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Global trends of coagulation for water and wastewater treatment by utilizing bibliometrics analysis

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ABSTRACT

Coagulation is one of the most extensively used techniques for drinking water, domestic wastewater, and industrial wastewater treatment due to its low cost and easy operation. The existing strict requirements on water quality facilitated the development of coagulation techniques and researches. Moreover, design and preparation of novel efficient coagulants have been emerging as a significant research topic in the past decades. This study quantitatively assessed current research trends on coagulation for water and wastewater treatment from 1992 to 2016 according to the Science Citation Index-Expanded (SCI-Expanded). Studies related to coagulation for water and wastewater treatment have been significantly increased from 1992 to 2016. Meanwhile, the word cluster analysis is utilized to trace the hotspot related to coagulation for water and wastewater treatment. The investigation showed two main conclusions. One is that the key pollutants in drinking water and wastewater are organic matter, suspensions, and humic substances, especially natural organic matter. The traditional coagulation technique was unsuitable with the continual increase of natural organic matter concentration and the changes of composition. Therefore, it is necessary to combine the conventional coagulation technique with the new technology to adapt to the complex situation of water, which is also the second conclusion. And the new technologies that can be combined with coagulation technique include membranes (nanofiltration, microfiltration, ultrafiltration) and electrocoagulation. The integration of traditional technology and new technology is also the trendency of water treatment in the future.

Keywords: Bibliometrics; Coagulation; Wastewater treatment; Water treatment; Coagulant; Landfill leachate

1. Introduction

Rapid economic and social development has raised pressure for safe and healthy drinking water for humans [1]. Thus, developing technologies to ensure water safety has become very urgent. One of the most important water-treatment methods is coagulation, which involves flocculation and agglomeration [2]. Flocculation is where particles bond together through adsorption onto polymer materials, and agglomeration is the coalescence of unsteady colloidal particles [3]. Coagulation can effectively reduce watercolor and turbidity, bacteria, viruses, high-molecular-weight

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substances, organic matter, some heavy metals, and radioactive substances, thereby playing a key part in the history of water treatment [4,5]. Hundreds of years ago, aluminum sulfate was used for water purification, which marked the beginning of coagulation becoming a water treatment technology [6]. Coagulation has been considered as the core part of the drinking water treatment process (including coagulation/flocculation, sedimentation, filtration, and disinfection) for more than 100 years [7]. To date, coagulation serves as an indispensable technology both for water and wastewater treatments. To develop strategies to purify wastewater, especially under the pressure of increasingly severe environmental pollution, the novel coagulation technique and its enhanced process, as well as the coagulants research had attracted great interests all over the world. There are three aspects of coagulation technique research: (i) kinds of water or wastewater to be treated; (ii) novel coagulation techniques; and (iii) new coagulants.

(i) Most water treatment is applied with coagulation technique to destabilize colloidal suspensions in order to remove turbidity and natural organic matter [8–10]. For natural water, polyaluminium chloride (PAC) and polydimethyl diallyl ammonium chloride (PDM) are used to control algae pollution in Taihu Lake in China [11]. The landfill leachate is a typical kind of organic wastewater with an extremely high concentration of contaminants. The composition of the landfill leachate is so complex that often leads to serious pollution of the surrounding environment. Textile wastewater containing dyes, pulp, acid, cellulose, inorganic salts, amino compounds, and heavy metals, such as copper, chromium, and arsenic, exhibits a complex composition and high toxicity [12]. About 10%–20% textile wastewater is being discharged into the sewage network directly [13].

(ii) Faced with the deterioration of water quality, conventional coagulation technique cannot meet the requirements. Some experimental research and production results show that conventional coagulation technology and filtration can only remove 20%–30% organic matter [7]. Therefore, developing more effective techniques, such as ultrafiltration, microfiltration, nanofiltration membranes, and electrocoagulation is urgent [14]. Membrane technology based separation methods (ultrafiltration, microfiltration, and nanofiltration membrane technology) have turned into the most appealing water treatment technology because of their excellent performance for separating virus and soluble organic matter in the water. However, membrane fouling restricts the wide application of ultrafiltration membrane. Combining electrocoagulation with pretreatment with nanofiltration can effectively reduce membrane fouling and improve the quality of water simultaneously [15]. These diversity treatment methods demonstrated the innovation and specialization in wastewater research, which was usually due to the needs of processing various wastewater substrates and strict effluent quality.

(iii) Another core of the coagulation and sedimentation process is the application of the coagulants, which determines the quality of the water treatment and the cost of the coagulation process. The development of coagulants and flocculants has undergone four stages, mineral salt, inorganic, organic, and compound coagulants [16]. In China, alum was used in disposing of water during the spring and autumn period. The first test in 1,827 using aluminum sulfate as the coagulant for water treatment marked the coagulation method as a water treatment technology [17]. Since then, simple inorganic coagulant (molysite and aluminum salts) have been widely used in the world, accounting for more than 95% of the global total market. Inorganic polymer flocculant or coagulant is becoming the main trend. More than 90% of water treatment applies PAC. However, the application of these coagulants has been limited because they have various disadvantages, such as nonbiodegradable, expensive, and other defects. Hence in practical applications, two or more coagulants can be used to improve the efficiency of coagulation in wastewater and drinking water treatment [18]. For example, using combined chitosan and aluminum chloride is effective in the treatment of toxic cyanobacteria in drinking water sources, the turbidity, algal density, and removal rates of chl-a could reach 95.16%, 96.67%,and 100% [19]. Another interesting research is about microbial coagulants/flocculants, which is still under experimental study. Microbial flocculants used in treating freshwater, seawater, sewage, and wastewater enhance membrane bioreactor and substance separation.

During the paper, the research trend of coagulation for water and wastewater treatment (CWWT) was comprehensively analyzed by bibliometric analysis from 1992 to 2016. The analysis included languages, document types, journals, categories, institutions, countries/territories, *h*-index, and the publication pattern. Moreover, research tendencies and hotspots in different periods were also analyzed. Analysis results clarify the key direction and hotspots and provide some constructive advice for future research on CWWT.

2. Data sources and analysis methods

All data were extracted from the SCI-Expanded database and the 2017 Journal Citation Report (JCR) of Thomson Reuters, on the 5th of September, 2016. The 2017 JCR indexes 11,459 journals across 236 scientific disciplines and 81 countries. The methodology adopted "word cluster analysis" (Mao et al., 2010) to probe the global tendency and hotspots on CWWT. (Coagulation* or coagulant* or flocculant* or flocculation*) and (wastewater* or "waste water*" or waste-water* or water) were designated as a topic in SCI-EXPANDED during the research period from 1992 to 2016.

The Microsoft Excel was used for the analysis of document's details, including document type, language, output, journal, subject category, institute, country, author keyword, and *h*-index. Each author's affiliation of the reported literature was used as the basis to calculate the contribution of different institutes and countries. Articles that originated from England, Scotland, Northern Ireland, and Wales were grouped under the UK head. Articles that came from Hong Kong were included under China heading for analysis. "Internationally collaborative publication" meant that researchers of the article were from different countries. "Inter-institutionally collaborative publication" referred to that various institutes were involved in the article. "Independent article" and "single institute article" referred to those authors were from the same country and institute, respectively. *H*-index meant that there were *h* papers and every article was cited no less than *h* times. Journal's JIF was acquired from the 2017 JCR Science Edition.

3. Results and discussion

3.1 Publication pattern

3.1.1. Document type and publication language

There were 16,866 publications marked by the ISI about CWWT research during the research period from 1992 to 2016, which were composed of 12 document types. The dominant document type was an article, which comprised 87% or 14,268 of the total publications. Other publication types were proceedings papers (1,456), review (513), meeting abstract (48), note (20), editorial material (19), letter (9), book chapter (6), correction (8), news item (3), retracted publication and discussion (1).

Articles were analyzed in the following research due to the dominant type of publications with 14,268. For language analysis, 96.5% articles (13,775) were published in English. Other languages included Polish (131), Portuguese (68), Chinese (56), Spanish (55), Japanese (53), French (34), German (34), Russian (13), Turkish (12), Czech (10), Rumanian (7), Hungarian (5), Croation (4), Korean (3), Serbo-Croatian (3), Serbian (2), and only one article each in French, Italian, and Slovak. Up to now, obviously, the dominant language is English in the journals included in SCI.

3.1.2. Characteristics of publication outputs

The general tendency of CWWT can be obtained with search terms of (coagulation* or coagulant* or flocculant* or flocculation*) and (wastewater* or "waste water*" or waste-water* or water). The first research in SCI-EXPANDED about CWWT was found in 1911. Fig. 1 shows that there were only two publications on CWWT related research in 1911 and almost no growth between 1911 and 1990. The number of publications increased significantly from 1991, mainly due to the increasing pollution of the water environment. Because of this, as an effective technique of wastewater and water treatment, coagulation attracted attention of researchers all over the world.

The number of articles reported per year increases dramatically from 132 in 1992 to 1,410 in 2016 within the investigation period. The cumulative annual number of articles from 1992 was described by an index model of C = –1642.04 + 1752.64*$e^{0.09Y}$ ($R^2 > 0.9999$) , the relationship of C (the cumulative number of articles) and Y (the number of years since 1992) is shown in Fig. 2. Based on this index model, 15,844 articles were published from 1992 to 2017. The number of articles came out in 2025 (3,209) is expected to be nearly twice than that in 2016 (1,410).

On the basis of 14,268 articles analysis, from the Table 1, during the research period from 1992 to 2016, the length of the paper remained basically stable with an average length of 9.3 pages. The number of references cited each article increased from 22 to 38, with an increase of 72.7%; the number of authors each article increased from 3.4 to 4.6 and the increment was 35%; the number of institutions per article had a great increment, an increase of approximately 100%; the number of participating countries increased from 1.1 to 1.3. The results suggested that a total number of researchers involved in the field of CWWT were gradually increasing, and the exploration of CWWT by various countries and scientific research institutions was continuously deepened.

3.1.3. Output in subject categories and journals

There are totally 14,268 articles published in 1,763 journals covering 105 subject categories. However, the majority of the journals (87%) published <10 articles. Table 2 summarizes the top 20 most productive journals (TP > 130) together with journal details, such as ISI category, the position of the journal in its category, JIF in 2017, h-index and Journal Country.

Literature could be evaluated by JIF and h-index of the journal. Table 2 shows that appropriately 38% articles related to CWWT were published in the top 20 most productive journals. Apparently, *Water Research* (689, 4.8%) ranked 1st for overall productivity, while the JIF (6.942) and h-index (93) of this journal in 2017 were also first. Followed by *Desalination and Water Treatment* (500; 3.5%), *Journal of Hazardous Materials* (362, 2.5%), *Desalination* (327; 2.3%), and *Separation and Purification Technology* (305; 2.1%). It is obviously indicated that coagulation technique has always been a significant measure of water treatment. In recent years, coagulation was also applied to desalination. By analyzing the attribution of the top 20 most productive journals, eight journals are from UK

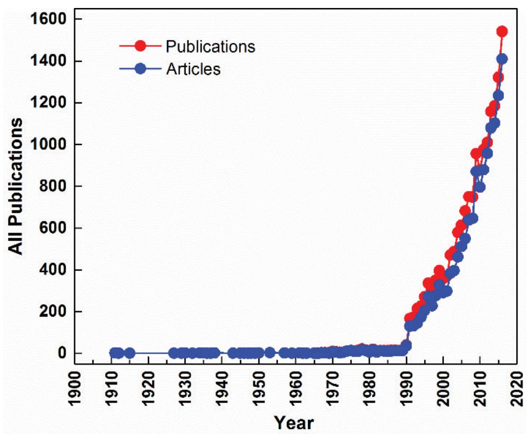

Fig. 1. Number of publications on coagulation technique for water and wastewater treatment-related research during last 110 years.

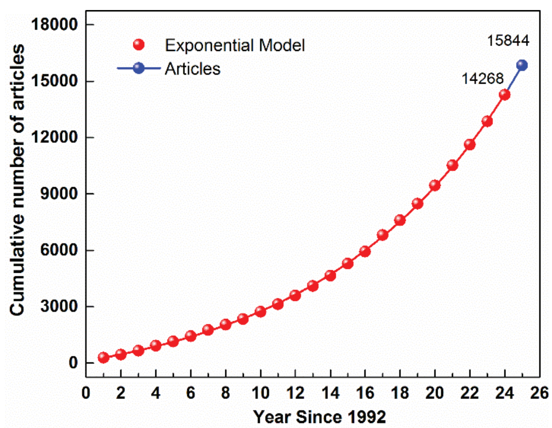

Fig. 2. Relationship between a cumulative number of publications and published year.

Table 1
Characteristics by year of publication outputs from 1992 to 2016.

Year	TP	AU	AU/TP	NR	NR/TP	PG	PG/TP	NC	NC/TP	NI	NI/TP
1992	132	447	3.4	3,014	22.8	1,252	9.5	151	1.1	151	1.1
1993	145	464	3.2	3,443	23.7	1,383	9.5	160	1.1	160	1.1
1994	174	546	3.1	4,547	26.1	1,762	10.1	194	1.1	194	1.1
1995	205	616	3.0	5,467	26.7	2,094	10.2	227	1.1	227	1.1
1996	272	887	3.3	7,409	27.2	2,789	10.3	303	1.1	303	1.1
1997	228	759	3.3	6,000	26.3	2,209	9.7	261	1.1	261	1.1
1998	276	903	3.3	7,738	28.0	2,601	9.4	331	1.2	331	1.2
1999	327	1,103	3.4	8,824	27.0	3,173	9.7	381	1.2	381	1.2
2000	290	996	3.4	7,341	25.3	2,699	9.3	326	1.1	326	1.1
2001	298	989	3.3	8,372	28.1	2,785	9.3	346	1.2	346	1.2
2002	384	1,310	3.4	9,820	25.6	3,533	9.2	455	1.2	455	1.2
2003	397	1,456	3.7	11,058	27.9	3,751	9.4	476	1.2	476	1.2
2004	462	1,753	3.8	13,389	29.0	4,306	9.3	574	1.2	574	1.2
2005	512	1,792	3.5	14,758	28.8	4,711	9.2	599	1.2	599	1.2
2006	550	1,992	3.6	15,740	28.6	4,892	8.9	663	1.2	663	1.2
2007	639	2,450	3.8	18,717	29.3	5,720	9.0	738	1.2	738	1.2
2008	646	2,552	4.0	18,887	29.2	5,589	8.7	774	1.2	774	1.2
2009	870	3,485	4.0	26,050	29.9	7,290	8.4	1,016	1.2	1,016	1.2
2010	796	3,314	4.2	26,057	32.7	6,815	8.6	952	1.2	952	1.2
2011	880	3,690	4.2	29,693	33.7	7,636	8.7	1,094	1.2	1,094	1.2
2012	958	4,158	4.3	32,627	34.1	8,328	8.7	1,165	1.2	1,165	1.2
2013	1,080	4,641	4.3	36,841	34.1	9,467	8.8	1,298	1.2	1,298	1.2
2014	1,103	4,984	4.5	39,043	35.4	9,964	9.0	1,364	1.2	1,364	1.2
2015	1,234	5,649	4.6	44,509	36.1	11,346	9.2	1,561	1.3	1,561	1.3
2016	1,410	6,504	4.6	54,884	38.9	13,625	9.7	1,771	1.3	1,771	1.3
Total	14,268	57,440		454,228		129,720		17,180		17,180	
Average			3.7		29.4		9.3		1.2		1.2

Note: TP – number of articles; AU – number of authors; NR – cited reference count; PG – page count; NI – institution count; NC – country count; and AU/TP, NR/P, PG/TP, NI/TP, and NC/TP – average number of authors, pages, references, institutions, countries, per articles.

(England), five journals are each from USA and Netherlands, one from Italy and Switzerland. The results revealed that research of developed countries on CWWT has always been in a dominant position. In addition, the ranking trend of the total number of articles, JIF and *h*-index was completely different. For example, *Desalination* and *Water Treatment are* ranked 2nd in top 20 most productive journals, while their corresponding JIF (1.631) and *h*-index (13) are ranked 16th and 20th, respectively; contrarily, with ranking of 15th among top 20 most productive journals, the JIF (6.198) and *h*-index (61) of *Environmental Science & Technology* are all ranked 3rd.

Research on CWWT involved 105 Web of Science categories because journals were classified into several subject categories. As illustrated in Fig. 3, there is a steady increment of CWWT related research starting from 2,000 in many subject categories. Engineering was the most common subject category, followed by environmental sciences & ecology, water resources, and chemistry. These top 4 subject categories had the same growth trend from 1992 to 2016. This is mainly because coagulation has already been a relatively mature technique in water treatment and widely used in engineering practice. Secondly, the research on the coagulation mechanism and coagulants is inseparable from the chemistry.

Of the 1,763 journals that published the 14,268 articles, according to the total number of articles and the percentage ranking, the productive four core journals related to CWWT from 1992 to 2016 are shown in Fig. 4. Approximately, 1,878 (13.2%) articles were published in these four journals. The number of articles published in *Desalination and Water Treatment* had slowly increased from 1992 to 2008 and significantly went up since 2008. The other three journals including *Water Research, Journal of Hazardous Materials, and Desalination*, which revealed the same growth trend and then fluctuated in recent years and showed a promising development since the year of 2002.

3.1.4. Publication performances: institutes and countries

According to the statistical analysis of the addresses and affiliates provided by the authors (at least one) of

Table 2
Top 20 most productive journals (1992–2016) with the number of papers, ISI category of journals, and the position of the journal in its category, JIF, *h*-index, and Journal Country

Journal	TP (%)	ISI category and position	JIF (R)	*h*-index (R)	Journal Country
Water Research	689 (4.8)	Engineering, Environmental (Q1: 2/49) Environmental Sciences (Q1: 8/229) Water Resources (Q1: 1/88)	6.942 (1)	93 (1)	England (UK)
Desalination and Water Treatment	500 (3.5)	Engineering, Chemical (Q3: 66/135) Water Resources (Q3: 43/88)	1.631 (16)	13 (20)	Italy
Journal of Hazardous Materials	362 (2.5)	Engineering, Environmental (Q1: 5/49) Engineering, Civil (Q1: 1/125) Environmental Sciences (Q1: 13/229)	6.065 (4)	67 (2)	England (UK)
Desalination	327 (2.3)	Engineering, Chemical (Q1: 11/135) Water Resources (Q1: 2/88)	5.527 (7)	41 (9)	Netherlands
Separation and Purification Technology	305 (2.1)	Engineering, Chemical (Q1:21/135)	3.359 (12)	39 (10)	Netherlands
Colloids and Surfaces A-Physicochemical and Engineering Aspects	289 (2.0)	Chemistry, Physical (Q2:65/145)	2.714 (13)	43 (8)	Netherlands
Journal of Membrane Science	275 (1.9)	Engineering, Chemical (Q1:8/135) Polymer Science (Q1:4/86)	6.035 (5)	61 (3)	Netherlands
Journal of Colloid and Interface Science	270 (1.9)	Chemistry, Physical (Q1:35/145)	4.233 (9)	47 (6)	USA
Water Science and Technology	268 (1.9)	Engineering, Environmental (Q3: 38/49) Environmental Sciences (Q4: 169/229) Water Resources (Q3: 61/88)	1.197 (17)	17 (17)	England (UK)
Chemical Engineering Journal	268 (1.9)	Engineering, Environmental (Q1:3/49) Engineering, Chemical (Q1:6/135)	6.216 (2)	38 (2)	Switzerland
Journal of Applied Polymer Science	241 (1.7)	Polymer Science (Q2:36/86)	1.860 (14)	28 (15)	USA
Environmental Technology	240 (1.7)	Environmental Sciences (Q3: 122/229)	1.751 (15)	21 (16)	England (UK)
Bioresource Technology	214 (1.5)	Agricultural Engineering (Q1:1/14) Biotechnology & Applied Microbiology (Q1:14/158) Energy & Fuels (Q1:9/92)	5.651 (6)	39 (10)	Netherlands
Langmuir	205 (1.4)	Chemistry, Multidisciplinary (Q2:46/166) Chemistry, Physical (Q2:41/145) Materials Science, Multidisciplinary (Q1:53/275)	3.833 (11)	49 (5)	USA
Environmental Science & Technology	201 (1.4)	Engineering, Environmental (Q1:4/49) Environmental Sciences (Q1:12/229)	6.198 (3)	61 (3)	England (UK)
Chemosphere	168 (1.2)	Environmental Sciences (Q1: 32/229)	4.208 (10)	45 (7)	England (UK)
Food Hydrocolloids	157 (1.1)	Chemistry, Applied (Q1:5/72) Food Science & Technology (Q1:5/129)	4.747 (8)	38 (12)	USA
Journal American Water Works Association	147 (1.0)	Engineering, Civil (Q3:90/125) Water Resources (Q4:72/88)	0.722 (20)	38 (12)	England (UK)
Separation Science and Technology	143 (0.9)	Chemistry, Multidisciplinary (Q3:117/166) Engineering, Chemical (Q3: 87/135)	1.106 (18)	17 (17)	USA
Journal of Water Supply Research and Technology-Aqua	135 (0.9)	Engineering, Civil (Q3:87/125) Water Resources (Q3:71/88)	0.824 (19)	17 (17)	England (UK)

Note: TP – number of articles; IF – impact factor; R – the rank during top 20 most productive journals.

journal articles, the research level, and achievements of various countries and territories agencies in the field of CWWT can be understood. 14,233 articles were analyzed except for 35, whose author addresses are all missing, on the basis of ISI Web of Science from 1992 to 2016. Among them, 133 countries/regions were involved. The analysis results of the top 20 most productive countries are shown in Table 3. It suggests that China and USA were the top two productive countries during the research period, accounting for 36.3% of total articles. In addition, the number of articles in China (2,826, 19.9%) and USA (2,335, 16.4%) were nearly three times of Canada (825, 5.8%). Moreover, 96.4% of the total numbers of articles are contributed from the top 20 most productive countries. The developed countries dominated by CWWT related research. In addition, some developing countries also made great contributions to the study of CWWT with 29.2%

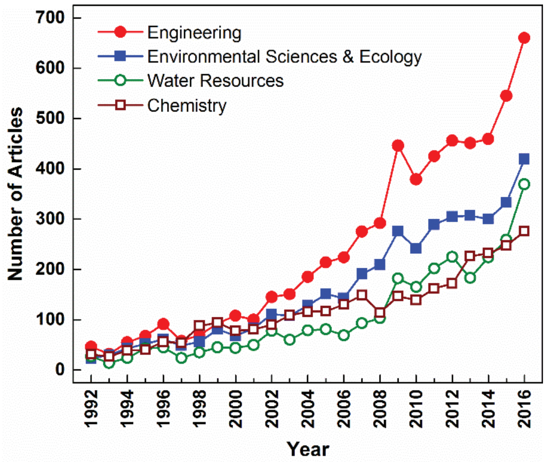

Fig. 3. Growth trends of the top four subject categories.

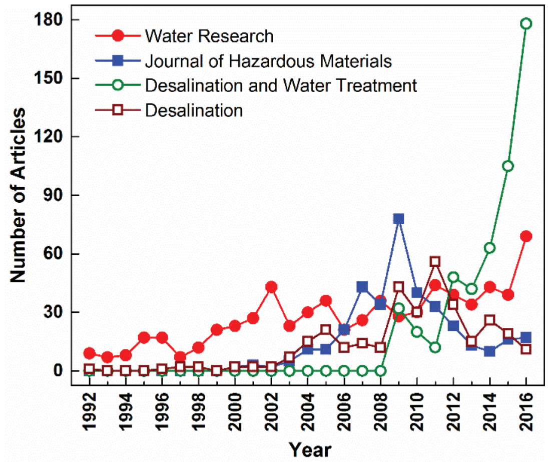

Fig. 4. Growth trends of the top four journals.

Table 3
Top 20 most productive countries of articles during 1992–2016

Country/Territories	TP	TP R (%)	Single Country SP	R (%)	Internationally-collaborated CP	R (%)	MC (P)	h-index [R]
China	2,826	1 (19.9)	2,237	7 (79.2)	589	14 (20.8)	USA (194)	76 (2)
USA	2,335	2 (16.4)	1,574	11 (67.4)	761	10 (32.6)	China (194)	112 (1)
Canada	825	3 (5.8)	545	13 (66.1)	280	8 (33.9)	USA (91)	60 (5)
UK	732	4 (5.1)	404	17 (55.2)	328	4 (44.8)	China (60)	68 (3)
JAPAN	681	5 (4.8)	512	9 (75.2)	169	12 (24.8)	China (41)	54 (9)
India	674	6 (4.7)	568	4 (84.3)	106	17 (15.7)	USA (18)	48 (12)
Australia	612	7 (4.3)	346	16 (56.5)	266	5 (43.5)	China (94)	61 (4)
France	563	8 (4.0)	284	20 (50.4)	279	1 (49.6)	USA (43)	59 (6)
South Korea	557	9 (3.9)	369	12 (66.2)	188	9 (33.8)	USA (65)	49 (11)
Spain	546	10 (3.8)	385	10 (70.5)	161	11 (29.5)	UK (21)	58 (7)
Germany	508	11 (3.6)	261	19 (51.4)	247	2 (48.6)	USA (43)	58 (7)
Taiwan	435	12 (3.1)	355	5 (81.6)	80	16 (18.4)	China (24)	47 (13)
Brazil	417	13 (2.9)	329	8 (78.9)	88	13 (21.1)	USA (16)	29 (18)
Turkey	383	14 (2.7)	331	2 (86.4)	52	19 (13.6)	USA (12)	53 (10)
Iran	363	15 (2.6)	309	3 (85.1)	54	18 (14.9)	Malaysia (15)	37 (16)
Poland	349	16 (2.5)	307	1 (88.0)	42	20 (12.0)	Norway (6)	19 (20)
Netherlands	267	17 (1.9)	155	15 (58.1)	112	6 (41.9)	USA (20)	43 (14)
Russia	243	18 (1.7)	194	6 (79.8)	49	15 (20.2)	Germany (15)	22 (19)
Malaysia	223	19 (1.6)	143	14 (64.1)	80	7 (35.9)	Iran (15)	34 (17)
Sweden	211	20 (1.5)	112	18 (53.1)	99	3 (46.9)	Finland (13)	39 (15)

Note: TP – articles in the study period; R (%) – the rank of total articles; SP – Single-country articles; CP – internationally collaborated articles; MC [P] – major collaborator (the number of collaborated articles between two countries).

of total articles. Especially, for the top 20 most productive countries, there are seven major industrialized countries, including Canada, France, Germany, Italy, Japan, the UK, and the USA, accounting for 41.1% (5,844) of total articles, and other 10 developing countries, accounting for 44.9% (6,388) of total articles.

The comparison of the growth trends of articles and citations per year between USA and China were investigated. Fig. 5 shows that the USA is ranked 1st with respect to the number of published articles per year from 1992 to 2016 (except in 2000). Furthermore, the research history of USA was much longer than China in this field of CWWT. The first paper of USA was published in 1929 while China published its first paper 62 years later. In addition, from the overall view, the number of citations per article in the USA was always higher than in China. However, the progress and significant impact that China has made on CWWT should not be ignored. The number of articles in China had experienced rapid growth during the last 10 years and even surpassed the USA in 2007, mainly due to human's concern for environmental issues and the development of education.

Fig. 6 shows the cooperation between countries, the most productive countries were USA and China. USA and China had cooperated with 27 and 13 countries respectively on

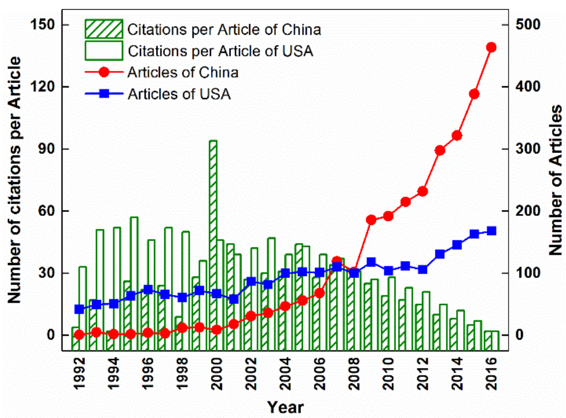

Fig. 5. Growth trends of articles and citations per year in USA and China from 1992 to 2016.

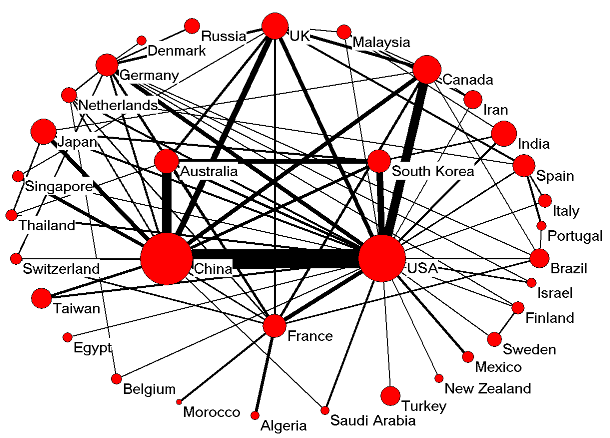

Fig. 6. Network diagram showing cooperation between countries with a minimum of 10 articles.

CWWT. The closest cooperation relationship was between China and USA with 194 cooperative articles. Other major cooperative countries were UK (9) and Canada (8). And the number of cooperation articles of China-Australia (94) and USA-Canada (91) were more than 90. According to the analysis of Fig. 6, it is not difficult to find that collaborative countries tended to be geographically correlated.

At the institution level, 14,233 articles were from 7,609 institutes in 205 countries, and 7,013 (49.3%) were independent publications, and 7,220 (50.7%) were inter-institutionally collaborative publications. The percentage of collaboration between countries (17.8%) was much lower than that between institutes. Table 4 shows the top 20 most productive institutes during the research period. There were ten institutes in China, and two each in Australia and UK, and one each in USA, Singapore, India, Malaysia, Canada, and Russia.

With the *h*-index of 40 (2nd), the Chinese Academy of Sciences, China is the most productive institute for the total articles (437), owning the maximum number of single institute articles (129), first authored articles (316), and corresponding authored articles (308), and its inter-institutionally collaborative articles (109) is also ranked 1st. It is well to be reminded that the Chinese Academy of Sciences, China, is not a separate research institution. It also includes multiple institutes in various fields in many cities. In this study, the publications of these institutes were considered as one heading if articles were divided into various branches the rankings would be the difference. In addition to the Chinese Academy of Sciences, China, Shandong University, with 202 articles, Harbin Inst Technology, with 192 articles, and University Massachusetts, with 150 articles, respectively ranked 2nd, 3rd, and 4th. Interestingly, Shandong University ranked 2nd with 202 articles, but the collaborative articles (90) ranked 16th, and Univ Leeds, UK, with *h*-index of 34 (4th) but ranked 18th in total articles. Furthermore, the top 20 most productive institutions were scattered in nine countries, and ten institutions were all from China. In addition, it is not difficult to find that institutions from the same country or territory were more likely to collaborate from Table 4.

3.2. Research tendency and hotspot

3.2.1. Author keywords

In recent years, bibliometric analysis of author keywords in different periods was used widely which could help researchers to quickly grasp the latest research trends in the academic field [20,21].We analyzed the 11,478 articles with author keywords information in this paper. The statistical result indicates that 222,418 author keywords were used between 1992 and 2016, however, 16,737 (74.7%) keywords were used only once, 2,515 (11.2%) keywords were used twice. A large proportion (85.9%) of the author's keywords appeared only once or twice, which reveals that the research lacks continuity and depth in the field. Only 845 (3.8%) keywords were used over ten times, indicating the hot issues in the field of CWWT. Changes of the keyword ranking with an interval of 5 years are indicative of research frontier. Table 5 shows the top 30 frequently used keywords from 1992 to 2016.

Table 4
Top 20 most productive institutions of articles during 1992–2016

Institution	TP	TP	Single-institution		Inner-institution collaborated			*h*-index
		R (%)	SP	*R* (%)	CP	*R* (%)	MC (P)	
Chinese Acad Sci, China	437	1 (3.1)	129	17 (29.5)	308	4 (70.5)	Univ Chinese Acad Sci, China (35)	40 (2)
Shandong Univ, China	202	2 (1.4)	112	5 (55.4)	90	16 (44.6)	Univ Technol Sydney, Australia (18)	31 (7)
Harbin Inst Technol, China	192	3 (1.3)	60	14 (31.3)	132	7 (68.8)	Tongji Univ, China (12)	32 (5)
Univ Massachusetts, USA	150	4 (1.1)	68	9 (45.3)	82	12 (54.7)	King Abdulaziz Univ, Saudi Arabia (14)	43 (1)
Tongji Univ, China	142	5 (1.0)	44	15 (31.0)	98	6 (69.0)	Harbin Inst Technol, China (12)	28 (9)
Natl Taiwan Univ, Taiwan	131	6 (0.9)	46	12 (35.1)	85	9 (64.9)	Taipei Med Univ, Taiwan (13)	29 (8)
Indian Inst Technol, India	117	7 (0.8)	70	3 (59.8)	47	18 (40.2)	Univ Lucknow, India (7)	32 (5)
Zhejiang Univ, China	104	8 (0.7)	61	4 (58.7)	43	17 (41.3)	Tongji Univ, China (4)	22 (12)
Russian Acad Sci, Russia	98	9 (0.7)	51	6 (52.0)	47	15 (48.0)	Tomsk State Univ, Russia (5)	14 (20)
Tsinghua Univ, China	96	10 (0.7)	25	19 (26.0)	71	2 (74.0)	Natl Univ Singapore, Singapore (4)	15 (19)
Natl Univ Singapore, Singapore	96	10 (0.7)	40	10 (41.7)	56	11 (58.3)	Inst Mat Res & Engn, Singapore (9)	37 (3)
Univ Alberta, Canada	94	12 (0.7)	38	11 (40.4)	56	10 (59.6)	Syncrude Canada Ltd, Canada (8)	21 (13)
S China Univ Technol, China	89	13 (0.6)	43	7 (48.3)	46	14 (51.7)	Minist Educ, China (10)	20 (15)
Univ Sains Malaysia, Malaysia	85	14 (0.6)	51	2 (60.0)	34	19 (40.0)	Univ Malaysia Perlis, Malaysia (6)	26 (10)
Univ Technol Sydney, Australia	85	14 (0.6)	26	16 (30.6)	59	5 (69.4)	Chonnam Natl Univ, South Korea (26)	20 (15)
Univ S Australia, Australia	75	16 (0.5)	21	18 (28.0)	54	3 (72.0)	Chinese Acad Sci, China (18)	21 (13)
Nanjing Univ, China	69	17 (0.5)	32	8 (46.4)	37	13 (53.6)	Nanjing Normal Univ, China (8)	19 (17)
Univ London Imperial Coll Sci Technol & Med, UK	68	18 (0.5)	17	20 (25.0)	51	1 (75.0)	Chinese Acad Sci, China (6)	23 (11)
Univ Leeds, UK	68	18 (0.5)	43	1 (63.2)	25	20 (36.8)	Russian Acad Sci, Russia (3)	34 (4)
Chongqing Univ, China	67	20 (0.5)	21	13 (31.3)	46	8 (68.7)	Beijing Forestry Univ, China (8)	16 (18)

Note: TP – articles in the study period; *R* (%) – the rank of total articles; SP – Single-institution articles; CP – Inner-institution

Due to "coagulation", "flocculation", "wastewater", "waste water", "waste-water" and "water" being searched as titled words, so we should ignore these most frequently author keywords. According to the results of Table 5, the three most frequently used keywords were "electrocoagulation" (492; 4.3%), "adsorption" (465; 4.1%), and "water treatment" (441; 3.8%). Those three keywords reflect that coagulation technique is a high-efficiency approach for water treatment, including wastewater treatment (319; 2.8%), drinking water (222; 1.9%) and drinking water treatment (112; 1.0%). Electrocoagulation, ranked 296 before 2000, however it attracted more attention since 2000 ranked even to 3rd. In addition, ''chitosan'' and "Zeta potential" will always be future hot issues because both of them ranked in the top 20 or so from 1990. Chitosan is a polymer coagulant organic with non-toxic and easily biodegradable characteristics, now widely used in drinking water treatment, and researchers have found that when mixing chitosan with other inorganic, organic flocculants to form a composite flocculant in drinking water treatment and a great effect was obtained. Zeta potential test can be used widely to determine the optimal conditions for coagulation experiment quickly and accurately [22]. Schward's research shows that the best coagulation efficiency can be achieved when the surface charge of the particles is close to zero or positive, and this condition can be obtained by adding suitable coagulants and selecting appropriate conditions [23].

The top 30 author keywords included the most important topics on CWWT related research as fellows: coagulation (flocculation, aggregation, sedimentation, electrocoagulation, and coagulation) (3,728; 16.6%), coagulant (chitosan and coagulant) (424; 1.9%), water treatment (wastewater treatment, water treatment, drinking water treatment, drinking water, and wastewater) (1,370; 6.1%). We all know that coagulation, the most widely used methods in wastewater treatment, or in drinking water, landfill leachate and textile wastewater. It can be used as a separate processing system but also can combine with other processing units. Coagulation can reduce the turbidity and color of wastewater, moreover, it can also remove varieties of organic compounds, heavy metals, and some radioactive substances. And the most important factor of efficiency is coagulants or flocculants. Chitosan may be welcomed mostly compared with another inorganic coagulant in the contemporary, which is the second largest

Table 5
Top 30 frequently used substantives in author keywords during 1992–2016 and five five-year periods

Author keyword	92–16 TP	92–16 *R* (%)	92–96 *R* (%)	97–01 *R* (%)	02–06 *R* (%)	07–11 *R* (%)	12–16 *R* (%)
Coagulation	1,607	1 (14.0)	2 (11.3)	2 (11.3)	1 (15.3)	1 (15.7)	1 (13.2)
Flocculation	1,142	2 (9.9)	1 (14.0)	1 (12.9)	2 (12.3)	2 (9.8)	2 (8.3)
Electrocoagulation	492	3 (4.3)	296 (0.2)	179 (0.3)	9 (2.3)	3 (5.9)	3 (5.0)
Adsorption	465	4 (4.1)	5 (2.7)	4 (4.1)	4 (4.5)	4 (4.0)	4 (4.0)
Water treatment	441	5 (3.8)	3 (3.3)	5 (3.0)	3 (5.6)	5 (3.6)	5 (3.6)
Wastewater treatment	319	6 (2.8)	5 (2.7)	13 (1.7)	10 (2.2)	7 (2.9)	6 (3.1)
Ultrafiltration	317	7 (2.8)	117 (0.4)	26 (1.3)	6 (2.6)	6 (3.2)	7 (3.0)
Wastewater	276	8 (2.4)	10 (2.0)	5 (3.0)	13 (1.9)	8 (2.7)	9 (2.3)
Emulsion	268	9 (2.3)	9 (2.2)	3 (5.0)	5 (3.9)	14 (1.6)	14 (1.8)
Natural organic matter	248	10 (2.2)	117 (0.4)	19 (1.4)	8 (2.4)	9 (2.6)	10 (2.1)
Turbidity	233	11 (2.0)	27 (1.1)	7 (2.8)	17 (1.6)	11 (2.1)	11 (2.1)
Drinking water	222	12 (1.9)	16 (1.6)	19 (1.4)	16 (1.7)	10 (2.1)	12 (2.0)
Chitosan	221	13 (1.9)	60 (0.7)	15 (1.6)	11 (2.1)	12 (2.0)	13 (2.0)
Coagulant	203	14 (1.8)	7 (2.4)	17 (1.5)	7 (2.5)	13 (1.8)	19 (1.5)
Membrane fouling	180	15 (1.6)	N/A	110 (0.4)	73 (0.6)	17 (1.4)	8 (2.4)
Zeta potential	176	16 (1.5)	20 (1.3)	11 (1.8)	13 (1.9)	18 (1.4)	20 (1.5)
Flocculant	171	17 (1.5)	16 (1.6)	19 (1.4)	24 (1.4)	14 (1.6)	21 (1.5)
Membrane	166	18 (1.4)	117 (0.4)	19 (1.4)	17 (1.6)	22 (1.2)	15 (1.6)
Microfiltration	161	19 (1.4)	27 (1.1)	51 (0.8)	23 (1.5)	14 (1.6)	23 (1.4)
Rheology	156	20 (1.4)	20 (1.3)	8 (2.1)	12 (2.0)	29 (1.0)	24 (1.3)
Sedimentation	153	21 (1.3)	4 (3.1)	13 (1.7)	17 (1.6)	19 (1.3)	32 (1.0)
Filtration	134	22 (1.2)	10 (2.0)	30 (1.1)	17 (1.6)	29 (1.0)	28 (1.1)
Activated sludge	132	23 (1.2)	16 (1.6)	43 (0.9)	21 (1.6)	26 (1.1)	28 (1.1)
Aggregation	131	24 (1.1)	27 (1.1)	15 (1.6)	15 (1.7)	41 (0.9)	32 (1.0)
Fouling	130	25 (1.1)	296 (0.2)	277 (0.2)	31 (1.0)	29 (1.0)	17 (1.5)
Ozonation	128	26 (1.1)	38 (0.9)	30 (1.1)	31 (1.0)	20 (1.3)	26 (1.1)
Stability	127	27 (1.1)	38 (0.9)	9 (2.0)	22 (1.5)	34 (0.9)	40 (0.9)
Humic acid	113	28 (1.0)	38 (0.9)	82 (0.5)	56 (0.7)	20 (1.3)	35 (1.0)
COD	113	28 (1.0)	117 (0.4)	51 (0.8)	41 (0.8)	22 (1.2)	36 (1.0)
Drinking water treatment	112	30 (1.0)	20 (1.3)	62 (0.7)	56 (0.7)	24 (1.2)	36 (1.0)

TP– articles in the study period, *R* (%)– the rank and percentage of the author keywords; N/A– No Available.

renewable resource on earth. And it is not toxic and harmless, but it can be biodegradable completely. The sludge can be used as fertilizer, so it is a rare environmental water treatment agent.

3.2.2. Hot issues

The purpose of statistical analysis is to search for the trend of scientific research, which could help researchers to master the research trends quickly. Researchers could summarize high –frequency words to obtain research hotspots. Through the combination of the author names, title, and abstract, this method could be used to trace the research frontier of previous work. [24–27]. This new method named "word cluster analysis" [28] has been used comprehensively.

Research tendency on CWWT was separated and extracted into four categories: the variation of water, the pollutant species, the novel technique types, and the diversity of coagulants. The attention of the research work was mainly focused on the treatment of drinking water, wastewater, landfill leachate, and textile wastewater. For target pollutants, organic matters, heavy metals, humic substances, and suspensions were given priority for a research study. The novel techniques developed recently including ultrafiltration, microfiltration, nanofiltration, and electrocoagulation, and the commonly used coagulants were chitosan, polyacrylamide (PAM PAC, and ferric chloride. The general growth tendency of related research frontier during last 25 years is shown in Fig. 7.

As shown in Fig. 7(a), coagulation technique was mainly applied in disposing drinking water in the early days as it was an important integral component of the conventional treating process [29]. The newly occurred problem of micro-polluted source water (both surface and groundwater) has further

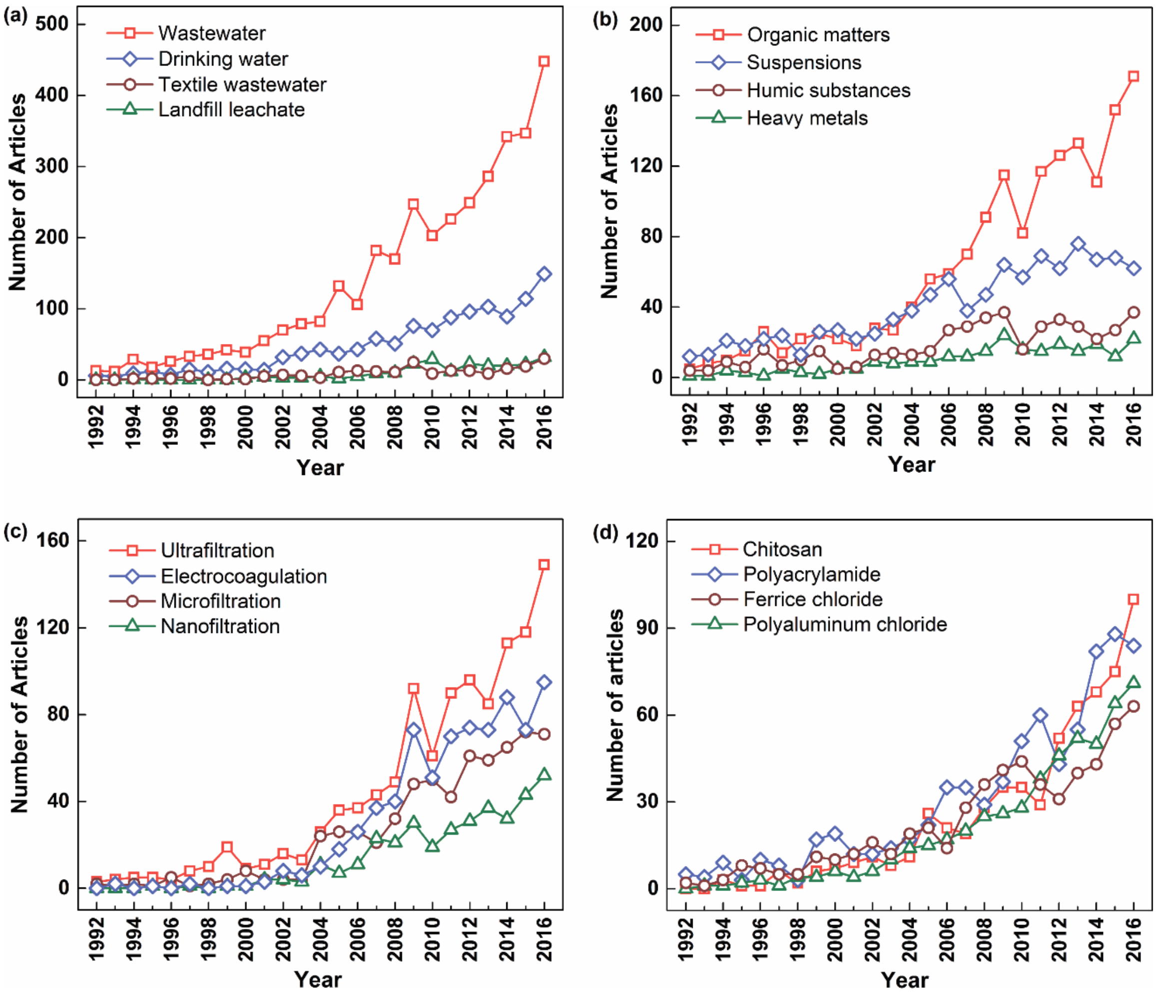

Fig. 7. Growth trends of hotspot-related articles from 1992 to 2016.

intensified the coagulation-related research work for drinking water treatment. As modernization, industrialization, and urbanization continue to increase, a large amount of municipal and industrial wastewater was produced. Consequently, more and more application of coagulation technology for the wastewater treatment has been reported. More specifically, the research of sewage is mainly about the landfill leachate and the textile wastewater.

Word cluster analysis showed that the main pollutants in drinking water and wastewater include organic matters, suspensions, humic substances, and heavy metals as shown in Fig. 7(b). The high content of organic matters is one of the major problems when treating drinking water, especially natural organic matter (NOM), a complex mixture of organic substances produced in aquatic ecosystems via various biological, geological, and hydrological cycles [10,30]. Natural organic matter in the water causes the problem of odor production, corrosion, biofilm growth in the distribution network, and which is also taken as one of the main causes of fouling of membranes [31–34]. The occurrence of natural organic matter in raw water has greatly challenged the treatment of drinking water since it has been the bottleneck for the conventional treating process, mainly due to the increased fluctuation of NOM in water (concentration and composition). Therefore, developing enhanced coagulation processes and searching for excellent technology to remove natural organic matter with high efficiency are necessary.

To meet the standards of drinking water or wastewater, finding excellent technology with high efficiency is necessary because conventional coagulation technique alone cannot adapt variable wastewater to meet strict water quality requirements. The combination of coagulation and other water treatment processes has a greater advantage for higher removal efficiency and lower coagulant dosage [35]. For example, using coagulation technique as a pretreatment in front of the membrane treatment cannot only remove hydrophobic organic matter, increase membrane flux, and decrease membrane contamination, but also control the production of disinfection by-products [36]. Using membranes has been utilized to treat municipal and industrial water [37]. In recent years, ultrafiltration, microfiltration, and nanofiltration membranes have rapidly increased in the field of drinking water treatment. However, membrane fouling could induce the degradation of membrane performance, mainly due to the deposition of small organic molecules on the membrane surface or inside the membrane pores [38]. Electrocoagulation can effectively absorb most of the organic materials, especially in removing organic compounds with less than one thousand molecular weight [39]. Therefore, electrocoagulation can prevent membrane fouling to some extent and be more effective than conventional coagulation techniques in removing natural organic matter, heavy metals, and humic substances from water. Moreover, electrocoagulation has been an effective treatment, because most of the suspended solids in the original sewage have been removed by the pretreatment. In the electrolysis process, the phenomenon of electrode surface adhesion does not appear and the electrode oxidation capacity cannot be reduced. The removal efficiency is very great even under harsh environmental conditions [40]. In addition, oxidation, adsorption, and ion exchange are also advanced technology that can be integrated with traditional coagulation technique.

The core of the coagulation and sedimentation process is the application of coagulants (coagulants' type and dosage), which determine the quality of the effluent and the cost of the coagulation process. In real practice, the main coagulants consist of inorganic materials with low molecules (e.g., ferric chloride), inorganic polymer (e.g., poly aluminum chloride), and modified organic polymer (e.g., chitosan), as shown in Fig. 7(d). The natural polymer coagulants, which are non-toxic, have no secondary pollution, efficient and easy to degrade, and serve as a renewable resource, should be focused on in further study [18]. The turbidity capability of chitosan is far superior to those of traditional polyacrylamide, poly aluminum chloride, and ferric chloride. The removal rate of COD is more than 85%. Combining two or more coagulants (metallic and polymeric, synthetic or natural) can benefit for the advantages of each other, while mutually overcoming their shortcomings, which is considered an effective way to improve the efficiency of the coagulation process in wastewater and drinking water treatments [41]. More and more novel composite or hybrid coagulants have been developed via various combination schemes, for example, the chitosan-aluminum chloride dual-coagulant removal technology can treat toxic cyanobacteria effectively in conventional treatment [19], polyferric chloride-lignin-acrylamide polymer and a zirconium-glycine complex for the removal of natural organic matter or humic acids from natural waters or synthetic solutions [42,43].

Given the continuous improvement of drinking water quality, further removing the pollutants for coagulation technique remains a challenge, which is also a great driving force to promote the development of the coagulation technique. Two main pathways are capable to obtain this objective. One way is to explore new coagulants, such as calcium aluminate, polyaluminum sulfate, potassium ferrate, and microbial flocculant [44]. However, in terms of the present stage, the treatment effect is not ideal. Thus, an adaptive application technology for different water quality should be further developed. The other way is to develop new types of coagulation based technologies. Considering the lack of water resources and water pollution, these technologies greatly increase the operation difficulty and cost of water mixing and coagulation. Therefore, developing new and efficient coagulation technology is necessary. The research and development of electrocoagulation, coagulation-membranes, and other technologies have achieved a breakthrough, and have a great significance for the improvement of water treatment technology [45].

3.2.3. A case study of the pre- and post-treatment on landfill leachate by coagulation technique

Leachates from municipal solid waste landfills are normally categorized as the hazardous and heavily polluted wastewater [46,47]. The characteristic features of landfill leachate are determined by the type of municipal solid waste being dumped, site hydrology, moisture content, the degree of solid waste stabilization, seasonal weather variations, landfill age, and the stage of decomposition in the landfill. After stabilization, the leachate are high strength of ammonia (3,000–5,000 mg L^{-1}) and chemical oxygen demand COD (5,000–20,000 mg L^{-1}), and low ratio of BOD_5/COD (<0.1) [48,49]. Landfill leachates could percolate through soils and subsoil and have been identified as potential sources of surface water contamination. Without proper collection, treatment and disposal, it could lead to severe, pollution of water such as streams, creeks, and water wells [49,50]. Coagulation/Precipitation technique has been used in landfill leachate as a pretreatment or deep treatment.

As a pretreatment of the landfill leachate, coagulation/precipitation technique can effectively improve the biochemical properties of leachate, reduce bio-toxicity, and remove most heavy metals at the same time [51]. The study indicated that the removal rate of the inorganic heavy metals was about 20% and those of some fungicides (e.g., dichlorodiphenyltrichloroethane, camphor) can be as high as 100% [45,52]. Toxicology experiments showed that garbage leachate toxicity can be reduced by more than 50% after coagulation treatment [53].

As deep treatment of landfill leachate, coagulation/precipitation technique is usually used for effluent of biochemical treatment, and COD removal was about 20% [54]. Guo reported that the combination of air stripping–Fenton–SBR–coagulation demonstrated outstanding treatment performances in the overall removal of COD (93.3%) and NH_3–N (98.3%) [55]. Moreover, coagulation technique can also be used for color removal, ferric chloride was superior to other metal salts at 800 mg/L and at pH 4, with over 94% removal [56,57].

4. Conclusions

Based on 16,866 articles of CWWT related research included in SCI-EXPANDED, the historical overview and development trends in the future were obtained by bibliometric analysis. Research related to CWWT has obviously increased over the last two decades. An index model was used to indicate the relationship between the year and the cumulative number of articles. Based on the index model, the number of articles in 2025 would be doubled than that in 2016. There are totally 1,763 journals published in 105 subject categories. The most productive journal on CWWT was *Water Research* with a top *h*-index of 93, accounting for 4.8% of overall, followed by *Desalination and Water Treatment* and *Journal of Hazardous Materials*. Engineering, environment sciences & ecology, water resources, and chemistry were the top four subject categories with same growth trends. Among all countries and intuitions, China and Chinese Academy of Sciences, China is ranked No.1, respectively. Moreover, with the highest *h*-index of 112 USA is the major collaborator with other nine countries of top 20 most productive countries.

The application of the word cluster analysis in tracing the frontier research on CWWT related research shows that coagulation is an important unit of water purification process and mainly used for drinking water and wastewater treatments. In the treatment of wastewater, about 12.7% research is about landfill leachate and textile wastewater. In these varieties waters, the main pollutants consist of organic matter, suspensions, humic substances, and heavy metals. In addition, the removal of the natural organic matter is one of the most important treatment requirements for the production of drinking water. Thus, coagulation technique alone cannot meet several strict requirements. Coagulation technique should be used with other membranes, such as ultrafiltration, microfiltration, nanofiltration, and electrocoagulation. Equally, the important factor is the type of coagulants, which determines the quality of the water treatment and the cost of the coagulation process. In practical engineering applications, the main coagulants consist of low inorganic molecules, such as ferric chloride, inorganic polymers (e.g., poly aluminum chloride), and modified organic polymer chitosan. Composite coagulants have been widely used in many applications, and microbial coagulants have improved the problems of secondary pollution and residual quantity, thus they will be used as a new generation of coagulants. The method described in this paper had been proved to be an effective approach reflecting the global trend and research focusing on the coagulation technique of water and wastewater treatment. The information of coagulation technique also provides a clear overview of their impact histories.

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