Bibliometric analysis of adsorption technologies using carbon

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Abstract

Adsorption technologies using carbon are playing a more and more important role in environmental protection. Therefore, a bibliometric analysis was carried out based on all the 7,235 related journal articles published during 1991-2010, which were searched from the two JCR subject categories of environmental engineering and environmental science on Science Citation Index Expanded. The results showed that the annual number of articles increased from 76 in 1991 to 923 in 2010, and the related research were more acceptable by the journals in environmental engineering. *Journal of Hazardous Materials* was the most productive journal and the USA was the most productive country. The Chinese Academy of Sciences ranked top one in the number of publications among the institutes. The analysis of author keywords, words in title and KeyWords Plus revealed that carbon based adsorbents were most widely used in the removal of phenol, heavy metals, methylene blue, polycyclic aromatic-hydrocarbons, and humic substances. The adsorption thermodynamics, adsorption kinetics were usually investigated. In some applications, adsorbates should be treated by catalysts and oxidation before adsorption. Biosorption was an emerging hot spot.

Keywords: adsorption; carbon; scientometrics; SCI; research trend

1. Introduction

To remove the pollutants from water, air and soil, various treatment techniques and processes have been applied [1], among which adsorption has been considered as an effective, efficient and economic method [2]. Therefore, adsorbents with different properties have been developed, such as activated carbon [3], clay minerals [4], zeolites [5], metal oxides [6], biomass [7] and polymeric materials [8]. Among these adsorbents, activated carbons are undoubtedly most popular throughout the world [9-11]. They have been made from different materials [12,13], by different techniques [14,15], and into different forms [16,17]. Biomass, which also mainly consist of carbon [18,19], are emerging as economical alternate adsorbents because of their fastness, low cost, easy availability, mild operating conditions, high efficiency and no nutrient requirements [20]. Recently, carbon nanotubes, another kind of carbon based adsorbent, have been studied for their strong interactions with both heavy metal ions and organic compounds due to their surface functional groups and hydrophobic surfaces [21]. The carbon based adsorbents have been applied to remove wide range of contaminants, such as heavy metals [22-24], phenols [20,25,26], dyes [27-29] and pesticides [20,30,31], which means they have become necessary materials for some environment researchers.

Since adsorption technologies using carbon are playing such an important role and paid so much attention to in environmental protection, study of the related literature is greatly needed. A common research tool for this study is bibliometric analysis, which uses quantitative analysis and statistics to describe patterns of publication within a given field or body of literature. Bibliometric analysis has already been widely applied in many environmental aspects for the scientific production and research trends [32-34]. The Science Citation Index (SCI), from the Institute for Scientific Information (ISI) Web of Science databases, is the most frequently chosen source database for bibliometric analysis because of its broad content of scientific accomplishment in all fields [35,36]. Conventionally, bibliometric analysis [37] often investigates the publication outputs of countries, research institutes, journals, research fields and journal citations. Nowadays, more information, e.g. source titles, author keywords and KeyWords Plus, is introduced to comprehensively reveal the trends [38,39].

In this study, a bibliometric analysis was carried out by investigating not only the traditional factors, but also the innovative ones to describe the global research trends of adsorption technologies using carbon during the period of 1991-2010. Findings from these investigations can help researchers to realize the development and follow the hot spots of carbon adsorbents in environmental aspects.

2. Date Sources and Methodology

Documents used in this study were derived from the Science Citation Index-Expanded (SCI-Expanded) database of Institute of Scientific Information (ISI), the Thomson Reuters. According to Journal Citation Reports (JCR), it indexes 8,005 journals with citation references across 174 scientific disciplines in 2010. Two hundred and eleven journals listed in the two JCR subject categories of environmental engineering (n = 45) and environmental sciences (n = 192) were considered in this study. (Adsorption, sorption, and biosorption) and (carbon, carbons, charcoal, charcoals, and charcoalresin) were used as a keyword to search titles, abstracts, author keywords, and KeyWords Plus in 1991-2010. Articles originating from England, Scotland, Northern Ireland, and Wales were reclassified as being from the United Kingdom (UK) [40]. Articles from Hong Kong were included in the ones from China. Collaboration type was determined by the addresses of the authors, where the term "single country article" was assigned if the researchers' addresses were from the same country. The term "internationally collaborative article" was designated to those articles that were coauthored by researchers from multiple countries [2]. The term "single institute article" was assigned if the researchers' addresses were from the same institute. The term "inter-institutionally collaborative article" was assigned if authors were from different institutes [41]. The impact factor of a journal was determined for each document as reported in the JCR 2010.

3. Results and Discussions

3.1 Document Type and Language

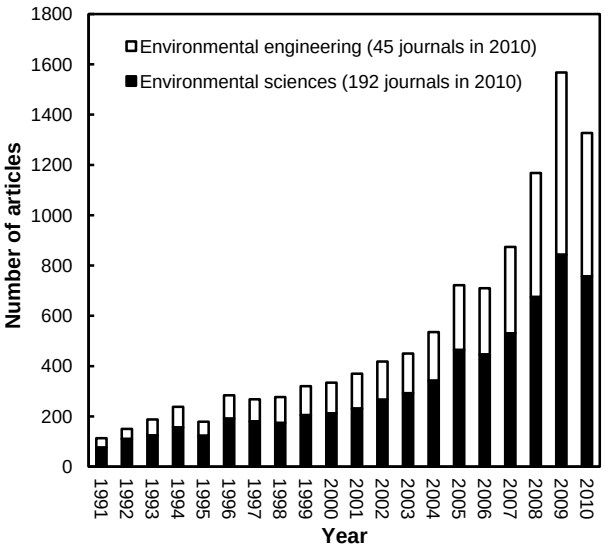
In total, 7,913 publications met the selection criteria mentioned, containing 8 document types. Journal article was the most frequently used document type and comprised 91% of 7,235 documents, followed distantly by proceedings paper (441; 5.6%). Others showing less significance were meeting review (176; 2.2%), editorial material (20; 0.25%), letter (17; 0.21%), note (14; 0.18%), correction (9; 0.11%) and reprint (1; 0.013%). As journal articles, which were peer-reviewed within this field, represented the majority of document types, 7,235 original articles were identified and further analyzed in the following study, while all the others were discarded.

These 7,235 articles were written in 7 languages. English, as the most popular language, comprised 99% of the total articles and was followed distantly by Polish (32; 0.44%) and French (28; 0.39%). Other languages that were less used were German (14), Spanish (4), Japanese (2) and Russian (1). Obviously, English was by far the dominant language in the journals listed in SCI-Expanded.

3.2 Publication Output

From 1991 to 2010, the annual number of articles related to adsorption technologies using carbon in environmental protection increased from 76 to 923. However, Fig. 1 shows that the annual number of articles did not increase monotonously during 1991-2010, with the acme number 1,018 reached in 2009.

Figure 1. Outputs of the publications during 1991-2010 and the distribution between the two categories.



The average number of authors, cited references and pages for each article in the year 1991 to 2010, together with the overall average

numbers of the three factors, are listed in Table 1. The overall average number of authors per article was 3.7, with the average number of authors for each article increasing from 2.8 in 1991 to 4.2 in 2010, indicating that the cooperation among authors was enhanced. With more and more related articles published, the average number of cited references increased from 25 in 1991 to 37 in 2010. While the average number of pages for each article decreased from 11in 1991 to 8.3 in 2010, with an overall average of 9.3 pages per article in the twenty years.

Table 1. Characteristics of articles for every year from 1991-2010.

Year	TP	AU/TP	NR/TP	PG/TP
1991	76	2.8	25	10
1992	112	3.1	24	11
1993	130	3.3	24	11
1994	161	2.9	25	11
1995	128	3.4	25	10
1996	203	3.2	27	11
1997	192	3.3	30	11
1998	192	3.4	28	10
1999	224	3.3	29	10
2000	226	3.4	29	10
2001	264	3.4	29	9.8
2002	288	3.5	31	10
2003	327	3.8	33	10
2004	381	3.7	34	9.6
2005	502	3.7	33	9.3
2006	496	3.7	34	9.1
2007	593	3.8	33	8.5
2008	799	3.9	35	8.5
2009	1018	3.9	36	7.9
2010	923	4.2	37	8.3
Average		3.7	33	9.3

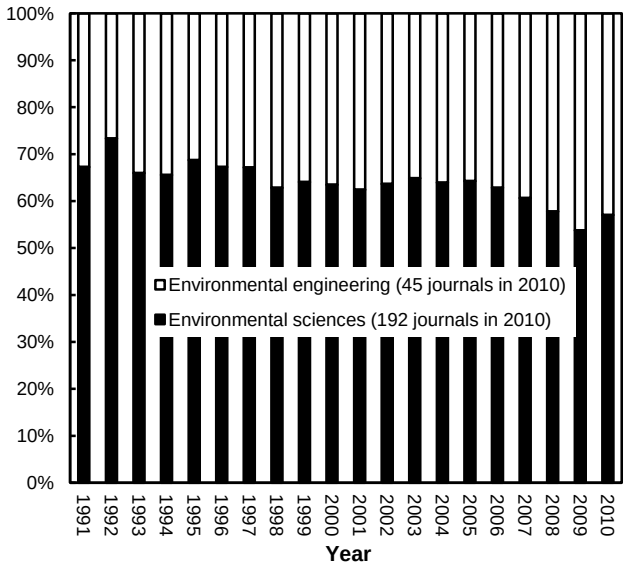
TP: number of articles; AU: number of authors; NR: cited reference count; PG: number of pages; AU/TP, NR/TP, and PG/TP: average number of authors, references, and pages per articles.

The average numbers of the three factors are listed in Table 1. The overall average number of authors per article was 3.7, with the average number of authors for each article increasing from 2.8 in 1991 to 4.2 in 2010, indicating that the cooperation among authors was enhanced. With more and more related articles published, the average number of cited references increased from 25 in 1991 to 37 in 2010. While the average number of pages for each article decreased from 11 in 1991 to 8.3 in 2010, with an overall average of 9.3 pages per article in the twenty years.

3.3 Category and Journal

Figure 1 shows that the annual numbers of articles related to carbon adsorbents published in both the categories of environmental science and environmental engineering increased during these years. From 1991 to 2010, the annual published articles in environmental science and environmental engineering had increased from 76 to 757 and from 37 to 570, respectively. Figure 2 shows that environmental engineering always had the smaller percentage of articles published than environmental science. However, taking the journal numbers of the two categories into consideration, the average number of articles per journal, for example in 2010, in environmental sciences (3.9) was less than in environmental engineering (12.7). That means articles related to carbon adsorbents were more acceptable by the journals in environmental engineering, which is confirmed by the rising ratio of the articles in engineering.

Figure 2. Comparison of the ratio between the publications of the two subject categories during 1991-2010.



In total, the 7,235 articles were published in 169 journals. Table 2 shows the top 10 journals, in which the most articles related carbon adsorbents were published, and their impact factors (IF). Approximately 66% of the carbon-adsorption articles reside in these 10 journals. *Journal of Hazardous Materials* ranked the first with 1,117 (15%) published papers, followed by *Environmental Science & Technology* with 841

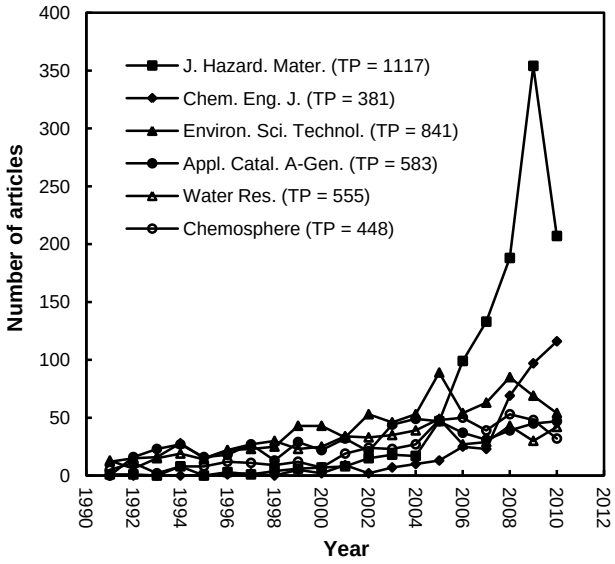
(12%) papers, which had the highest impact factor among the ten journals.

Table 2. The top 20 productive journals during 1991-2010.

Journals	Number of publications (%)	Impact factor
Journal of Hazardous Materials	1,117 (15)	3.723
Environmental Science & Technology	841 (12)	4.825
Applied Catalysis A-General	583 (8.1)	3.383
Water Research	555 (7.7)	4.546
Chemosphere	448 (6.2)	3.155
Chemical Engineering Journal	381 (5.3)	3.074
Applied Catalysis B-Environmental	326 (4.5)	4.749
Environmental Technology	198 (2.7)	1.007
Environmental Toxicology and Chemistry	162 (2.2)	3.026

Figure 3 shows the trends of annual number of publications of the top 6 productive journals in the twenty years. Before 2005, the six journals all had a slow rate of increasing in annual publications, and *Journal of Hazardous Materials* did not have a dominant position. After 2005, *Journal of Hazardous Materials* had a high increasing rate, with the annual publications of 47 in 2005 increasing to 207 in 2010. However it did not increase all the way up. The acme was reached in 2009, in which the annual publications was as high as 354. While the other five journals had a much slower growth after 2005, *Journal of Hazardous Materials* had ranked top one since 2006. It is also impressive that *Chemical Engineering Journal* had a high increasing rate after 2007; hence its annual publications reached the second place in 2010.

Figure 3. Comparison of the growth trends of the top six productive journals during 1991-2010.



3.4 Country of Publication

The analysis of authors' countries and institutions was restricted to the total 7,226 articles, because the other 9 articles did not have the information about the authors' addresses in SCI-Expanded. Table 3 shows the top 10 countries/territories ranked by the number of articles. Among the 7,226 articles with author address information, international collaborations accounted for 18% of the articles, compared to 82% from single country. Totally there were 103 countries publishing articles about adsorption technologies using carbon in the twenty years. Twenty four countries had no single-country articles and six had no internationally collaborative articles. Five indicators, namely total number of articles, independent, collaborative, first author, and corresponding author articles by countries and institutions were innovatively used recently to explore the contribution of scientific researches, providing diversified information for evaluation [33,41]. In this research, the five indicators were also investigated. The USA ranked top one on all indicators, with total number of 1,853 (26%), single-country publications of 1,388 (23%), internationally collaborative publications of 465 (37%), first author publications of 1,612 (22%), and corresponding author publications of 1,449 (21%). This result is usual, as the USA was top in most research fields in publications [42,43]. Moreover, only five countries (the USA, the UK, France, Japan and Germany) of G7 (the USA, Germany, the UK, Japan, France, Canada, and Italy) were listed in the top ten most productive countries, while Canada ranked 12 with 271 articles and Italy ranked 16 with 156 articles.

G7 had high productivity in total articles (50%), independent articles (43%), and collaborative articles (79%). It is obvious that G7 had a leading place in developing adsorption technologies using carbon, especially in international cooperating.

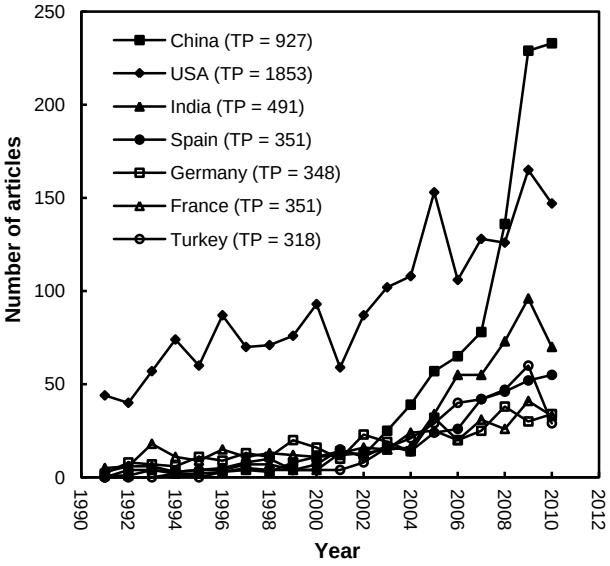
Table 3. The top 10 most productive countries during 1991-2010.

Country	TP	TP rank (%)	SP rank (%)	CP rank (%)	FP rank (%)	RP rank (%)
USA	1,853	1 (26)	1 (23)	1 (37)	1 (22)	1 (21)
China	927	2 (13)	2 (11)	2 (21)	2 (11)	2 (12)
India	491	3 (6.8)	3 (6.9)	10 (6.1)	3 (6.3)	3 (6.5)
France	351	4 (4.9)	8 (3.6)	4 (11)	7 (3.8)	8 (3.4)
Spain	351	4 (4.9)	6 (4.1)	6 (8.3)	5 (4.0)	5 (4.0)
Germany	348	6 (4.8)	9 (3.3)	3 (12)	9 (3.4)	9 (3.3)
Turkey	318	7 (4.4)	4 (4.9)	23 (2.3)	4 (4.2)	4 (4.4)
Japan	317	8 (4.4)	7 (3.8)	8 (7.1)	8 (3.8)	7 (3.9)
Taiwan	297	9 (4.1)	5 (4.2)	14 (3.8)	6 (3.8)	6 (4.0)

TP: number of total articles; SP: single institute articles: CP: inter-institutionally collaborative articles; FP: first author articles; RP: corresponding author articles.

Meanwhile, China ranked the second on all indicators and had the highest increasing rate among the top ten countries, with the number of annual total publications increased from 1 in 1991 to 233 in 2010. Figure 4 shows the comparison of the publication trends of the top seven countries. Most of these countries had a sharp increase in articles after 2002, while the USA had a winding rise. In 2008-2010, China ranked top one in annual number of total publications.

Figure 4. Comparison of the growth trends of the top seven productive countries during 1991-2010.



3.5 Institute of Publication

The 7,226 articles with author information were submitted by 3,661 institutes, among which 2,199 institutes published only one article, 996 published two articles, and 687 published three articles. Of the 7,226 articles, 3,811 (53%) were single-institution articles and 3,415 (47%) were inter-institution articles. Table 4 shows the top 21 institutes which were ranked by the number of articles, including their number and percentage of total articles, single institute articles and inter-institution articles, as well as first and corresponding author articles. These indicators were used in recent researches to evaluate the performance of the institutes [44]. Among the top 21 institutes, the USA had 8 (38%), China had 6 (29%), Spain had 2 (9.5%), India, Taiwan, Malaysia, Portugal and Sweden had 1 (4.8%) each. Leading was the Chinese Academy of Sciences in China (200), followed by Institute de Ciències del Mar (CSIC) in Spain (102) and Indian Institute of Technology in India (100).

Moreover, in the top 21 most productive institutes, U.S Environmental Protection Agency, the University of Illinois (USA) and National Taiwan University (Taiwan) had relative higher ranks of single institute articles than that of inter-institution articles. The University of Massachusetts (USA), the University of Cincinnati (USA), Peking University (China) and Stockholm University (Sweden) had much higher ranks of single-institution articles than that of inter-institutionally collaborative articles.

Table 4. The top 20 most productive institutes during 1991-2010.

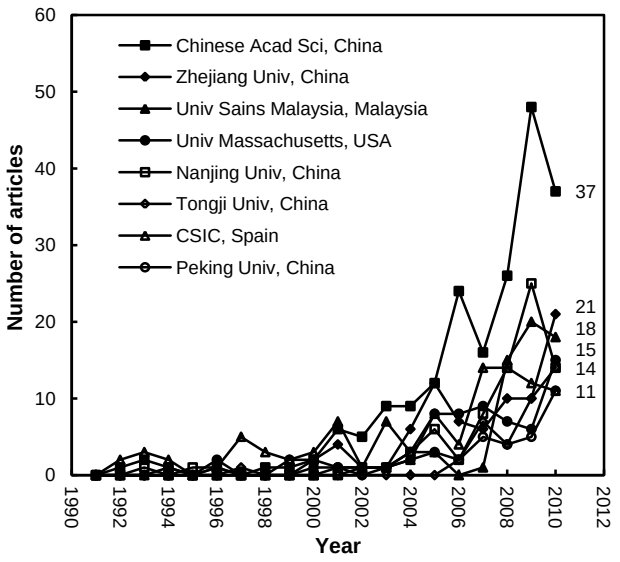
Institute	TP	TP rank (%)	SP rank (%)	CP rank (%)	FP rank (%)	RP rank (%)
Chinese Academy of Sciences, China	200	1 (2.8)	1 (1.8)	1 (3.8)	1 (2.1)	1 (2.2)
Consejo Superior de Investigaciones Cientificas (CSIC), Spain	102	2 (1.4)	4 (1.1)	3 (1.8)	3 (1.0)	3 (1.0)
Indian Institutes of Technology, India	100	3 (1.4)	2 (1.7)	11 (1.1)	2 (1.2)	2 (1.2)
U.S. Environmental Protection Agency, USA	94	4 (1.3)	12 (0.6)	2 (2.1)	8 (0.71)	8 (0.72)
University of Illinois, USA	84	5 (1.2)	10 (0.63)	3 (1.8)	7 (0.79)	7 (0.76)
Zhejiang University, China	82	6 (1.1)	6 (0.84)	6 (1.5)	4 (0.84)	4 (0.86)
Nanjing University, China	77	7 (1.1)	7 (0.76)	8 (1.4)	4 (0.84)	4 (0.86)
National Taiwan University, Taiwan	66	8 (0.91)	24 (0.42)	6 (1.5)	10 (0.53)	11 (0.54)
Universiti Sains Malaysia, Malaysia	62	9 (0.86)	3 (1.3)	86 (0.35)	6 (0.80)	6 (0.83)
Hong Kong University of Science & Technology, Hong Kong	61	10 (0.84)	5 (1.0)	19 (0.67)	9 (0.61)	9 (0.66)
University of Massachusetts, USA	61	10 (0.84)	79 (0.21)	5 (1.6)	12 (0.50)	12 (0.50)
U.S. Geological Survey, USA	59	12 (0.82)	20 (0.45)	10 (1.2)	14 (0.46)	13 (0.45)
U.S. Army Engineering Research and Development Center, USA	49	13 (0.68)	166 (0.13)	9 (1.3)	28 (0.33)	25 (0.34)
University of Porto, Portugal	47	14 (0.65)	10 (0.63)	19 (0.67)	10 (0.53)	10 (0.56)
University of Cincinnati, USA	47	14 (0.65)	55 (0.26)	11 (1.1)	14 (0.46)	33 (0.29)
University of Michigan, USA	47	14 (0.65)	8 (0.68)	27 (0.61)	13 (0.48)	29 (0.31)
University of Granada, Spain	40	17 (0.55)	18 (0.50)	27 (0.61)	19 (0.40)	16 (0.41)
Pennsylvania State University, USA	40	17 (0.55)	12 (0.60)	45 (0.50)	14 (0.46)	19 (0.40)
Peking University, China	39	19 (0.54)	46 (0.29)	14 (0.82)	23 (0.36)	24 (0.35)
Tongji University, China	38	20 (0.53)	24 (0.42)	24 (0.64)	17 (0.44)	13 (0.45)
Stockholm University, Sweden	38	20 (0.53)	98 (0.18)	13 (0.91)	39 (0.29)	33 (0.29)

TP: number of total top articles; SP: single institute articles: CP: inter-institutionally collaborative articles; FP: first author articles; RP: corresponding author articles

The University of Massachusetts (USA), the University of Cincinnati (USA), Peking University (China) and Stockholm University (Sweden) had much higher ranks of single-institution articles than that of inter-institutionally collaborative articles. It seems that the institutes mentioned above tended to do research independently. On the contrary, University Sains Malaysia (Malaysia) and Pennsylvania State University (USA) ranked higher in inter-institution articles than in single institute articles, which means they preferred collaborative research.

The trends of annual publications of the top eight institutes are revealed in Fig. 5. All the eight institutes had increased in their annual publications in the twenty years. The Chinese Academy of Sciences grew sharply after 2003 and it always had the highest increasing rate, followed by the Nanjing University in China and the University Sains Malaysia.

Figure 5. Comparison of the growth trends of the top eight productive institutes during 1991-2010.



3.6 Distribution of Title Words, Author Keywords and KeyWords Plus

Author keywords can provide information about the articles from the views of the authors. However, not all the articles have author keywords. In the total of 7,235 articles, only 5,614 articles have author keywords. Based on these 5,614 articles, 11,430 author keywords were provided, with 11,051 used less than 10 times, meaning that most author keywords were rarely used. Table 5 shows the top 30 author keywords which were most frequently used. The frequencies of the top 30 author keywords in the 20 years and in each five years are also presented.

Except the author keywords used in this search (adsorption, sorption, biosorption and carbon), the other words listed in the top 30 author keywords were classified by their research objects. In the adsorption mechanism, the researchers usually related to the adsorption thermodynamics ("thermodynamics", "isotherm", "adsorption isotherm", and "isotherms") and adsorption kinetics ("kinetics" and "adsorption kinetics"). In the adsorbent, the activated carbon ("activated carbon" and "granular activated carbon") was popular. In the environmental issues dealt with, soil and waste water treatment ("water treatment", "wastewater", and "wastewater treatment") were the common concerns. In the adsorbed substances, phenol, heavy metals ("cooper" and "heavy metals") and Methylene blue were focused.

According to the frequency analysis of the author keywords in every five years, some research focus changed its word forms. Take an example of adsorption isotherms. In 1991 to 1995 the majority of authors used "isotherms" as the keyword, while most authors in 1996 to 2000 used "adsorption isotherm" or "isotherm". In 2001 to 2005 the three kinds of keywords had almost the same frequency. And in 2006 to 2010, the frequency of the three keywords all increased, and most authors tended to use "isotherm" as the keyword.

Meanwhile, some keywords had a significant increase in the twenty years, such as biosorption. In 1991 to 1995, it ranked 111 with the frequency of 0.3%; while in 2006 to 2010, it ranked 6 with the frequency of 3.3%. Therefore, biosorption was an emerging hot spot in recent years.

Since 1,701 articles had no author keywords, the analysis of words in titles is necessary to fulfill the investigation of the research trend. In the top 30 words in titles, some words such as "effect" and "influence" had little meaning in investigating the research trend. By comparing the top 30 words in title and the top 30 author keywords (Table 6), it can be found that most words were the same in both, while some words such as "catalysts", "catalytic" and "oxidation" appeared only in titles. The papers with these

three words in title usually related to the process of adsorptions of heavy metals, in which the metal ions had to be oxidated with catalysts [45-47]. Some papers investigated the roles of activated carbon in wet oxidation of phenols to remove them [48,49]. And some other papers revealed the properties of catalysts to oxidate the carbon monoxide by adsorbing it [50].

Table 5. Top 30 most frequently used author keywords during 1991–2010 and 4 five-year periods.

Author keywords	TP	91-10 R (%)	91-95 R (%)	96-00 R (%)	01-05 R (%)	06-10 R (%)
adsorption	1,505	1 (27)	1 (19)	1 (19)	1 (25)	1 (29)
activated carbon	742	2 (13)	2 (12)	2 (12)	2 (13)	2 (13)
sorption	411	3 (7.3)	3 (10)	3 (10)	3 (7.4)	4 (7.0)
kinetics	343	4 (6.1)	5 (3.9)	5 (3.9)	4 (3.6)	3 (7.8)
desorption	167	5 (3.0)	7 (3.0)	4 (4.2)	5 (2.6)	7 (2.9)
isotherm	150	6 (2.7)	111 (0.59)	39 (1.0)	41 (1.0)	5 (3.9)
phenol	143	7 (2.5)	7 (3.3)	8 (3.1)	9 (2.2)	8 (2.5)
biosorption	128	8 (2.3)	111 (0.3)	88 (0.59)	37 (1.1)	6 (3.3)
biodegradation	115	9 (2.0)	4 (4.2)	6 (3.6)	13 (1.8)	21 (1.6)
soil	111	10 (2.0)	17 (1.6)	12 (2.2)	7 (2.3)	16 (1.8)
copper	110	11 (2.0)	7 (3.1)	15 (1.8)	6 (2.4)	18 (1.7)
adsorption isotherm	108	12 (1.9)	238 (0.15)	15 (1.8)	27 (1.3)	10 (2.4)
isotherms	108	12 (1.9)	25 (1.3)	134 (0.45)	21 (1.4)	9 (2.5)
sediment	106	14 (1.9)	25 (1.2)	11 (2.4)	18 (1.6)	14 (2.0)
heavy metals	106	14 (1.9)	67 (0.74)	29 (1.2)	12 (2.0)	12 (2.1)
water treatment	99	16 (1.8)	15 (1.8)	29 (1.2)	8 (2.3)	19 (1.6)
wastewater	99	16 (1.8)	N/A	22 (1.3)	11 (2.0)	15 (1.9)
granular activated carbon	99	16 (1.8)	6 (3.6)	7 (3.3)	9 (2.2)	33 (1.1)
methylene blue	87	19 (1.5)	N/A	453 (0.15)	86 (0.6)	10 (2.4)
adsorption kinetics	82	20 (1.5)	25 (1.3)	88 (0.59)	36 (1.1)	17 (1.8)
wastewater treatment	78	21 (1.4)	N/A	22 (1.3)	19 (1.5)	24 (1.5)
thermodynamics	77	22 (1.4)	N/A	453 (0.15)	86 (0.6)	13 (2.1)
dissolved organic carbon	73	23 (1.3)	38 (1.0)	12 (2.2)	16 (1.7)	39 (1.0)
natural organic matter	73	23 (1.3)	67 (0.74)	19 (1.6)	24 (1.4)	28 (1.3)

KeyWords Plus were given by SCI to evaluate the researches comprehensively, and totally 6,974 articles had KeyWords Plus. In Table 6 were listed the top 30 most frequently used KeyWords Plus, most of which were also listed in the top 30 author keywords. However, the differences could add up to the information of research trend. For instance, the KeyWords Plus showed us that "polycyclic aromatic-hydrocarbons" and "humic substances" were also the hot spots in the last twenty years.

4. Conclusions

In this study on the 7,913 journal articles related to carbon adsorption, which were published in the categories of environmental science and environmental engineering in SCI-Expanded from 1991 to 2010, bibliometric analysis was carried out by investigating publication outputs of countries, research institutes, journals, research fields, journal citations, source titles, author keywords and KeyWords Plus. Some findings were obtained on worldwide research performance and trend.

For the articles, English was the dominant language. The annual number of publications in environmental science and environmental engineering both increased a lot, which indicated that the attention paid to adsorption technologies using carbon to address

environmental issues had been increasing. *Journal of Hazardous Materials* was the most productive journal and the USA was the most productive country. However, publications of Journal of Hazardous Materials decreased greatly in 2009 and the USA was surpassed by China in 2008. The Chinese Academy of Sciences ranked top one in the number of publications among the institutes. The analysis of author keywords, words in title and KeyWords Plus revealed that carbon based adsorbents were most widely used in the removal of phenol, heavy metals methylene blue, polycyclic aromatic-hydrocarbons, and humic substances. The adsorption thermodynamics, adsorption kinetics were usually investigated. In some applications, adsorbates should be treated by catalysts and oxidation before adsorption. Biosorption was an emerging hot spot.

Table 6. Comparisons among the top 30 most used author keywords, words in title and KeyWords Plus during 1991-2010.

Rank	Author keywords	Words in title	KeyWords Plus
1	adsorption	carbon	adsorption
2	activated carbon	adsorption	sorption
3	sorption	activated	activated carbon
4	kinetics	removal	removal
5	desorption	organic	water
6	isotherm	sorption	waste-water
7	phenol	aqueous	kinetics
8	biosorption	water	carbon
9	biodegradation	soil	aqueous-solutions
10	soil	effect	aqueous-solution
11	copper	catalysts	equilibrium
12	adsorption isotherm	solution	degradation
13	isotherms	soils	polycyclic aromatic-hydrocarbons
14	sediment	treatment	sediments
15	heavy metals	matter	oxidation
16	water treatment	solutions	heavy-metals
17	wastewater	effects	matter
18	granular activated carbon	wastewater	desorption
19	Methylene blue	oxidation	soils
20	adsorption kinetics	kinetics	biosorption
21	wastewater treatment	compounds	surface
22	thermodynamics	acid	humic substances
23	dissolved organic carbon	surface	adsorbents
24	natural organic matter	natural	soil
25	ozone	carbons	carbon-monoxide
26	lead	equilibrium	ions
27	chromium	granular	organic-matter
28	cadmium	catalytic	transport
29	regeneration	influence	black carbon
30	equilibrium	sediments	acid

References

[1] Jeffrey PJ WR, Aarne VP. Environmental Pollution and Control, 4th ed. Vol. 106-119, 299-314. 1998: Butter Worth-Heinemann.

[2] Ho YS. (2007) Bibliometric analysis of adsorption technology in environmental science, Journal of Environmental Protection Science;1:1-11.

[3] Alam MZ, Muyibi SA, Mansor MF, Wahid R. (2007) Activated carbons derived from oil palm empty-fruit bunches: Application to environmental problems, J. Environ. Sci.;19:103-108.

[4] Sanchez-Martin MJ, Rodriguez-Cruz MS, Andrades MS, Sanchez-Camazano M. (2006) Efficiency of different clay minerals modified with a cationic surfactant in the adsorption of pesticides: Influence of clay type and pesticide hydrophobicity, Appl. Clay Sci.;31:216-228.

[5] Walton KS, Abney MB, Le Van MD. (2006) CO_2 adsorption in Y and X zeolites modified by alkali metal cation exchange, Microporous Mesoporous Mat.;91:78-84.

[6] Dong DM, Nelson YM, Lion LW, Shuler ML, Ghiorse WC. (2000) Adsorption of Pb and Cd onto metal oxides and organic material in natural surface coatings as determined by selective extractions: New evidence for the importance of Mn and Fe oxides, Water Res.;34:427-436.

[7] GardeaTorresdey JL, Tiemann KJ, Gonzalez JH, Henning JA, Townsend MS. (1996) Ability of silica-immobilized Medicago sativa (alfalfa) to remove copper ions from solution, J. Hazard. Mater.;48:181-190.

[8] Zhang AY, Wei YZ, Kumagai M. (2004) Synthesis of a novel macroporous silica-based polymeric material containing 4,4',(5')-di(tert-butylcyclohexano)18-crown-6 functional group and its adsorption mechanism for strontium, React. Funct. Polym.;61:191-202.

[9] Yang RT H-MA, Adsorbents: Fundamentals and Applications. 2003: John Wiley & Sons.

[10] Dabrowski A. (2001) Adsorption - from theory to practice, Adv. Colloid Interface Sci.;93:135-224.

[11] Babel S, Kurniawan TA. (2003) Low-cost adsorbents for heavy metals uptake from contaminated water: A review, J. Hazard. Mater.;97:219-243.

[12] Malik PK. (2003) Use of activated carbons prepared from sawdust and rice-husk for adsorption of acid dyes: A case study of Acid Yellow 36, Dyes Pigment.;56:239-249.

[13] Ahmadpour A, Do DD. (1997) The preparation of activated carbon from macadamia nutshell by chemical activation, Carbon;35:1723-1732.

[14] Jagtoyen M, Derbyshire F. (1998) Activated carbons from yellow poplar and white oak by H_3PO_4 activation, Carbon;36:1085-1097.

[15] Lozano-Castello D, Lillo-Rodenas MA, Cazorla-Amoros D, Linares-Solano A. (2001) Preparation of activated carbons from Spanish anthracite I. Activation by KOH, Carbon;39:741-749.

[16] Aygun A, Yenisoy-Karakas S, Duman I. (2003) Production of granular activated carbon from fruit stones and nutshells and evaluation of their physical, chemical and adsorption properties, Microporous Mesoporous Mat.;66:189-195.

[17] Kadirvelu K, Faur-Brasquet C, Le Cloirec P. (2000) Removal of Cu(II), Pb(II), and Ni(II) by adsorption onto activated carbon cloths, Langmuir;16:8404-8409.

[18] Mousavi HZ, Seyedi SR. (2011) Nettle ash as a low cost adsorbent for the removal of nickel and cadmium from wastewater, Int. J. Environ. Sci. Technol.;8:195-202.

[19] Farooq U, Kozinski JA, Khan MA, Athar M. (2010) Biosorption of heavy metal ions using wheat based biosorbents: A review of the recent literature, Bioresour. Technol.;101:5043-5053.

[20] Aksu Z. (2005) Application of biosorption for the removal of organic pollutants: A review, Process Biochem.;40:997-1026.

[21] Ren X, Chen C, Nagatsu M, Wang X. (2011) Carbon nanotubes as adsorbents in environmental pollution management: A review, Chem. Eng. J.;170:395-410.

[22] Kadirvelu K, Thamaraiselvi K, Namasivayam C. (2001) Adsorption of nickel(II) from aqueous solution onto activated carbon prepared from coirpith, Sep. Purif. Technol.;24:497-505.

[23] Veglio F, Beolchini F, (1997). Removal of metals by biosorption: A review, Hydrometallurgy;44:301-316.

[24] Di ZC, Ding J, Peng XJ, Li YH, Luan ZK, Liang J. (2006) Chromium adsorption by aligned carbon nanotubes supported ceria nanoparticles, Chemosphere;62:861-865.
[25] Dabrowski A, Podkoscielny P, Hubicki Z, Barczak M. (2005) Adsorption of phenolic compounds by activated carbon: A critical review, Chemosphere;58:1049-1070.
[26] Lin D, Xing B. (2008) Adsorption of phenolic compounds by carbon nanotubes: Role of aromaticity and substitution of hydroxyl groups, Environ. Sci. Technol.;42:7254-7259.
[27] Choy KKH, McKay G, Porter JF. (1999) Sorption of acid dyes from effluents using activated carbon, Resour. Conserv. Recycl.;27:57-71.
[28] Fu YZ, Viraraghavan T. (2001) Fungal decolorization of dye wastewaters: A review, Bioresour. Technol.;79:251-262.
[29] Lawrence NS, Wang J. (2006) Chemical adsorption of phenothiazine dyes onto carbon nanotubes: Toward the low potential detection of NADH, Electrochem. Commun.;8:71-76.
[30] Hameed BH, Salman JM, Ahmad AL. (2009) Adsorption isotherm and kinetic modeling of 2,4-D pesticide on activated carbon derived from date stones, J. Hazard. Mater.;163:121-126.
[31] Yan XM, Shi BY, Lu JJ, Feng CH, Wang DS, Tang HX. (2008) Adsorption and desorption of atrazine on carbon nanotubes, J. Colloid Interface Sci.;321:30-38.
[32] Li J, Wang MH, Ho YS. (2011) Trends in research on global climate change: A Science Citation Index Expanded-based analysis, Glob. Planet. Change;77:13-20.
[33] Zhang G, Xie S and Ho YS. (2010) A bibliometric analysis of world volatile organic compounds research trends, Scientometrics;83:477-492.
[34] Ho YS. (2008) Bibliometric analysis of biosorption technology in water treatment research from 1991 to 2004, Int. J. Environ. Pollut.;34:1-13.
[35] Bayer AE, Folger FJ. (1966) Some correlates of a citation measure of productivity in science, Sociol. Educ.;39:381-390.
[36] Braun T, Schubert AP, Kostoff RN. (2000) Growth and trends of fullerene research as reflected in its journal literature, Chem. Rev.;100:23-37.
[37] Glanzel W, Moed HF. (2002) Journal impact measures in bibliometric research, Scientometrics;53:171-193.
[38] Kostoff RN, Toothman DR, Eberhart HJ, Humenik JA. (2001) Text mining using database tomography and bibliometrics: A review, Technol. Forecast. Soc. Chang.;68:223-253.
[39] Chiu WT, Ho YS. (2007) Bibliometric analysis of tsunami research, Scientometrics;73:3-17.
[40] Chiu WT, Ho YS. (2005) Bibliometric analysis of homeopathy research during the period of 1991 to 2003, Scientometrics;63:3-23.
[41] Mao N, Wang MH, Ho YS. (2010) A bibliometric study of the trend in articles related to risk assessment published in Science Citation Index, Hum. Ecol. Risk Assess.;16:801-824.
[42] Schubert A. (1998) The profile of the Chemical Engineering Journal and Biochemical Engineering Journal as reflected in its publications, references and citations, 1983-1996, Chem. Eng. J.;69:151-156.
[43] Marx W, Cardona M. (2003) The impact of Solid State Communications in view of the ISI Citation data, Solid State Commun.;127:323-336.
[44] Ho YS, Satoh H, Lin SY. (2010) Japanese lung cancer research trends and performance in Science Citation Index, Intern. Med.;49:2219-2228.
[45] Bissen M, Frimmel FH. (2003) Arsenic: a review. Part II: Oxidation of arsenic and its removal in water treatment, Acta Hydrochim. Hydrobiol.;31:97-107.
[46] Lucking F, Koser H, Jank M, Ritter A. (1998) Iron powder, graphite and activated carbon as catalysts for the oxidation of 4-chlorophenol with hydrogen peroxide in aqueous solution, Water Res.;32:2607-2614.
[47] Leupin OX, Hug SJ. (2005) Oxidation and removal of arsenic (III) from aerated groundwater by filtration through sand and zero-valent iron, Water Res.;39:1729-1740.
[48] Chen H, Sayari A, Adnot A, Larachi F. (2001) Composition-activity effects of Mn-Ce-O composites on phenol catalytic wet

oxidation, Appl. Catal. B-Environ.;32:195-204.
[49] Fortuny A, Font J, Fabregat A. (1998) Wet air oxidation of phenol using active carbon as catalyst, Appl. Catal. B-Environ.;19:165-173.
[50] Bollinger MA, Vannice MA. (1996) A kinetic and DRIFTS study of low-temperature carbon monoxide oxidation over Au-TiO_2 catalysts, Appl. Catal. B-Environ.;8:417-443.