Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2013.812991

52 (2014) 6040–6049
September

Taylor & Francis
Taylor & Francis Group

A bibliometric investigation of research trends on sulfate removal

Zhengfang Ye[a,*], Baogang Zhang[b,*], Ye Liu[b], Jing Zhang[b], Zhongyou Wang[a], Haitao Bi[a]

[a]*The Key Laboratory of Water and Sediment Sciences, Ministry of Education, Department of Environmental Engineering, Peking University, Beijing 100871, China*
Tel. +86 10 62755862; Fax: +86 10 62755862; email: yezhengfang@iee.pku.edu.cn
[b]*Key Laboratory of Groundwater Circulation and Evolution, Ministry of Education, School of Water Resources and Environment, China University of Geosciences, Beijing 100083, China*
Tel. +86 10 82322281; Fax: +86 10 82321081; email: zbgcugb@gmail.com

Received 27 January 2013; Accepted 31 May 2013

ABSTRACT

Sulfate contamination has become a global problem, which attracts wide concern of researchers in this field. In this study, a bibliometric analysis was employed to analyze the scientific outputs on sulfate removal, in terms of source countries, institutes, distribution of words in titles, author keywords, KeyWords Plus. Three categories including removal field, removal methods, and products have further contributed to revealing the research trends in the past 20 years, based on the online version of Science Citation Index Expanded, Web of Science from 1991 to 2010. It is concluded that researchers have paid most attention to desulfuration in water. This would probably continue as the main developing research trend, thus helping researchers establish future research directions in this area.

Keywords: Bibliometric; Research trend; Sulfate removal; Sulfide

1. Introduction

Sulfate is a widely used material for painting, plastic, medicine, and paper making etc [1]. These sulfate containing industrial effluents would pose a threat to the quality of freshwater resources and consequently the well-being of humans and the environment at large [2,3]. Besides, sulfate contained in water may accumulate toxic levels and cause ecological damage, so standards are set to regulate the sulfate concentration in drinking water. A maximum limit of 200 mg/l in drinking water was recommended by the WHO.

Chemical and biological methods have been studied in recent years to remove sulfate. Biological treatment with sulfate-reducing bacteria (SRB) has been considered as the most promising alternative for the treatment of types of industrial wastewaters [4–7]. Over the past several decades, the number of scientific articles on sulfate removal has enjoyed a rapid increase and even papers presenting the latest research achievements have been published in authoritative scientific journals such as *Nature* [8].

The bibliometric method is an effective means for the analysis of scientific production and research trends [9–12], which has been widely employed to evaluate kinds of topics, such as global biodiversity [13], adsorption technology [14], climate change [15], water resources [16], wetland [17], solid waste [18], desalination [19], and aerosol research [20]. The Science Citations Index Expanded (SCI-EXPANDED), from the Institute of Scientific Information (ISI) Web

*Corresponding author.

of Science databases, is the most important and the most frequently used source for a broad review of scientific accomplishments in all fields. The conventional bibliometric methods may center on the citation analysis, namely scholarly outputs of authors, institutions, countries. However, the newly developed bibliometric analysis is closer to the research itself by employing the "word cluster analysis" to further evaluate words in the title [21], author keywords, and KeyWords Plus in the study of research trends [22].

In this study, a bibliometric analysis of language, source country, institution, and the most cited papers was performed to describe performance in sulfate removal. In addition, the distribution of words in the title, author keywords, and KeyWords Plus was analyzed to study the research trends during the period 1991–2010. These investigations can help researchers to realize the research advancements of sulfate removal and future research direction.

2. Data sources and methodology

Documents in this study were based on the online database of the Science Citation Index (SCI), retrieved from the ISI Web of Science, Philadelphia, USA. According to Journal Citation Reports (JCR), it indexed 40,134 major journals with citation references across 174 scientific disciplines in 2010. Five terms, including "sulfate reduction," "sulfate-reducing bacteria," "sulfate," "adsorption," and "sulphate," were chosen to search titles, abstracts, and keywords from 1991 to 2010. Articles originating from England, Northern Ireland, Scotland, and Wales were reclassified as from the UK. Articles addressed in Hong Kong were not included in China. Besides, the reported impact factor (IF) of each journal was obtained from the 2010 JCR. Collaboration type was determined by the addresses of authors, where the term "single country publication" was assigned if the researchers' addresses were from the same country. The term "internationally collaborative publication" was designated to those articles that were coauthored by researchers from multiple countries. The term "single institute publication" was assigned if the researchers' addresses were from the same institute. The term "internationally collaborative publication" was designated to those articles that were coauthored by researchers from multiple institutes. Words in titles were separated, and then, conjunctions and prepositions such as "and," "with," "of," "in," and "on" were discarded, they were meaningless for further analysis. All keywords, both those reported by authors and those assigned by ISI, as well as words in the title were identified and separated into 4 five-year spans (1991–1995, 1996–2000, 2001–2005, and 2006–2010, respectively), their ranks and frequencies of use were calculated with different words with identical meaning and misspelled keywords considered as a single.

The focus of the following discussion was to determine the pattern of scientific production and research activity trends which consisted of authorship, institutes, countries, and trends in the research subjects addressed.

3. Results and discussion

3.1. Document type and language of publication

A total of 42,383 articles were included in 14 document types during the 20-year study period, and the document type was dominated by articles, which accounted for 86.8% of all the publications. Despite the fact that articles, proceeding papers (6.9%), reviews (3.6%) were also significant parts of total. A less-significant portion was comprised of book chapter (0.01%), correction (0.1%), addition (0.01%), discussion (0.01%), editorial material (0.2%), letter (0.1%), meeting abstract (0.6%), news item (0.01%), note (0.6%), and reprint (0.02%). In 1990–2010, the number of publications kept increasing steadily, and a significant increase was observed in both the number of publications and articles (Fig. 1) from 2002 to 2010. This indicated that sulfate removal had been a hot spot and had attracted increasing concern.

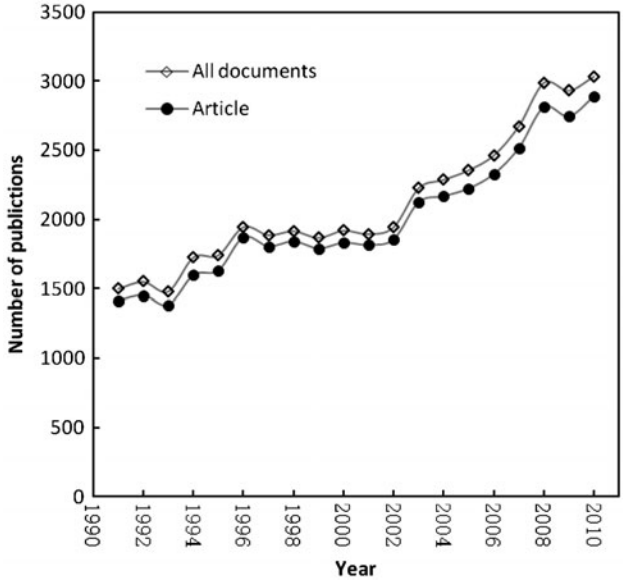

Fig. 1. World SCI-EXPANDED journal publications with sulfate removal, remove sulfate, sulfate reduction or reduce sulfate in titles during 1991–2010.

Articles, as the dominant document type, were further identified and analyzed. The articles were written in various languages, with English as the dominant one, which took up 98%. The five most frequently used languages following English were German (0.4%), Japanese (0.3%), French (0.3%), and Portuguese (0.2%). Hungarian, Greek, Coatian Korean, Lithuanian, Romanian, and Serbo-Croatian were minor publication languages in sulfate removal. These meant that English papers had covered the most research areas in the aspect of the sulfate removal and were benefit for communication.

All journals relating sulfate removal were analyzed, with the IF, IF rank, number of articles in the 20-year study period. In total, 42,383 articles on sulfate removal were published in 37,183 journals from 1991 to 2010. The top 20 most productive journals based on the number of articles were further analyzed (Table 1). *Journal of Biological Chemistry* was the most productive journal with high TP and IF (5.328), followed by *Applied and Environmental Microbiology*. However, although *Applied and Environmental Microbiology*'s TP and IF were lower than the former journal, it enjoyed the highest TC/TP and NR/TP. Besides, NR/TP was topped by *Geochimica Et Cosmochimica Acta*, whose articles were most frequently cited. Researchers focusing on sulfate removal could read papers published on these journals for suggestions.

3.2. Distribution of country/territory and institute

Contribution of different countries/territories was estimated by the affiliation location of at least one author of the published paper (Fig. 2). In the past 20 years, USA had a notable advantage in article production, establishing an advantage in sulfate removal (Table 2). China had chased up rapidly with a late start though, especially in 2006–2010, which indicated research on sulfate removal had earn an increasing attention as well as huge potential in China. Germany, Japan, UK, and Canada witnessed a stable increase during the 20-year study. The increase in all articles of productive countries revealed an increasing attention to sulfate removal.

Among the top 20 institutes (Table 3), 12 were in USA, two in Canada, and one each in China, Russia, Germany, Japan, Spain, and France. Results showed that sulfate removal research was dominated by institutes in USA, which to some extent leaded research trends. There was not any advantage of quantity in China, but Chinese Academy of Sciences, as the only Chinese institute in top 20, had

Table 1
The top 20 most productive journals based on total number of articles

Journal	TP	TP (%)	IF	TC	TC/TP	NR	NR/TP
Journal of Biological Chemistry	866	2.16	5.328	42,529	49.11	38,471	44.42
Applied and Environmental Microbiology	626	1.56	3.778	38,820	62.01	28,022	44.76
Environmental Science & Technology	484	1.21	4.827	16,414	33.91	18,178	37.56
Water Research	379	0.94	4.546	9,545	25.18	11,473	30.27
Geochimica Et Cosmochimica Acta	370	0.92	4.101	16,106	43.53	22,451	60.68
Water Science and Technology	322	0.80	1.056	4,417	13.72	4,869	15.12
Journal of Hazardous Materials	307	0.76	3.723	3,113	10.14	9,502	30.95
Journal of Geophysical Research-Atmospheres	276	0.69	3.303	11,575	41.94	14,327	51.91
FEMS Microbiology Ecology	269	0.67	3.456	6,808	25.31	12,655	47.04
Langmuir	249	0.62	4.269	6,283	25.23	9,585	38.49
Biochemistry	241	0.60	3.226	8,080	33.53	11,119	46.14
Journal of Bacteriology	224	0.56	3.726	8,676	38.73	9,748	43.52
Chemosphere	216	0.54	3.155	3,570	16.53	6,686	30.95
Water Air and Soil Pollution	213	0.53	1.765	2,446	11.48	6,671	31.32
Chemical Geology	207	0.52	3.722	4,629	22.36	11,726	56.65
Desalination	207	0.52	1.851	1937	9.36	4,342	20.98
Industrial & Engineering Chemistry Research	191	0.48	2.072	2,936	15.37	5,343	27.97
Hydrometallurgy	185	0.46	1.922	1,811	9.79	4,097	22.15
Atmospheric Environment	178	0.44	3.226	4,327	24.31	6,146	34.53
Journal of Virology	168	0.42	5.189	8,595	51.16	8,797	52.36

Notes: TP: total number of articles, IF 2010 ISI: impact factor, TC: total citation count, NR: cited reference count, TC/TP: average of citations in a paper, NR/TP: the average cited reference count per article.

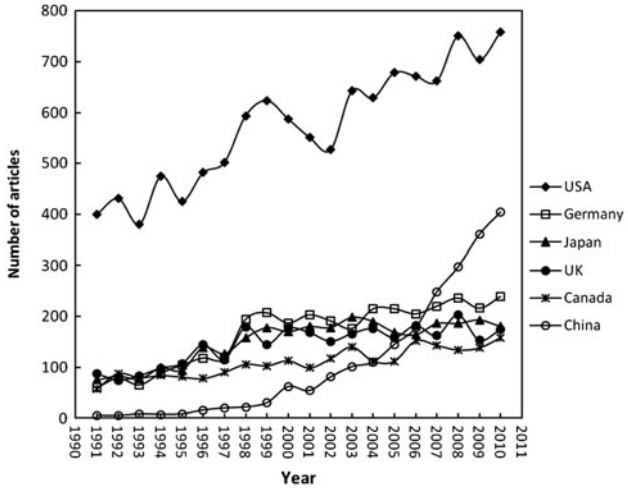

Fig. 2. Comparison the growth trends of the top five productive countries.

contributed the most articles on sulfate removal. Among single institutes, University of Wisconsin and University of Washington had the highest TC/SP, while University of Illinois in USA ranked the first in terms of TC/TP among all inter-institutionally collaborative institutes. Another observation in Table 3 was that the percentage of collaborative articles was generally higher than that of individual institutes, which indicated that academic communities of sulfate removal research were more collaborated.

3.3. Distribution of paper titles, author keywords, and Keywords Plus

Title of an article, as a media, helps readers identify the subjective focus and emphasis specified by authors. The analysis of paper titles was previously applied in mapping trends in aerosol, stem cell, and atmospheric simulation research. All single words in titles of sulfate removal-related articles were analyzed in this study. Words that were useless for further study, such as "by," "and," "the" and "to," were discarded.

Keywords, which reflected research trends of articles, were of concern to readers. As a significant part of bibliometric analyzing method, keywords analysis had developed rapidly in recent years, but it was rarely applied in research trends analysis. In this study, keywords were classified into 4 five-year periods (1991–1995, 1996–2000, 2001–2005, and 2006–2010, respectively). Results indicated that many keywords appeared just once or twice. The large number of once only keywords probably indicated a lack of continuity in research and a wide disparity in research foci. It was also reasoned that probably some new research fields earned less concern. All the keywords ranking top 50 in all articles are listed in Table 4. Sulfate and reduction undoubtedly ranked the first and second, respectively, as the dominant factors for research. SRB ranked 10th in 1991–1995, but fourth in 1996–2010, which showed that SRB obtained more concern in recent years. Some biological terms including "cells," "protein," "proteoglycans," and "metabolism" earned increasing attention in 1991–2000, but the attention decreased in 2001–2010, as were replaced by "mechanism." Results showed that mechanism of SRB was paid more attention; thus, a complete researching system was established. In addition, the rates of "kinetics" and "microbial" increased steeply, which implied that chemical and biological mechanisms of removal methods were receiving attention of researchers.

3.4. Most cited articles

The time-dependence of citations might be informative for tracking the impact of an article. Table 5 showed the most frequently cited articles of sulfate removal in each year since publication through 2010. The article "Requirement of heparan-sulfate for Basic Fibroblast Growth-Factor (BFGF)-mediated fibroblast growth and myoblast differentiation" in 1991 was the most frequently cited, followed by "The complete genome sequence of the hyperthermophilic, sulfate-reducing archaeon archaeoglobus fulgidus" in 1997, and "Isis-4-A randomized factorial trial assessing early oral captopril, oral mononitrate, and intravenous magnesium-sulfate in 58,050 patients with suspected acute myocardial-Infarction" in 1995. All the top three articles were from USA, which again proved the influence of USA on sulfate removal. Among the most frequently cited articles each year, 12 articles included authors were from the USA, two from the UK, five from Germany, two from Australia, and one each from China, Argentina, Switzerland, Netherlands, Sweden, Canada, Belgium. Besides, it was always accompanied with other substances to remove sulfate as shown in 2000, 2001, and 2007 articles.

3.5. Hot issues

Research trends in sulfate removal were separated into three categories, including removal field, removal methods, and product. In terms of the sulfate removal field, "water" had a distinctly higher rank (the fifth) over the last two decades. The percentage of "water" had increased gradually, showing that more attention was paid to the research on "water" [23,24]. "Soil" ranked 35 with few changes observed in the growing rate. Compared with "water," soil was less concerned in sulfate removal fields. Due to the importance of

Table 2
Top 20 most productive country/territory based on total number of articles

Country	TP	Single-country				Internationally-callaborated			
		SP	SP (%)	TC	TC/SP	CP	SP (%)	TC	TC/SP
USA	11,478	8,319	72.48	237,618	28.56	3,159	27.52	85,654	27.11
Germany	3,334	1,902	57.05	48,888	25.70	1,432	42.95	40,143	28.03
Japan	3,024	2,347	77.61	39,267	16.73	677	22.39	14,170	20.93
UK	2,902	1,631	56.20	40,861	25.05	1,271	43.80	32,689	25.72
Canada	2,186	1,377	62.99	27,090	19.67	809	37.01	19,865	24.56
China	2,160	1,634	75.65	12,904	7.90	526	24.35	6,382	12.13
France	1,867	983	52.65	22,346	22.73	884	47.35	22,673	25.65
India	1,355	1,173	86.57	10,630	9.06	182	13.43	2,470	13.57
Australia	1,297	733	56.52	12,286	16.76	564	43.48	14,274	25.31
Italy	1,216	807	66.37	13,209	16.37	409	33.63	9,434	23.07
Netherlands	1,158	611	52.76	16,955	27.75	547	47.24	13,484	24.65
Spain	1,149	717	62.40	10,874	15.17	432	37.60	7,568	17.52
Sweden	924	449	48.59	9,906	22.06	475	51.41	14,330	30.17
South Korea	754	545	72.28	5,586	10.25	209	27.72	2,634	12.60
Brazil	728	551	75.69	4,670	8.48	177	24.31	3,900	22.03
Switzerland	657	242	36.83	7,055	29.15	415	63.17	12,914	31.12
Denmark	643	315	48.99	8,734	27.73	328	51.01	9,666	29.47
Taiwan	631	507	80.35	6,641	13.10	124	19.65	1,861	15.01
Russia	595	380	63.87	1,446	3.81	215	36.13	4,017	18.68
Poland	474	339	71.52	1,772	5.23	135	28.48	1,517	11.24

Notes: TP: total number of articles, SP: single institute articles, CP: inter-institutionally collaborative articles, TC: total citation count.

Table 3
Top 20 most productive institutes based on total number of articles

Institute	TP	Single-institute				Inter-institutionally collaborative			
		SP	SP (%)	TC	TC/SP	CP	CP (%)	TC	TC/SP
Chinese Academy of Sciences, China	435	177	40.69	2053	11.60	258	59.31	2,614	10.13
Russian Acad. Sci., Russia	371	174	46.90	606	3.48	197	53.10	2,899	14.72
Harvard University, USA	313	61	19.49	2,660	43.61	252	80.51	9,331	37.03
Max Planck Inst. Marine Microbiol., Germany	278	63	22.66	2,945	46.75	215	77.34	9,014	41.93
University of Georgia, USA	259	76	29.34	1,349	17.75	183	70.66	5,302	28.97
University of Toronto, Canada	258	93	36.05	2,378	25.57	165	63.95	4,272	25.89
University of Tokyo, Japan	255	59	23.14	1,476	25.02	196	76.86	4,778	24.38
CSIC, Spain	253	84	33.20	1,876	22.33	169	66.80	2,669	15.79
CNRS, France	248	38	15.32	1,243	32.71	210	84.68	5,981	28.48
US Geological Survey, USA	230	68	29.57	2,335	34.34	162	70.43	5,205	32.13
University of Illinois, USA	217	88	40.55	2,345	26.65	129	59.45	5,927	45.95
University of Washington, USA	211	53	25.12	3,346	63.13	158	74.88	4,743	30.02
University of Texas, USA	208	86	41.35	2,474	28.77	122	58.65	4,389	35.98
University of Minnesota, USA	206	78	37.86	2,721	34.88	128	62.14	4,203	32.84
University of Wisconsin, USA	204	53	25.98	3,346	63.13	151	74.02	4,509	29.86
University of Oklahoma, USA	203	77	37.93	1,722	22.36	126	62.07	3,495	27.74
University of Calif. Davis, USA	194	73	37.63	1997	27.36	121	62.37	3,074	25.40
University of Calif. Berkeley, USA	192	59	30.73	2,112	35.80	133	69.27	3,917	29.45
University of N. Carolina, USA	188	58	30.85	2,960	51.03	130	69.15	3,561	27.39
McGill University, Canada	181	61	33.70	929	15.23	120	66.30	3,867	32.23

Notes: TP: total number of articles, SP: single institute articles, CP: inter-institutionally collaborative articles, TC: total citation count.

Table 4
Top 50 most frequent keywords used during 1991–2010 and in 4 five-year periods

Keyword	TP	91–10 R (%)	91–95 R (%)	96–00 R (%)	01–05 R (%)	06–10 R (%)
Sulfate	6,585	1 (16.41)	1 (15.73)	1 (16.38)	1 (16.53)	1 (16.71)
Reduction	3,510	2 (8.75)	3 (7.04)	3 (8.78)	2 (8.88)	2 (9.57)
SRB	3,022	3 (7.53)	10 (5.41)	4 (7.2)	4 (7.52)	4 (8.96)
Cells	2,827	4 (7.04)	9 (5.49)	2 (8.99)	5 (7.19)	6 (6.47)
Water	2,731	5 (6.8)	22 (3.77)	8 (5.75)	3 (7.58)	5 (8.64)
Removal	2,522	6 (6.28)	27 (2.97)	19 (4.22)	6 (6.59)	3 (9.33)
Oxidation	2,326	7 (5.8)	18 (4.41)	15 (5.48)	7 (6.27)	7 (6.43)
Expression	2,305	8 (5.74)	16 (4.68)	6 (6.34)	8 (6.07)	9 (5.68)
Growth	2,263	9 (5.64)	15 (4.84)	5 (6.35)	10 (5.61)	10 (5.62)
Acid	2,156	10 (5.37)	20 (3.88)	11 (5.65)	9 (5.63)	8 (5.82)
Sulfur	2,127	11 (5.3)	12 (5.16)	10 (5.67)	13 (5.34)	14 (5.09)
Sediments	2,081	12 (5.19)	19 (4.24)	14 (5.55)	12 (5.37)	13 (5.33)
Protein	1,954	13 (4.87)	7 (6.12)	12 (5.63)	15 (4.7)	21 (3.77)
Sulfate reduction	1,923	14 (4.79)	14 (4.85)	17 (4.91)	14 (4.71)	15 (4.74)
Rat	1,918	15 (4.78)	5 (6.7)	13 (5.56)	16 (4.59)	27 (3.31)
Iron	1,883	16 (4.69)	23 (3.19)	22 (4)	11 (5.41)	11 (5.45)
Purification	1,878	17 (4.68)	2 (8.07)	9 (5.7)	27 (3.48)	30 (2.99)
Characterization	1,783	18 (4.44)	6 (6.29)	16 (5.13)	25 (3.54)	23 (3.62)
Binding	1,689	19 (4.21)	8 (5.52)	7 (5.84)	19 (3.73)	40 (2.72)
Adsorption	1,627	20 (4.05)	50 (1.92)	29 (3.36)	17 (4.41)	11 (5.45)
Degradation	1,576	21 (3.93)	25 (3.15)	25 (3.87)	18 (4)	16 (4.34)
Bacteria	1,535	22 (3.82)	26 (3.03)	24 (3.95)	21 (3.67)	17 (4.31)
Human	1,530	23 (3.81)	11 (5.27)	18 (4.76)	29 (3.35)	42 (2.7)
Identification	1,505	24 (3.75)	13 (5.05)	20 (4.12)	25 (3.54)	34 (2.92)
Proteins	1,405	25 (3.5)	4 (6.75)	21 (4.04)	44 (2.5)	67 (2.07)
Model	1,360	26 (3.39)	39 (2.34)	31 (3.22)	24 (3.61)	20 (3.93)
Kinetics	1,354	27 (3.37)	29 (2.77)	43 (2.53)	23 (3.64)	19 (4.09)
Inhibition	1,318	28 (3.28)	21 (3.86)	26 (3.78)	35 (3.04)	37 (2.8)
Metabolism	1,305	29 (3.25)	17 (4.49)	27 (3.63)	31 (3.21)	56 (2.33)
Copper	1,253	30 (3.12)	64 (1.7)	45 (2.48)	30 (3.32)	18 (4.21)
Carbon	1,221	31 (3.04)	51 (1.91)	33 (2.99)	34 (3.15)	22 (3.64)
Sulphate	1,215	32 (3.03)	1,661 (0.15)	23 (3.97)	22 (3.66)	24 (3.52)
Anaerobic	1,209	33 (3.01)	35 (2.5)	28 (3.49)	36 (3.02)	32 (2.97)
Activity	1,163	34 (2.9)	35 (2.5)	35 (2.95)	33 (3.16)	35 (2.89)
Surface	1,152	35 (2.87)	55 (1.82)	30 (3.27)	32 (3.17)	33 (2.96)
Soil	1,145	36 (2.85)	46 (1.99)	32 (3.17)	28 (3.38)	41 (2.71)
Mechanism	1,101	37 (2.74)	38 (2.37)	37 (2.59)	37 (2.84)	31 (2.98)
System	1,078	38 (2.69)	41 (2.27)	50 (2.38)	40 (2.69)	28 (3.13)
Sulfide	1,059	39 (2.64)	40 (2.33)	40 (2.55)	42 (2.67)	36 (2.85)
Mice	1,042	40 (2.6)	72 (1.66)	53 (2.21)	43 (2.62)	26 (3.37)
Microbial	1,037	41 (2.58)	80 (1.56)	60 (1.97)	38 (2.78)	25 (3.43)
Receptor	945	42 (2.35)	28 (2.89)	37 (2.59)	52 (2.31)	76 (1.92)
Properties	915	43 (2.28)	43 (2.1)	47 (2.42)	58 (2.19)	53 (2.36)
Sodium	910	44 (2.27)	55 (1.82)	44 (2.49)	44 (2.5)	64 (2.19)
Analysis	903	45 (2.25)	107 (1.3)	51 (2.26)	40 (2.69)	48 (2.44)
Nitrogen	897	46 (2.24)	59 (1.79)	47 (2.42)	46 (2.46)	64 (2.19)
Nitrate	896	47 (2.23)	83 (1.51)	70 (1.8)	47 (2.41)	38 (2.79)
Proteoglycans	882	48 (2.2)	31 (2.61)	33 (2.99)	51 (2.32)	150 (1.33)
Oxygen	877	49 (2.19)	65 (1.68)	46 (2.46)	54 (2.26)	62 (2.22)
Formation	873	50 (2.18)	59 (1.79)	51 (2.26)	59 (2.15)	54 (2.35)

Notes: TP: total number of keywords, R (%): rank and percentage of keywords in total articles.

Table 5
Most frequently cited articles during 1991–2010

Year	TC	TC/Y	Article/Journal	Country
1991	1,182	59	Requirement of Heparan-Sulfate for BFGF-Mediated Fibroblast Growth and Myoblast Differentiation	USA
1992	418	22	Identification of the BFGF Binding Sequence in Fibroblast Heparan-Sulfate	UK, Australia
1993	531	30	The Relative Roles of Sulfate Aerosols and Greenhouse Gases in Climate Forcing	USA
1994	424	25	Water Activities, Densities, and Refractive-Indexes of Aqueous Sulfates and Sodium-Nitrate Droplets of Atmospheric Importance	USA
1995	958	60	Isis-4-A Randomized Factorial Trial Assessing Early Oral Captopril, Oral Mononitrate, and Intravenous Magnesium-Sulfate in 58,050 Patients with Suspected Acute Myocardial-Infarction	Argentina, Switzerland, USA
1996	349	23	Late Proterozoic Rise in Atmospheric Oxygen Concentration Inferred from Phylogenetic and Sulphur-Isotope Studies	Germany
1997	1,031	74	The Complete Genome Sequence of the Hyperthermophilic, Sulphate-Reducing Archaeon Archaeoglobus Fulgidus	USA
1998	440	34	Novel Division Level Bacterial Diversity in a Yellowstone Hot Spring	USA
1999	340	28	Transient Climate Change Simulations with a Coupled Atmosphere-Ocean GCM Including the Tropospheric Sulfur Cycle	Germany, Netherlands, Sweden
2000	412	37	Atmospheric Influence of Earth's Earliest Sulfur Cycle	USA
2001	406	41	Oxygen Reduction on a High-Surface Area Pt/Vulcan Carbon Catalyst: A Thin-Film Rotating Ring-Disk Electrode Study	Germany
2002	284	32	Oligonucleotide Microarray for 16S rRNA Gene-Based Detection of all Recognized Lineages of Sulfate-Reducing Prokaryotes in the Environment	Germany
2003	254	32	Coagulation by Hydrolysing Metal Salts	UK, Australia
2004	189	27	The Genome Sequence of the Anaerobic, Sulfate-Reducing Bacterium *Desulfovibrio Vulgaris* Hildenborough	USA, Canada
2005	193	32	Tubular Microbial Fuel Cells for Efficient Electricity Generation	Belgium
2006	137	27	Symbiosis Insights through Metagenomic Analysis of a Microbial Consortium	Germany, USA
2007	158	40	Geochip: A Comprehensive Microarray for Investigating Biogeochemical, Ecological and Environmental Processes	USA
2008	155	52	Regulation of Inflammatory Responses by Il-17F	USA
2009	63	32	Manganese-and Iron-Dependent Marine Methane Oxidation	USA
2010	22	22	Sulfur Dioxide Emissions in China and Sulfur Trends in East Asia Since 2000	USA, China

Notes: TC: total citations of articles from publication to 2010, C/Y: number of citations/year.

water and the main sulfate pollution route, water was the main research field of sulfate removal [25]. Information on removal methods was also showed in Table 4. SRB ranked the third, which indicated that sulfate removed by SRB was the most concerned method owing to its harmless and effective characters [26]. Following SRB, adsorption and degradation also had high ranks, implying that adsorption and degradation were also effective methods to remove sulfate. The higher rank of "degradation" indicated that researchers concentrated on use biological means to remove sulfate. All results proved that biological method was the main method of sulfate removal [27–29]. Numerous products were formed during sulfate removal, among which sulfur and sulfide were the most predominant [30]. Sulfur was the ideal product of sulfate removal as it is insoluble and recyclable. However, some by-products were also produced, such as sulfide, sulfite, which caused great concern to researchers due to the harm to environment [31]. Sulfide hydrogen, as one of the products, was toxic and harmful to the nervous system. Because of the toxicity of sulfide hydrogen, more emphasis was placed on it to avoid its appearance [32].

4. Conclusions

In this study, an alternative perspective on the global research trends in sulfate removal was provided. Bibliometric analyses were conducted, including analysis of patterns of publications, journal and subject categories, country and institutional distribution, distribution and changes of words in article titles, author keywords, hot issues and most cited articles. A total number of 40,134 journals were listed in the—SCI subject categories. The subject category "environmental sciences" had the greatest number of output and the most rapid growth, indicating a research emphasis on the interactional relationship between sulfate and environmental problems.

At the country level, the USA had won a dominant position in research on sulfate removal by contributing the most articles, single-country articles, and internationally collaborative articles. China had the highest growth rate in the number of articles since 2007 and ranked second in 2010.

Chinese Academy of Sciences, Russian Acad. Sci., Harvard University, Max Planck Inst. Marine Microbiol., and University of Georgia were the five most productive institutions. Additionally, inter institutional collaborations were more prevalent than single institute. Analysis of the most cited articles revealed that biological method was the main method to remove sulfate in various fields. A new bibliometric method, "word cluster analysis," through synthetically analyzing the distribution and changes of words in article titles, author keywords, KeyWords Plus, would help researchers realize the development of sulfate removal research and establish future research directions.

It can be concluded that the main field of sulfate removal was water. The research in soil gradually decreases in contrast to the gradual increase in water. Biological method will continue to be the leading research method. The adsorption method has a bright prospect in the future. Sulfide will continue to be the research hot spot due to its harm to environment.

In conclusion, Sulfate removal research trended toward collaborative. USA was the leading country in sulfate removal, which had significant influence on the research. SRB earned more concern in sulfate removal methods. Due to environmental and health risk, one of the products of sulfate, sulfide was paid more attention to avoid its appearance. Through analysis, sulfate removal research trends are shown to researchers, which is helpful to establish future research directions.

Acknowledgements

Financial support is gratefully acknowledged from the Fundamental Research Funds for the Central Universities (2011YYL109) and the Research Fund for the Doctoral Program of Higher Education of China (20120022120005).

References

[1] K. Ingvorsen, M.Y. Nielsen, C. Joulian, Kinetics of bacterial sulfate reduction in an activated sludge plant, FEMS Microbiol. Ecol. 46 (2003) 129–137.
[2] Y.I. Korenman, O.A. Kriwsheeva, Coefficients of caffeine distribution in aliphatic alcohol-ammonium sulfate-water systems, Russ. J. Phys. Chem. 86 (2012) 1676–1678.
[3] X. Zhou, L. Liu, C. Chen, N. Ren, Reduction of produced elementary sulfur in denitrifying sulfide removal process, Appl. Microbiol. Biotechnol. 90 (2011) 1129–1136.
[4] R. Silva, L. Cadorin, J. Rubio, Sulphate ions removal from an aqueous solution: I. Co-precipitation with hydrolysed aluminum-bearing salts, Miner. Eng. 23 (2010) 1220–1226.
[5] V. Baskaran, M. Nemati, Anaerobic reduction of sulfate in immobilized cell bioreactors, using a microbial culture originated from an oil reservoir, Biochem. Eng. J. 31 (2006) 148–159.
[6] M. Higo, K. Isobe, D. Kang, Molecular diversity and spore density of indigenous arbuscular mycorrhizal fungi in acid sulfate soil in Thailand, Ann. Microbiol. 61 (2011) 383–389.
[7] A. Wiessner, U. Kappelmeyer, P. Kuschk, M. Kästner, Sulphate reduction and the removal of carbon and ammonia in a laboratory-scale constructed wetland, Water Res. 39 (2005) 4643–4650.
[8] R.S. Oremland, L.M. Marsh, S. Polcin, Methane production and simultaneous sulphate reduction in anoxic, salt marsh sediments, Nature 296 (1982) 143–145.
[9] J.F. Li, Y.H. Zhang, X.S. Wang, Y.S. Ho, Bibliometric analysis of atmospheric simulation trends in meteorology and atmospheric science journals, Croat. Chem. Acta 82 (2009) 695–705.
[10] J. Qin, Semantic similarities between a keyword database and a controlled vocabulary database: An investigation in the antibiotic resistance literature, J. Am. Soc. Inform. Sci. 51 (2000) 166–180.
[11] W.T. Chiu, Y.S. Ho, Bibliometric analysis of 1998. Survey of azo colorants in Denmark: Tsunami research, Scientometrics 73 (2007) 3–17.
[12] L.L. Li, G.H. Ding, N. Feng, M.H. Wang, Y.S. Ho, Global stem cell research trend: Bibliometric analysis as a tool for mapping of trends from 1991 to 2006, Scientometrics 80 (2009) 39–58.
[13] X.J. Liu, L. Zhang, Global biodiversity research during 1900–2009: A bibliometric analysis, Biodivers. Conserv. 20 (2011) 807–826.
[14] R. Malarvizhi, M.H. Wang, Research trends in adsorption technologies for dye containing wastewaters, World Appl. Sci. J. 8 (2010) 930–942.
[15] J.F. Li, M.H. Wang, Trends in research on global climate change: A science citation index expanded-based analysis, Global Planet. Change 77 (2011) 13–20.
[16] M.H. Wang, J.F. Li, Research articles published in water resources journals: A bibliometric analysis, Desalin. Water Treat. 28 (2011) 353–365.
[17] L. Zhang, M.H. Wang, J. Hu, Y.S. Ho, A review of published wetland research, 1991–2008: Ecological engineering and ecosystem restoration, Ecol. Eng. 36 (2010) 973–980.

[18] H.Z. Fu, Y.S. Ho, Y.M. Sui, Z.S. Li, A bibliometric analysis of solid waste research during the period 1993–2008, Waste Manage. 30 (2010) 2410–2417.
[19] H. Tanaka, Y.S. Ho, Global trends and performances of desalination research, Desalin. Water Treat. 25 (2011) 1–12.
[20] S. Xie, J. Zhang, Y.S. Ho, Assessment of world aerosol research trends by bibliometric analysis, Scientometrics 77 (2008) 113–130.
[21] W. Zhang, W. Qian, Y.S. Ho, A bibliometric analysis of research related to ocean circulation, Scientometrics 80 (2009) 305–316.
[22] W. Huang, B. Zhang, C. Feng, M. Li, J. Zhang, Research trends on nitrate removal: A bibliometric analysis, Desalin. Water Treat. 50 (2012) 67–77.
[23] B. Zhang, J. Zhang, Q. Yang, C. Feng, Y. Zhu, Z. Ye, J. Ni, Investigation and optimization of the novel UASB-MFC integrated system for sulfate removal and bioelectricity generation using the response surface methodology (RSM), Bioresour. Technol. 124 (2012) 1–7.
[24] F. Liang, Y. Xiao, F. Zhao, Effect of pH on sulfate removal from wastewater using a bioelectrochemical system, Chem. Eng. J. 218 (2013) 147–153.
[25] R. Haghsheno, A. Mohebbi, H. Hashemipour, A. Sarrafi, Study of kinetic and fixed bed operation of removal of sulfate anions from an industrial wastewater by an anion exchange resin, J. Hazard. Mater. 166 (2009) 961–966.
[26] T. Jong, D.L. Parry, Removal of sulfate and heavy metals by sulfate reducing bacteria in short-term bench scale upflow anaerobic packed bed reactor runs, Water Res. 37 (2003) 3379–3389.
[27] A.J. Silva, M.B. Varesche, E. Foresti, M. Zaiat, Sulphate removal from industrial wastewater using a packed-bed anaerobic reactor, Process Biochem. 37 (2002) 927–935.
[28] C. Boukhalfa, Sulfate removal from aqueous solutions by hydrous iron oxide in the presence of heavy metals and competitive anions: Macroscopic and spectroscopic analyses, Desalination 250 (2010) 428–432.
[29] C. Boukhalfa, A. Mennour, L. Reinert, H. Fuzellier, Sulfate removal from aqueous solutions by hydrous iron oxide macroscopic, thermal and spectroscopic analyses, Desalination 214 (2007) 38–48.
[30] O. Mizuno, Y.Y. Li, T. Noike, The behavior of sulfate-reducing bacteria in acidogenic phase of anaerobic digestion, Water Res. 32 (1998) 1626–1634.
[31] V.I. Starostin, O.G. Sorokhtin, A new interpretation for the origin of the Norilsk type PGE–Cu–Ni sulfide deposits, Geosci. Front. 4 (2011) 583–591.
[32] M. Coma, S. Puig, N. Pous, M.D. Balaguer, J. Colprim, Biocatalysed sulphate removal in a BES, Bioresour. Technol. 130 (2013) 218–223.