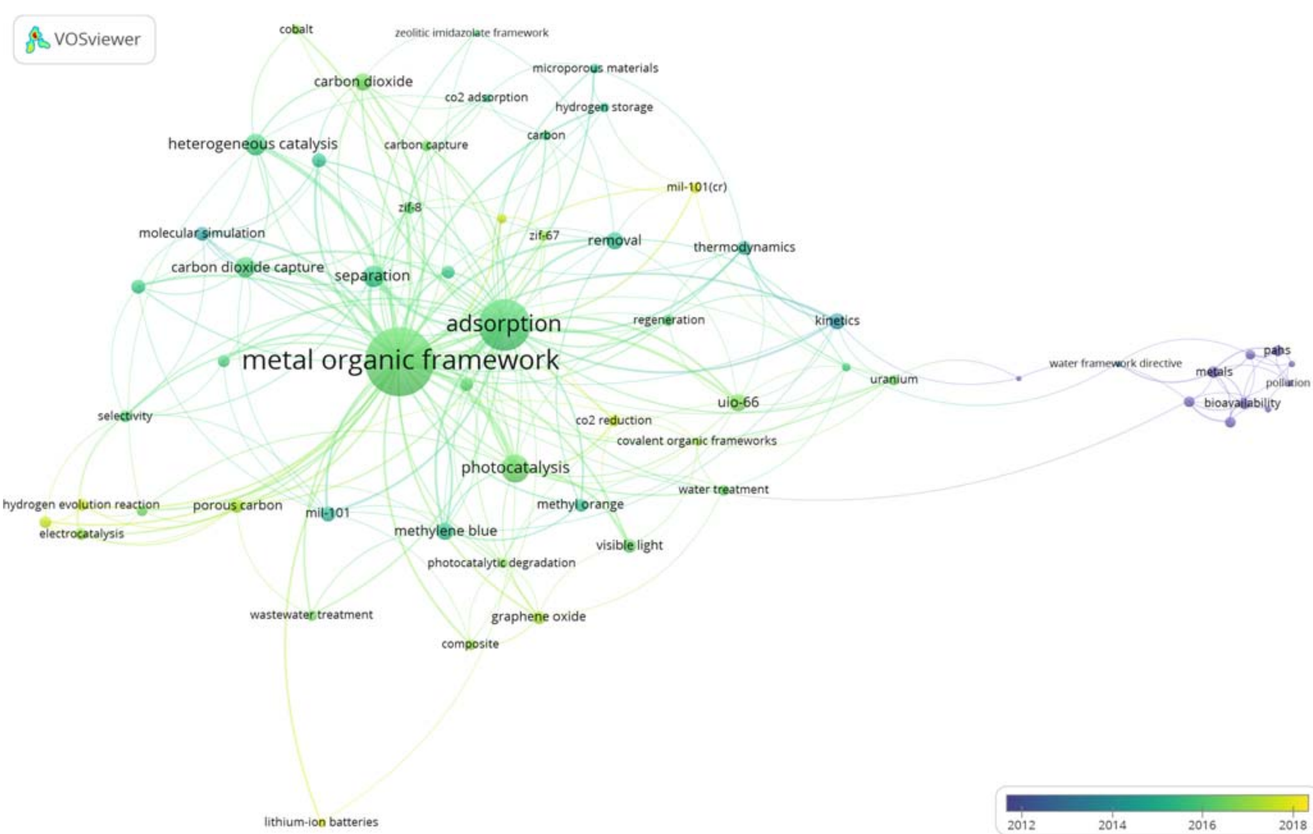

Fig. 7 The co-occurrence map of keywords on the research of MOFs in the field of environmental science from 1999 to 2018

publishing time about 2012, "metals", "heavy metals" and "copper" were usually used as keywords, indicating that MOFs usually used for the removal of heavy metals at that time. As shown in Fig. 7, most keywords are in green color with the publishing time about 2016 because the research on MOFs-ES developed rapidly during that period. MOFs were usually used in the process of adsorption, separation and catalytic degradation of pollutants at that time. The keywords with publishing time about 2017 included "porous carbon", "graphene oxide", "composite" and "covalent organic frameworks", indicating that some hybrid MOFs materials have been synthesized and used in the field of environmental science. The keywords published in about 2018, which were represented by the yellow color, included "hydrogen evolution reaction", "oxygen reduction reaction", "peroxymonosulfate", "CO_2 reduction" and "lithium-ion batteries", showing that novel applications of MOFs have been explored. Thus, it can be concluded that the initial application of MOFs in the environmental science field mainly focused on gas adsorption, wastewater treatment and catalytic degradation of various pollutants, and now some new applications of MOFs have been developed. It can be predicted that the novel applications will be continuously explored.

The environmental applications of MOFs

MOFs have attracted extensive attention from researchers in the field of environmental science due to their excellent properties. The environmental applications of MOFs mainly focused on two aspects, namely the removal of toxic gases and the removal of various pollutants in the liquid phase by MOFs.

MOFs for the removal of toxic gases

Releasing toxic pollutants into the atmosphere has become a global risk. General harmful compounds, including SOx, NOx, CO, NH_3, H_2S, compounds containing nitrogen or sulfur, hydrocarbons, volatile organic compounds (VOCs), are of main concern for air contamination (Barea et al. 2014). The effective adsorption and degradation of these compounds are of great significance to the environment and human health. Thus, developing new sorbents has gained more and more attention, with MOFs showing great prospects due to their various advantages.

MOFs have been used for the removal of toxic gases or toxic vapors, such as CO, NO_X, sulfur-containing compounds and ammonia, and so on. The removal of toxic gases by MOFs is shown in Table 8. Zhang et al. (2019) prepared a series of amine-modified MOF-199 for the removal of H_2S. The results showed that tertiary amine triethanolamine functionalized MOF-199 had a much higher adsorption capacity for H_2S than that of parent MOF-199. Brandt et al. (2019) studied the removal of SO_2 by MOF-177, which showed the highest capacity for SO_2 adsorption by far with a maximum uptake of 25.7 mmol/g at 293 K and 0.97 bar. Gong et al. (2019) combined the nonthermal plasma technology with MOFs synthesis for the enhanced removal of NO. The results showed that this synergistic method could achieve an ultra-efficient NO removal through the reduction of NO to N_2. In addition, MIL-101(Cr) and copper-doped MIL-101(Cr) were used for the removal of VOCs (Wang et al. 2018). The results indicated that MIL-101(Cr) and copper-doped MIL-101(Cr) had a promising potential for the removal of VOCs.

Though MOFs have shown great performance in removing toxic gases, a full set of design rules has not been established for the synthesis of MOFs capable of removing broad-spectrum toxic gases (DeCoste and Peterson 2014). The main target for the removal of hazardous gases by MOFs is to explore high-affinity binding sites of MOFs and to enhance the resistance of MOFs to those toxic gases with high corrosiveness (Li et al. 2018a). The appropriate pore size and shape of MOFs is not enough for the effective capture of harmful gases or vapors. Special interactions between hazardous gases and the adsorbents are desirable. Therefore, the effective synthesis rules for MOFs should be aimed at specific surface chemistry of MOFs, rather than only optimizing surface area (Barea et al. 2014). The degradation of hazardous gases into nontoxic substances could be considered as an ideal method for air purification because it could overcome the problems of adsorbent saturation and secondary pollution (Barea et al. 2014). In addition, the possible mechanisms of removing toxic gases over MOFs is not quite clear. Further research is stilled needed to understand the mechanism for removal of toxic gases by MOFs, to further improve the stability and recyclability of MOFs, to improve photocatalytic efficiency and the selectivity for highly toxic gaseous pollutants (Wen et al. 2019).

MOFs for removal of pollutants from the liquid phase

The occurrence of various pollutants in an aquatic environment has also attracted worldwide attention. The common pollutants in an aquatic environment mainly include organic pollutants, heavy metals and new emerging contaminants. On account of its importance to ecology and environment, the removal of pollutants with high toxicity and hard degradable properties from an aquatic environment is of great importance. MOFs are attractive candidates for the removal of pollutants in the liquid phase.

Several water-stable MOFs have been studied to remove various pollutants from wastewater. MOFs used for adsorption of pharmaceuticals and personal care products, veterinary drugs, industrial emerging contaminant and miscellaneous organic contaminants from aquatic systems were reviewed and summarized by Dhaka et al. (2019). Some new advances for the removal of heavy metals and organic pollutants from the liquid phase by MOFs are shown in Table 9. Xiong et al.

Table 8 Removal of toxic gases by MOFs

Toxic gases	MOFs	Conditions	Q_{max} (mg/g)	Reference
H_2S	MIL-101(Cr)	303.1 K, 20 bar	1308.52	(Hamon et al. 2009)
	MIL-100(Cr)	303.1 K, 20 bar	569.07	(Hamon et al. 2009)
	MIL-47(V)	303.1 K, 20 bar	497.51	(Hamon et al. 2009)
	TEA/MOF-199	303 K	93.37	(Zhang et al. 2019)
	MOF-199	303 K	56.91	(Zhang et al. 2019)
	Zn-MOF-74	298 K, 1 bar	55.88	(Liu et al. 2017)
	MOF-5	298 K, 1 bar	37.82	(Liu et al. 2017)
	UiO-66-NH_2	298 K, 1 bar	30.96	(Liu et al. 2017)
	MIL-100(Fe) gel	298 K, 1 bar	30.67	(Liu et al. 2017)
SO_2	MOF-177	293 K, 0.97 bar	1646.34	(Brandt et al. 2019)
	NH_2-MIL-125(Ti)	293 K, 0.95 bar	368.02	(Brandt et al. 2019)
	MIL-160	293 K, 0.97 bar	245.35	(Brandt et al. 2019)
	MFM-300(In)	298 K and 1 bar	539.42	(Savage et al. 2016)
	MOF-74	298 K	194	(Britt et al. 2008)
	MOF-199	298 K	32	(Britt et al. 2008)
NH_3	IRMOF-3	298 K	105	(Britt et al. 2008)
	MOF-74	298 K	93	(Britt et al. 2008)
	MOF-199	298 K	87	(Britt et al. 2008)
	MOF-177	298 K	42	(Britt et al. 2008)
CO	MOF-74-Ni	298 K, 1 bar	169.18	(Bloch et al. 2014)
	MOF-74-Co	298 K, 1 bar	166.66	(Bloch et al. 2014)
	MOF-74-Fe	298 K, 1 bar	162.18	(Bloch et al. 2014)
	MOF-177	194.5 K and 1.08 bar	129.97	(Saha and Deng 2009)
	MOF-177	237 K and 1.08 bar	84.03	(Saha and Deng 2009)
	HKUST-1	298 K,1 bar	40.61	(Chowdhury et al. 2012)
	MIL-101(Cr)	298 K,1 bar	28.85	(Wang et al. 2014b)
	$CuAlCl_4$ doped MIL-101(Cr)	298 K,1 bar	63.30	(Wang et al. 2014b)
	MIL-100(Fe)	298 K,1 bar	10.64	(Peng et al. 2015)
	Cu(I)@MIL-100(Fe)	298 K,1 bar	77.87	(Peng et al. 2015)
NO	MIL-88A	298 K	75.03	(McKinlay et al. 2013)
	MIL-88B	298 K	48.02	(McKinlay et al. 2013)
	MIL-88-B-NO_2	298 K	30.01	(McKinlay et al. 2013)
NO_2	UiO-66-NH_2	293 K, moist condition	1400	(Peterson et al. 2016)
	UiO-66-NH_2	293 K, dry condition	930	(Peterson et al. 2016)
	HKUST-1	293 K, moist condition	1200	(Peterson et al. 2016)
	HKUST-1	293 K, dry condition	300	(Chowdhury et al. 2012)
	UiO-66	Room temperature, dry condition	73	(Ebrahim et al. 2013)
	UiO-66	Room temperature, moist condition	40	(Ebrahim et al. 2013)
	UiO-67	Room temperature, dry condition	79	(Ebrahim et al. 2013)
	UiO-67	Room temperature, moist condition	118	(Ebrahim et al. 2013)
Cl_2	IRMOF-3	298 K	335	(Britt et al. 2008)
	IRMOF-62	298 K	92	(Britt et al. 2008)

(2019) synthesized two novel lanthanide modified MOFs with good thermal and water stability, which also exhibited good selectivity for the separation of Th(IV) from REs(III). Liu et al. (2019) synthesized a water-stable copper-based MOF

Table 9 Removal of pollutants by MOFs from the liquid phase

Pollutants	MOFs	Conditions	Q_{max} (mg/g)	Reference
Heavy metals				
Hg^{2+}	PCN-221 MOF	Room temperature, pH 7.1, 30 min	233.65	(Seyfi Hasankola et al. 2020)
	UiO-66-EDTA	303 K, pH 5, 600 min	371.6	(Wu et al. 2019)
	UiO-66-DMTD	298 K, pH 3, 180 min	670.5	(Fu et al. 2019)
	TMU-31	Room temperature, pH 5, 20 min	476.19	(Hakimifar and Morsali 2019)
	TMU-32	Room temperature, pH 5, time 20 min	416	(Hakimifar and Morsali 2019)
Cd^{2+}	nFe_3O_4@MIL-88A(Fe)/APTMS	Room temperature, pH 6, 30 min	693.0	(Mahmoud et al. 2020)
	UiO-66-EDTA	303 K, pH 5, 600 min	237.2	(Wu et al. 2019)
Pb^{2+}	nFe_3O_4@MIL-88A(Fe)/APTMS	Room temperature, pH 6, 30 min	536.22	(Mahmoud et al. 2020)
	TMU-31 and TMU-32	Room temperature, pH 5, 5 min	909	(Hakimifar and Morsali 2019)
	UiO-66-EDTA	303 K, pH 5, 600 min	357.9	(Wu et al. 2019)
Cr(VI)	nFe_3O_4@MIL-88A(Fe)/APTMS	Room temperature, pH 2, 30 min	1092.22	(Mahmoud et al. 2020)
	Form-UiO-66	298 K, pH 2, 720 min	243.9	(Wang et al. 2019b)
	Ac-UiO-66	298 K, pH 2, 720 min	151.52	(Wang et al. 2019b)
Eu^{3+}	UiO-66-EDTA	303 K, pH 5, 600 min	195.2	(Wu et al. 2019)
Cu^{2+}	f-ZIF-8@GO	298 K, pH 6, 1440 min	1872.24	(Wei et al. 2019)
	UiO-66-EDTA	303 K, pH 5, 600 min	291.7	(Wu et al. 2019)
Ni^{2+}	UiO-66-EDTA	303 K, pH 5, 600 min	281.3	(Wu et al. 2019)
Mn^{2+}	UiO-66-EDTA	303 K, pH 5, 600 min	243.5	(Wu et al. 2019)
Organic pollutants				
Congo red	Ni-Zn MOF	303 K, 720 min	460.90	(Yang and Bai 2019)
	Ni MOF	303 K, 720 min	276.70	(Yang and Bai 2019)
	Zn MOF	303 K, 720 min	132.20	(Yang and Bai 2019)
Methyl orange	MIL-101(Cr)	298 K, pH 7	420.2	(Xu et al. 2019)
Diclofenac sodium	[Cu(BTTA)]n·2DMF	298 K, pH 6.5, 450 min	650	(Liu et al. 2019)
Bisphenol A	Cu-BDC@GrO	298 K, pH 4, 360 min	182.2	(Liu et al. 2019)
	Cu-BDC@CNT	298 K, pH 4, 360 min	164.1	(Ahsan et al. 2019)
Phosphate	UiO-66-NH_2	298 K, pH 4, 1440 min	153.9	(Guan et al. 2020)
	UiO-66-Br	298 K, pH 4, 1440 min	132.5	(Guan et al. 2020)
	UiO-66-NO_2	298 K, pH 4, 1440 min	117.7	(Guan et al. 2020)
	UiO-66	298 K, pH 4, 1440 min	74.5	(Guan et al. 2020)

and used for the removal of pharmaceutical drugs from an aqueous medium. This material displayed a much higher adsorption capacity towards diclofenac sodium. Sun et al. (2019) investigated the adsorption of two typical anti-inflammatory drugs (ibuprofen and naproxen) by two types of MOFs (UiO-66 and UiO-66-NH_2). The mechanism for the adsorption of ibuprofen and naproxen by MOFs was revealed according to experimental results and the calculation of density functional theory. Possible mechanisms for adsorptive removal of pollutants over MOFs are shown in Fig. 8. Four mechanisms were included in the simulation for the adsorption of ibuprofen and naproxen by MOFs, and the results showed that the binding energies of the four mechanisms followed the order of π-π interaction > hydrogen bonding > Lewis acid/base complexing > anion-π interaction. This study provided a new approach to further understand the removal mechanism of pollutants by MOFs.

In addition, the improvement of photocatalytic efficiency for pollutants by MOFs was also studied. He et al. (2019) reported a magnetic MIL-101(Fe)/TiO_2 material for photodegradation of tetracycline under sunlight. The results showed that the combination of MIL-101(Fe) with TiO_2 could improve the catalytic performance, which showed higher degradation efficiency of tetracycline and excellent reusability. Yu et al. (2019) combined photocatalysis of MOFs and ozone as electron acceptors to reduce the charge carrier recombination. MIL-88A(Fe) with a large number of Lewis acid sites and photo-response property showed an excellent photocatalytic

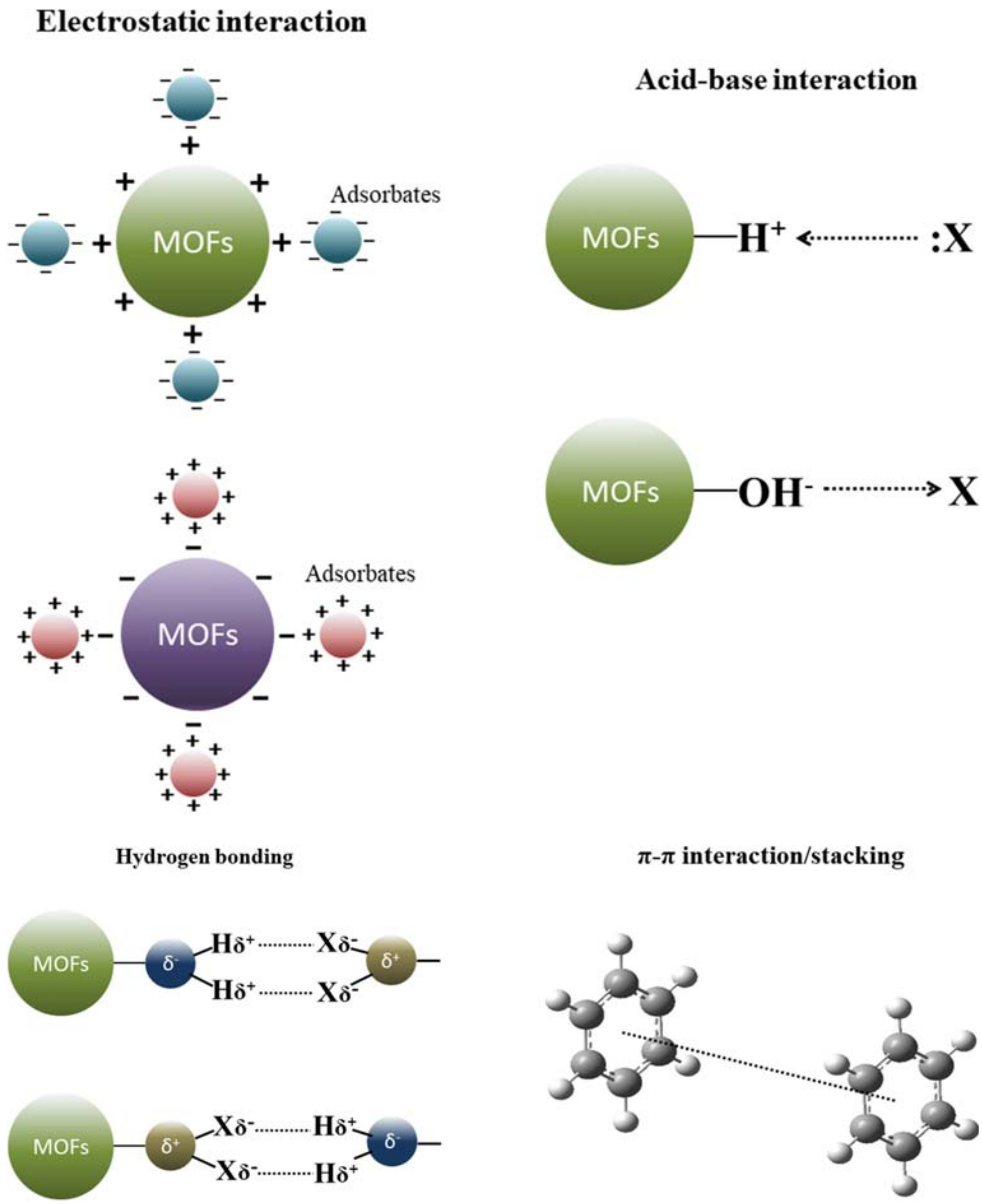

Fig. 8 Possible mechanisms for adsorptive removal of pollutants over MOFs (adopted from (Dhaka et al. 2019, Hasan &Jhung 2015))

ozonation activity due to O_3-induced synergic effect. In addition, it is reported that the combining of MOFs with graphitic carbon nitride could further improve the photocatalytic activity of the material under visible light or sunlight irradiation (Wang et al. 2019a). However, further study is still required to better understand the photocatalytic mechanisms of MOFs and the crucial structural characteristics of controlling their photocatalytic activity (Wang et al. 2014a).

Although a lot of efforts have been made to improve the performance of MOFs in removing pollutants from solution, there are still many challenges needed to be overcome. The removal mechanism of pollutants in the liquid phase by MOFs should be further studied to improve the capacity of existing MOFs and develop new types of MOFs. In addition, applications of MOFs in the real environment are usually limited by their poor stability due to the weak coordination between the metal and organic linkers (Dhaka et al. 2019). It is important to further improve the stability of MOFs while enhancing the capacity of MOFs. On the other hand, the high cost of MOFs would also limit the applications of MOFs. It is necessary to reduce the cost of MOFs through developing simple synthetic methods and easy regeneration methods (Dhaka et al. 2019). Thus, in order to realize the practical application of MOFs in environmental science, further research is still needed to improve the water stability and recyclability of MOFs, and reducing the cost for fabrication of MOFs.

Conclusions and perspective

MOFs have gained more and more attention in recent years in the field of environmental science due to their excellent properties. Bibliometric analysis was used in this study to review the overall development of MOFs in the field of environmental science. As a nascent field, the research on MOFs-ES has entered a fast-developing stage and it may get a faster development in the next few years. Though European and American countries started their research on MOFs-ES earlier, the obvious migration of centres of gravity for publications and citations was noteworthy due to the growing up of Asian countries. In the last decade, China has become the leading country with the largest number of publications. However, Asian countries such as China and South Korea should further strengthen their international cooperation. The information provided by this study could enhance collaboration among the groups working on research of MOFs-ES.

For future research of MOFs, new types of MOFs are still being synthesized and their environmental applications of MOFs are still being developed. In order to improve the capacity of MOFs for pollutants, the removal mechanism of pollutants by MOFs should be further studied. In addition, improving the water stability of MOFs is still a major challenge for their environmental application. What's more, in order to promote the wide applicability of MOFs, researchers must strive to minimize the cost of MOFs by developing simple synthetic methods, easy regeneration methods and sustainable disposal of waste materials.

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