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A bibliometric analysis of industrial wastewater treatments from 1998 to 2019☆

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ABSTRACT

For the foreseeable future, industrial water demand will grow much faster than agriculture. The demand together with the urgency of wastewater treatment, will pose big challenges for most developing countries. We applied the bibliometric analysis combined with social network analysis and S-curve technique to quantitatively analyze 9413 publications related to industrial wastewater treatment in the Scientific Citation Index (SCI) and Social Sciences Citation Index (SSCI) databases from 1998 to 2019. The results showed that: (1) Publications on industrial wastewater treatment have increased from 120 in 1998 to 895 in 2019 with a steady annual increment rate, and researchers have focused more on the application and optimization of existing technologies. (2) China had the highest number of publications ($n = 1651$, 19.66% of global output) and was a core country in the international cooperation network, whereas the United States and European countries produced higher quality papers. (3) By analyzing the co-occurrence and clusters of keywords and comparing three wastewater treatment categories (physical, chemical, biological), adsorption ($n = 1277$), oxidation ($n = 1085$) and activated sludge process ($n = 1288$) were the top three techniques. Researchers have shifted their focus to treatment technologies for specific wastewater type, such as textile wastewater, pulp and paper wastewater, and pharmaceutical wastewater. The S-curve from articles indicates that physical and chemical treatment technologies are attached with great potential in the near future, especially adsorption and advanced oxidation, while the biological treatment technologies are approaching to the saturation stage. Different pattern is observed for the S-curve derived from patents, which stressed the limited achievement until now and further exploration in the field application for the three treatment categories. Our analysis provides information of technology development landscape and future opportunities, which is useful for decision makers and researchers who are interested in this area.

1. Introduction

Globally, the industrial demand for water will continue to grow significantly driven by population growth, economic development and other socio-economic factors (United Nations World, 2018). However, rapid industrial development has caused serious water pollution. Major polluting industries, such as the textile industry, paper industry, and printing and dyeing industry, emit large quantities of wastewater, containing various pollutants, e.g. toxic heavy metals, phenolic organic compounds and other persistent organic pollutants (Fu and Wang, 2011). These pollutants have caused serious environmental and human health problems and threatened the Target 6.3 in Sustainable Development Goal 6, which have accelerated the establishment of more strict emission and recovery standards in developing countries (Anastopoulos et al., 2015). Besides, after appropriate treatment, wastewater is regarded as potential water resource for recycling and reuse, which is associated with economic and financial benefits (United Nations Worl, 2017).

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The industrial wastewater treatment is complicated considering the various compounds at different concentration levels contained in the wastewater. Moreover, the treatment is rather challenged considering that each type of industrial wastewater is different, and varied even within an industry depending on specific production process. At present, researchers have carried out a large number of valuable researches or reviews on industrial wastewater treatment technologies, such as adsorption (Babel and Kurniawan, 2004), membrane filtration (Leiknes, 2009), advanced oxidation process (Comninellis et al., 2008; Stasinakis, 2008), membrane bioreactor (Dvorak et al., 2016) and so on. The research involved the performance optimization of technologies (Chen et al., 2003; Guinea et al., 2010), the dynamics and mechanism of treatment processes (Kannan and Sundaram, 2001; Sauer et al., 2002), and the removal of a specific pollutant (Mohammadi et al., 2015), etc. While there is a lack of quantitative methods to systematically summarize the entire industrial wastewater treatment literature. It is difficult to understand the research hotspot and future research trends in the field of industrial wastewater from a macro perspective.

Bibliometrics is one of the most effective tools for quantitative and qualitative analysis of scientific activities (Wallin, 2005). Bibliometrics focuses on analyzing the quantity of the external features of the literature (such as articles, books and patents) and references (citations and co-citations) by using statistical and mathematical methods to discover quantitative patterns based on the subject matter (Chiu and Ho, 2005; Zhou et al., 2007). Statistical indicators are used to evaluate the research productivity of individuals, institutions or countries in a certain field, and the output measurements can provide good knowledge and information about the state of research, thus helping researchers to identify and develop new research directions (De Battisti and Salini, 2013). Generally, bibliometrics can be divided into two categories. One category is based on the level of activity, which provides data on the influence of research, such as hot topics in this field, pivotal countries and journals. The other category is applying relationship indicators and social network analysis to trace links and interrelationships between different keywords, countries and institutes (Ramos-Rodriguez and Ruiz-Navarro, 2004). These two categories ultimately show us what topics, themes, and research methods are central or peripheral to a field and how they changed over time. Although some researchers have conducted valuable bibliometric analysis on industrial wastewater, there are still some limitations. Some researchers focused on limited research coverage, e.g. only in Arab region (Zyoud et al., 2016), others analyzed some certain topics, e.g. granular sludge (Zheng et al., 2018), membrane water treatment technology (Dai et al., 2015), biodegradation and photocatalytic degradation (Singh and Borthakur, 2018), pharmaceutical wastewater treatment (Qian et al., 2015), advanced oxidation process (Garrido-Cardenas et al., 2020; Usman and Ho, 2020), nitritation-anammox process (Kumwimba et al., 2020). Despite one global study (Zheng et al., 2015), the technology development landscape derived from both scientific research and R&D outputs are less understood, which relies on both paper and patent datasets analysis. The combination of literature and patent outcomes have the advantage of identifying the technology development pace, extent to better inform future technological theoretical innovation and basic research directions (Ardito et al., 2018).

To fill the research gap in previous studies, this study used bibliometric analysis to quantitatively and qualitatively evaluate the publications of industrial wastewater treatment from 1998 to 2019 based on research paper and patents database. Specifically, (1) we analyzed the overall research output of industrial wastewater and the research productivity of global countries in this field; (2) we analyzed keywords and summarized research hotspots in this field by using social network analysis; (3) we identified technological development processes, hotspots and trends by using S-curve derived from article and patent database, which can provide quantitative and qualitative scientific guidance for the future industrial wastewater treatment research.

2. Methods

2.1. Bibliometric analysis

We used the keywords ("wastewater treat*" or "water pollution control" or "polluted water control" or "sewage treat*" or "effluent treat*") AND ("industrial" or "industry") to search the Web of Science Core Collection between 1998 and 2019. We obtained 9413 publications, and then extracted various records for these publications, including keywords, author information, institutional affiliation, journals and citations, which allowed us to determine the academic performance, key issues and solutions in the field of industrial wastewater treatment. Descriptive statistical analysis was done by using Microsoft Excel 2016 software, including publication types, contributions of different countries and occurrence frequencies of keywords. In order to analyze the academic influence of different countries, we employed the h-index, which could measure the productivity and citation impact of the publications of a scientist or scholar. The original definition of the h-index, proposed by Hirsch, was that a scientist with an index of h has published h papers, each of which has been cited by other papers at least h times (Hirsch, 2005). The main advantages of this index are that it is simple to compute and it considers both the quantity and the impact of a researcher's publications (Alonso et al., 2009).

2.2. Social network analysis

Social network analysis (SNA) uses network and graphical theories to determine social structure, which conceptualizes the social structure or ties connecting members and resources. SNA focuses on the characteristics of relationships rather than on the characteristics of individual members (Otte and Rousseau, 2002). The data from bibliometric analysis can be used to visualize networks. The visual representation of social networks is crucial to understand the network and convey the results. We used SNA to track international collaboration patterns among the top 30 productive countries and construct keyword networks of different stages, so as to better explore the implicit information of publications and understand the relationships. The occurrence and co-occurrence frequencies of countries and keywords were both calculated by Bibexcel software. The symmetric proximity matrixes established by Bibexcel could be directly used as inputs to the mapping software Pajek to visualize their network relationships (Kim and Jang, 2018; Hu et al., 2020).

2.3. S-curve

Many simulation methods have been developed to predict the future of technologies. Since a product or technology is expected to follow an S-curve, many researchers used the S-curve to simulate the technology development to assess the technological maturity (Bengisu and Nekhili, 2006; Liu and Wang, 2010; Du et al., 2019). The evolution of technical systems generally goes through four stages: emerging, growth, maturity and decay (saturation) (Ernst, 1997), which could be obtained by the S-curve simulation. To quantitatively analyze the future development of industrial wastewater technology, we employed the Logistic model (performed in Loglet Lab 4 software developed by Rockefeller University) to make S-curve simulations of three major treatment technology categories (physical, chemical, and biological), as

Equation (1) showed:

$$Y_t = \frac{K}{1 + e^{-a(t-b)}} \tag{1}$$

where Y_t represents the dependent variable for S-curve, i.e. the cumulative publications annually, t represents the time variable for the S-curve, a and b are model parameters, and K is the "publication ceiling value" in this study (Franses, 1994).

2.4. Patent analysis

The patent information contains the information related to technology, economy, management and law. Patent analysis can analyze the above-mentioned content in the patent literature, the technology development in a certain field and predict the future development trend (Daim et al., 2006). To make a comprehensive analysis of industrial wastewater treatment technology, we used the same search strategy (keywords and time horizon) as that of the bibliometric analysis to search the Derwent database. The extracted patents were classified by their international classification code into three technology categories, and logically arranged by S-curve. The simulation results were compared with the S-curve derived from the articles, to supplement the research hotspots relevant with R&D activities, which may be missed in the bibliometric analysis of scientific research articles.

3. Results and discussion

3.1. Publication types

The total 9413 publications can be categorized into 12 types. Among them, "Article" accounted for 89.64% of the total publications (8438 articles) and was the most frequent type. The remaining publication types were "Review" (9.90%), "Proceedings Paper" (8.79%) and Others (e.g., "Editorial Material", "Book Chapter", "Meeting Abstract", and "Book Review"). Given that "Article" was the dominant type of publications, only articles were analyzed in later analysis.

With the expansion of industrial development and the increasingly serious problems of water pollution, the number of articles related to industrial wastewater treatment increased from 120 in 1998 to 895 in 2019 (Fig. 1). However, the annual growth rate of published articles did not change much. The main reason may be that some pioneering traditional wastewater treatment technologies, such as filtration, the activated sludge, rotating biological reactors, membrane bioreactors, etc., were proposed and studied by researchers in the twentieth century (Lofrano and Brown, 2010). Over the past two decades, the studies have shifted their focus to innovative and practical treatment technologies and treatment materials for industrial wastewater.

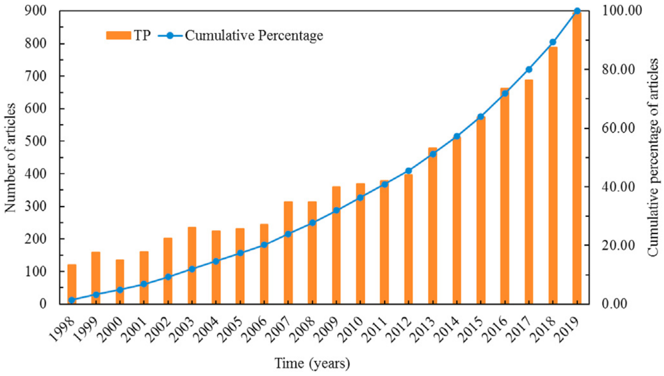

Fig. 1. Annual articles and cumulative percentage of articles on industrial wastewater treatment. Note: The blue curve represents the cumulative percentage of articles in each year. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.2. Country performance

3.2.1. Contributions of different countries

We analyzed the contributions of various countries by extracting the address information of the authors, and found that the authors were from 120 countries/regions. Table 1 shows the top 20 most productive countries, in terms of the number of total published articles, and lists the percentage of articles published, total citations, average citations per paper, and h-index for each country. Furthermore, the annual trend of articles published by the top five countries are displayed in Fig. 2.

China's article output ranked first, accounting for 19.66% of the total, but the average citations per paper ranked 15th, and the h-index (60), lower than that of the United States (73). The research and practical work of industrial wastewater treatment in China started in the 1960s, and industrial wastewater prevention has been the focus of environmental protection. The slow development and limited research output may be due to the insufficient data on industrial wastewater treatment for reporting the flow and number of plants, which was a worldwide concern (World Health Organization, 2018). Limited wastewater treatment capacity due to high operating costs and large gaps in actual processing efficiency compared to theoretical studies, also influenced the academic research (Ministry of Housi, 2012). Various laws and regulations have been formulated to control environmental water pollution. The "Twelfth Five-Year Plan" (2011–2015) was proposed by the Chinese government in 2010, and part of the plan focused on solving the water pollution problem. This plan may stimulate the growth of articles publications in this field in China (Fig. 2) (The Chinese State Council, 2012), which presented rapid growth by 19.57% annually from 2010 to 2015, exceeding publications from other countries in the following year. The subsequent policies, e.g. The Thirteenth Five Year Planed in 2016 (The Chinese State Council, 2016), The Action Plan for Prevention and Control of Water Pollution (The Chinese State Council, 2015) (i.e., "Water Ten") in 2015 aiming at halting water pollution industries, played an important role in promoting the academic research output. In 2019, publications of China reached 295, far exceeding other countries.

The USA published 9.78% of the total publications, performed well in the average citations per paper (26.29, ranked 3rd) and h-index (73, ranked 1st), indicating that USA were attached with higher academic influence in the industrial wastewater treatment field. It can be inferred from Fig. 2 that the USA started the research earlier, and its annual number of papers issued from 1998 to 2006 was significantly higher than other countries. The Clean Water Act of 1972 was one of the most encompassing and controversial regulations in USA history. As a result, USA water quality has been improved since then in spite of the higher cost relative to benefits, which is higher than 1 as discussed by some work (Keiser and Shapiro, 2018). As the third largest publication nation, India, had lower average citation per paper (19.22, ranked 11th) but high h-index (53, ranked 4th). Additionally, an Indian author wrote the paper that had the highest number of citations (1054), which was "Kinetics and mechanism of removal of methylene blue by adsorption on various carbons - a comparative study" published in *Dyes & Pigments* (Kannan and Sundaram, 2001).

It was to be noticed that the European countries showed similar performance, with higher academic influence and active international cooperation. Spain's publications with international

Table 1
Publication contributions of the top 20 productive countries.

Country/Region	TP (R)	Percentage (%)	AC/paper (R)	CP (R)	h-index (R)
China	1651 (1)	19.66	13.96 (15)	410 (1)	60 (2)
USA	821 (2)	9.78	26.29 (3)	375 (2)	73 (1)
India	670 (3)	7.98	19.22 (11)	142 (7)	53 (4)
Spain	579 (4)	6.89	22.54 (6)	207 (3)	56 (3)
Brazil	472 (5)	5.62	13.25 (16)	98 (13)	38 (10)
UK	387 (6)	4.61	27.25 (2)	203 (4)	53 (4)
Germany	378 (7)	4.50	22.42 (8)	181 (5)	46 (6)
Turkey	338 (8)	4.02	13.01 (17)	56 (16)	34 (14)
Italy	329 (9)	3.92	19.18 (12)	130 (8)	39 (8)
Canada	312 (10)	3.72	19.81 (9)	125 (9)	39 (8)
France	296 (11)	3.52	23.34 (5)	149 (6)	43 (7)
Iran	277 (12)	3.30	9.79 (19)	43 (19)	26 (17)
South Korea	252 (13)	3.00	19.23 (10)	99 (11)	34 (14)
Poland	245 (14)	2.92	9.33 (20)	47 (18)	24 (19)
Australia	231 (15)	2.75	24.59 (4)	115 (10)	38 (10)
Japan	206 (16)	2.45	22.52 (7)	99 (11)	35 (12)
Malaysia	171 (17)	2.04	14.16 (14)	71 (15)	26 (17)
Portugal	161 (18)	1.92	18.16 (13)	55 (17)	29 (16)
Mexico	152 (19)	1.81	12.11 (18)	41 (20)	24 (19)
Netherlands	126 (20)	1.50	36.18 (1)	78 (14)	35 (12)

Note: TP = total publications, AC/paper = average citations per paper, CP = the number of publications with international collaborations, R = the ranking of one country in different indicators, i.e. TP, AC/paper, CP, h-index. Publications from North Ireland, Scotland, Wales, England were included in the United Kingdom. Publications from Hong Kong and Taiwan were included in China.

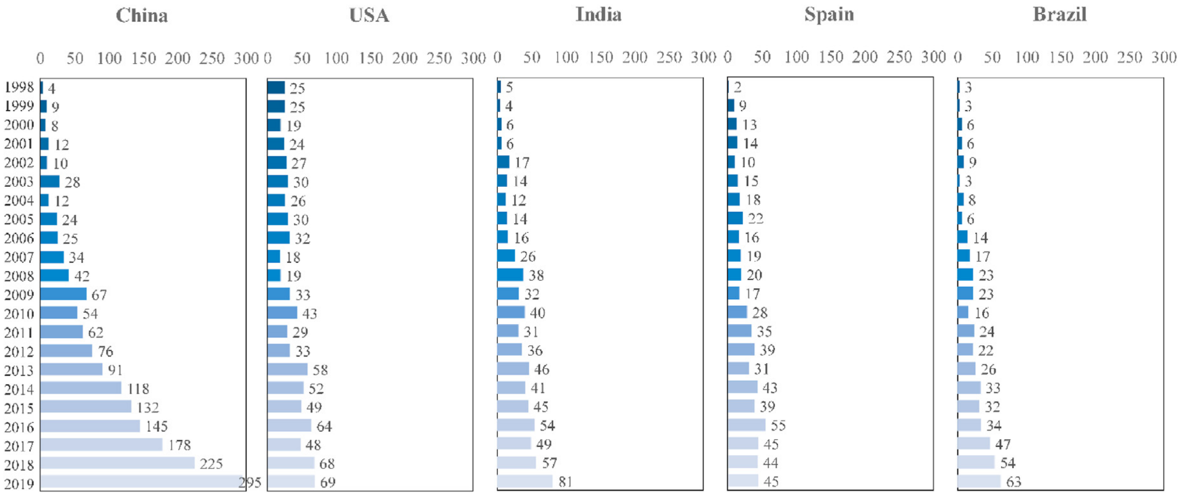

Fig. 2. Annual number of articles of the top five countries.

collaborations and h-index both ranked 3rd, and it was in the center of Europe countries' cooperation network (further discussed in 3.2.2). Other European countries such as Netherlands, the UK and France had smaller numbers of publications; however, the average citations per paper were ranked 1st (36.18), 2nd (27.25) and 5th (23.34), respectively, indicating the higher academic influence. Brazil, was the country with the largest number of publications in South America, while, only 98 out of 472 publications, i.e., 21% of the total output was cooperative researches, far less than other developed countries, e.g. 375 out of 821, 46% in USA. And, Brazil did not get a good score for the academic influence, i.e., 10th in h-index and 16th in the average citations per paper. The results showed that in Brazil, the academic influence and international cooperation needed to be further enhanced for better achievement in both quality and quantity in the wastewater field.

3.2.2. International collaboration patterns

International academic collaboration among the top 30 most productive countries was analyzed by SNA and is shown in Fig. 3. Each point in the figure represented a country, and the size of the point represented the number of publications in that country. The lines connecting these points represented the cooperative relationships between countries, and the line thickness reflected the number of collaborative publications, which was a proxy for the closeness of the relationship. The cooperation between each pair of countries was determined by the affiliations of coauthors and their significant collaborations throughout the research project (Bozeman et al., 2013; Katz and Martin, 1997). It was clear that all countries benefit from collaborative publications. Compared to previous research on groundwater remediation (Zhang et al., 2017), the international collaboration network involved in industrial wastewater treatment was more complex and integrated. China had the largest number of collaborative publications, with 410 articles (Table 1). The network can be broadly divided into three parts, which were subnetworks centered on the USA, China and the European Union (EU). The cooperative network centered on the USA and China has a relatively large scope. These two countries showed the closest collaboration (with 109 coauthored articles), followed

Fig. 3. International collaborative relationships among the top 30 productive countries.

by the collaborations between China and Canada (34), the USA and South Korea (26), China and Japan (25), the USA and Canada (24) and China and Australia (23). Unlike the cross-regional collaboration between Asian and American countries, some European countries preferred cooperation within the EU, pointing to a Europeanization of shared co-authorship (Mattsson et al., 2008), such as among Spain, Germany, the UK, Italy, France, Portugal, and Switzerland (among these countries, the UK, Germany, Spain and other EU countries also had some collaborations with researchers in China, the USA and Brazil).

3.3. *Industrial wastewater treatment*

3.3.1. *Article keywords analysis*

All of the authors' keywords were divided into four stages, i.e., 1998–2002, 2003–2007, 2008–2012, and 2013–2019. The keywords of each stage were processed and classified. The social network analysis method was used to explore the research focus of each stage in the industrial wastewater treatment field (Fig. 4 for 2013–2019, others in the *SM*, Figure S1-S3).

The research focus for industrial wastewater treatment can be divided into five types: technology categories, processes, pollutant types, industrial applications and theories. The first stage was from 1998 to 2002, and the technologies involved in the first stage focused on treatment technologies, e.g. anaerobic digestion, ozonation and adsorption. For the second stage (2003–2007), large differences were observed, which involved more research topics and the network was more complex. Researchers began to explore more pollutants (such as PAHs, phenol, and copper) and more physico/chemical treatment technologies (such as reverse osmosis, nanofiltration, and advanced oxidation). In addition, biological treatment method, which was more economical and environmentally friendly, was examined more. We found that membrane biological reactors (MBRs), biofilm, and biosorption were widely discussed in the second stage, but adsorption was still the most important industrial wastewater treatment technology.

In the third stage (2008–2012), the technology categories were similar to but more specific than that in the second stage, e.g. microfiltration, photocatalysis and TiO2-based photocatalysis, and electrocoagulation. The largest difference was that the activated sludge process had more publications than adsorption and became the main treatment technology. For the fourth stage (2013–2019), the theory of life cycle assessment (LCA), adsorption isotherms and optimization began to appear in the network diagram, showing that researchers were more focused on the feasible applications of various technologies. LCA can determine the environmental and human impacts for the construction, use and end-of-life phases and determine which phase has the greatest impact. Accordingly, it has become a valuable tool to determine the technologies with the lowest impacts, and has been applied to municipal wastewater treatment plants (Corominas et al., 2013).

The major types of industrial wastewater changed during these four stages and attracted more and more attention. The focus gradually increased from one type (textile wastewater) to six types (pharmaceutical, textile, dairy, tannery, pulp and paper and coking wastewaters). In the past, researchers paid less attention to specialized treatment for industrial wastewater, while more on the domestic sewage treatment and centralized treatment, which may be challenged by the complexity of the chemical pollutants in industrial wastewater. When conducting research on industrial wastewater treatment, it is important to differentiate the industry type and determine the specific pollutants to select the best treatment process and technologies.

3.3.2. *Treatment technology analysis*

The pollutants needed to be removed from industrial wastewater include conventional pollutants (e.g., carbonaceous - CBOD, nitrogenous - NBOD, TSS, and phosphate) and toxic pollutants (e.g., heavy metals, antibiotics, drugs, personal care products, polyaromatic hydrocarbons - PAHs, pesticides, herbicides, and toxic organics). Industrial wastewater treatment technologies can be divided into physical treatment, chemical treatment and biological treatment based on different treatment mechanisms. Physical treatment methods are often used as the first-stage treatment (or primary treatment) to remove the solids by settling them. Membrane filtration processes are another example of physical treatment. Biological and chemical treatments, which are sometimes referred to as secondary treatment, are commonly used after primary settling. The main task for conventional pollutants treatment is to remove colloidal and dissolved organic matter in the wastewater. For industrial wastewater, chemical methods are commonly used for the tertiary treatment of toxic pollutants. The combined

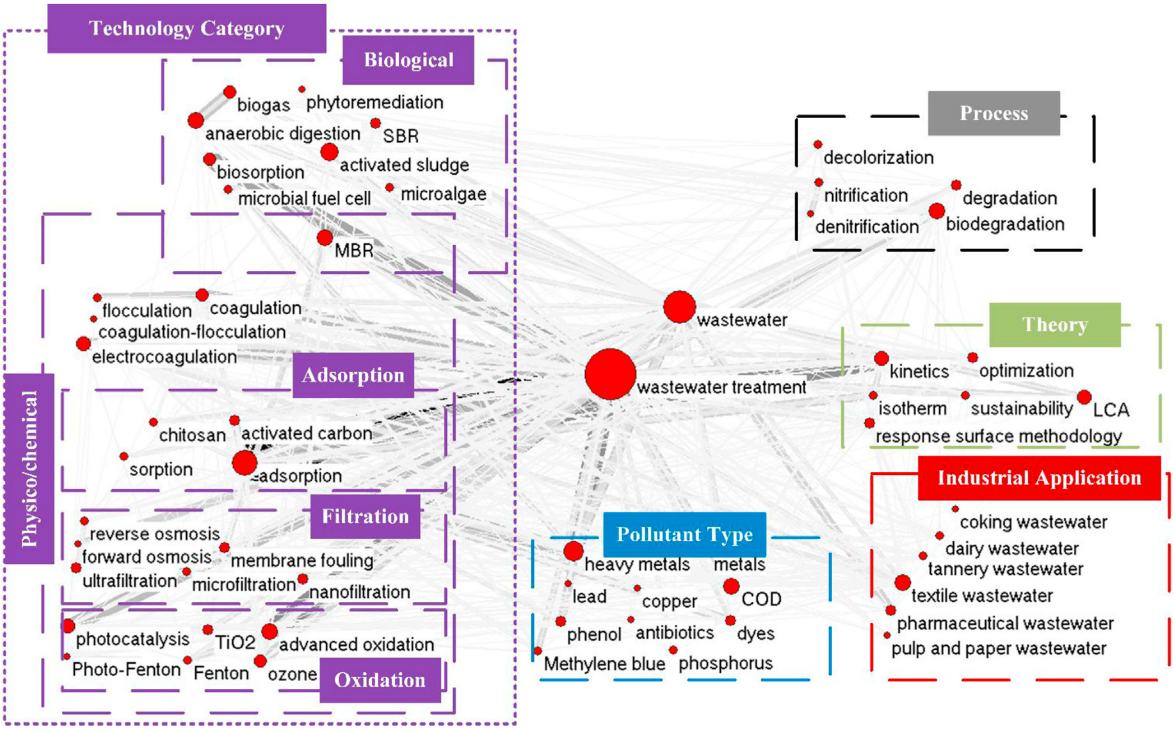

Fig. 4. The keywords co-occurrence network for industrial wastewater treatment between 2013 and 2019.

physical chemical treatment method means to add coagulants and use settling to remove the coagulated particles.

To simulate the overall trends of physical, chemical and biological treatment methods, we applied the S-curve. To further explore specific treatment technologies tendency, we subdivided and clustered common industrial wastewater technologies from the three treatments categories, including adsorption, filtration, oxidation, activated sludge processes, and biofilm (Zheng et al., 2015). Their development trends were shown in Fig. 5. The S-curves derived from the articles showed that physical, chemical and biological industrial wastewater treatment methods entered into the maturity stage in 2017, 2017 and 2014, respectively. Physical and chemical treatment technologies would have a much longer time before reaching the declining stage and have a greater potential for innovation and development. Among these technologies, adsorption, oxidation, and coagulation could be further developed in the next 5–10 years by academic research and innovation. Differently, the biological treatment technologies were closer to the saturation stage, e.g. biofilm and anaerobic process would enter the maturity stage around 2024, and the activated sludge would enter the maturity stage around 2025. The total articles of the biological treatment method were 2361, higher than physical (1814) and chemical (1469). Both S-curve and publication output indicated the popularity of biological treatment method. The biological

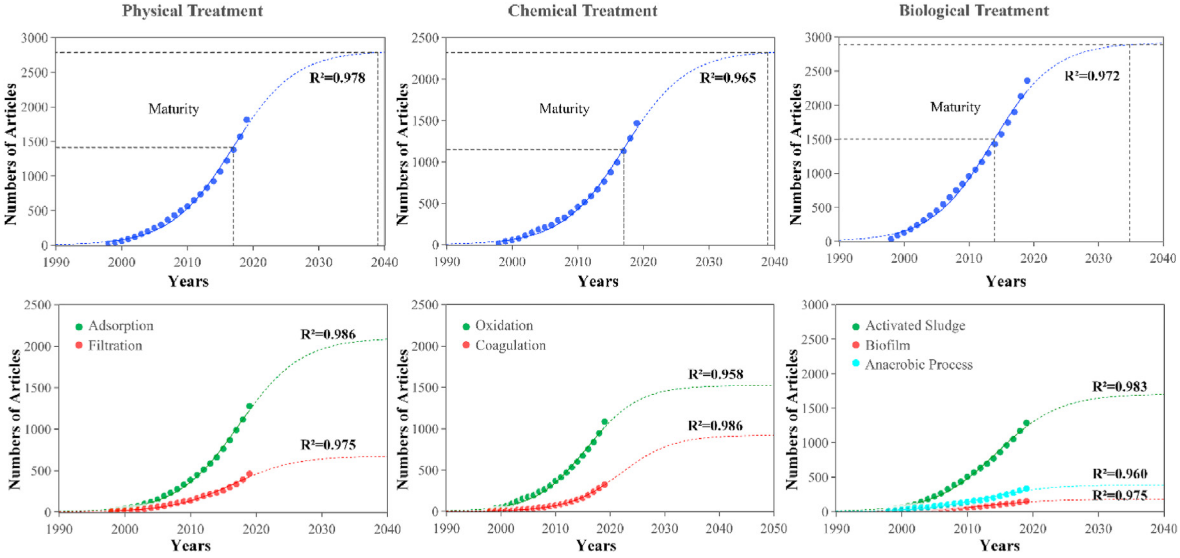

Fig. 5. The S-curves of different industrial wastewater treatment methods and technologies derived from articles.

treatments developed rapidly in the past ten years. The composition of industrial wastewater became more complicated by containing more non-degradable organic matter with the development of the industry. Biological treatment method had the advantages of high efficiency, low cost, and convenient operation, and have played a crucial role in industrial wastewater treatment (Kotsou et al., 2004). With the researchers' much attention and the huge amount of studies, the maturity of biological treatment technologies has improved rapidly. In terms of specific technologies, compared with biofilm and anaerobic process, more research on the activated sludge is necessary.

3.3.2.1. Physical treatment technology. Physical treatment separates and removes soluble, nonsoluble and suspended pollutants in the wastewater, while does not change the chemical properties of the removed contaminants. The common technologies are adsorption, gravity separation (e.g. precipitation, air flotation), centrifugal separation, membrane filtration (e.g. nanofiltration, microfiltration, ultrafiltration, reverse osmosis).

The keyword analysis showed that adsorption is the major research topic in physical treatment, with 1277 published articles. Its development has shown a clear upward trend, and surpassed activated sludge after 2012 (Fig. 6). And there was still much room for the development of adsorption according to S-curve simulation (Fig. 5). Adsorption was highly efficient, produced high quality effluents, and was widely used to remove chemical contaminants that were difficult to degrade by conventional biological wastewater treatment (Chern and Wu, 2001; Aksu and Tezer, 2005).

The keywords "heavy metals", "activated carbon" and "adsorption" showed high frequency of co-occurrence. While the keywords "kinetics" and "isotherm" showed higher connection with adsorption in 2013–2017. Adsorption was one of the most effective methods for advanced treatment of wastewater, which was usually used to reduce harmful metals. Among them, activated carbon was the most widely used adsorbent with good adsorption capacity of heavy metal ion (Zhang et al., 2005). In addition, during the study period, the keyword "dyes" and "adsorption" also showed high frequency of co-occurrence. As one of the commonly used dyes in cotton, wood and silk coloring, "methylene blue" has been studied a lot in the past two years (Olusegun et al., 2018; Wong et al., 2018; Budnyak et al., 2018), and the keyword ranking has risen from 408th (in 1998–2002) to 25th (in 2018–2019). Due to its high toxicity, stable chemical properties and low biodegradability, adsorption was often used as an economical physical pretreatment (Zhai et al., 2019). In most commercial systems, the activated carbon was used as the preferred adsorbent to remove dyes from wastewater (Ozacar and Sengil, 2002). The adsorption capacity of activated carbon was related to its porous sized distribution, large specific surface area and surface chemistry. However, the use of activated carbon may be expensive depending on its adsorption capacity and the difficulties in reactivation and reuse. Thus, many researchers tried to develop cheap and effective adsorbents as alternatives from industry or agriculture (Garg et al., 2004; Ahmaruzzaman, 2011; Kesraoui et al., 2016), e.g. waste carbon slurry, corn cob, coconut shell, recycled cotton waste (Wanassi et al., 2017), shea nut shells (Itodo et al., 2011), waste tire rubber (Gupta et al., 2011), biosorbents (chitosan, peat) (Auta and Hameed, 2014; Thirugnanasambandham et al., 2014) and so on. The "chitosan" got more attention recently, with ranking shifted to 57th (in 2013–2017) from 364th (in 1998–2002). However, most of the above studies on low-cost adsorbents and new adsorbents have remained at the experimental stage, and few articles reported pilot- or plant-scale applications. In the design of industrial adsorption towers, it is necessary to quantify the influence of many process parameters (e.g. empty bed contact time, superficial velocity, effluent flow rate, effluent concentration and sorbent particle size) (Gupta, 1998; McKay and Bino, 1990; Walker and Weatherley, 2000).

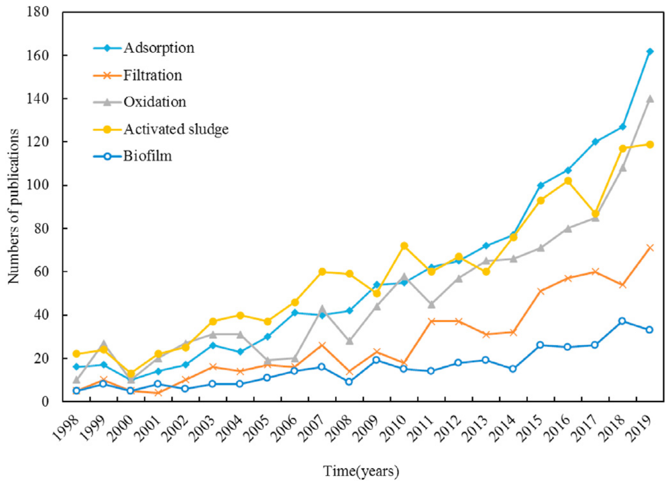

Fig. 6. Annual publication performance of the top five industrial wastewater treatment technologies.

Filtration, as a separation technology with low energy consumption and high efficiency, has also received extensive attention. The keywords "ultrafiltration", "reverse osmosis", and "nanofiltration" co-occurred frequently, which were often used for technology combination or comparison (Nataraj et al., 2006; Balannec et al., 2005; Aouni et al., 2012). Among them, the research on nanofiltration was later than others, and the keyword "nanofiltration" rose from 94th (in 1998–2002) to 29th (in 2013–2017). This technology can effectively separate the components in the solution and was widely used in the textile industry with complex pollutants in wastewater (Van der Bruggen et al., 2001; Ong et al., 2014). The preparation of high-performance nanofiltration membranes was a research hotspot in the relevant fields. It was also worth noting that "forward osmosis" was discussed in 2013–2019, which did not appear in the first three stages. It was a new concentration-driven membrane separation technology developed in recent years, with the advantages of low energy consumption, good separation effect, less membrane pollution and simple membrane process and equipment. It has been applied to the treatment of many kinds of industrial wastewater, such as textile wastewater, coal-fired power plant wastewater and fossil fuel combustion power plants wastewater (Korenak et al., 2019; Lee et al., 2018; Gwak et al., 2019).

3.3.2.2. Chemical treatment technology. Chemical treatment separates and removes dissolved or colloidal contaminants in wastewater by chemical reactions and mass transfer, or converts them into harmless substances. Common technologies include coagulation and flocculation, oxidation and reduction, advanced oxidation and reduction, electrodialysis, and so on.

Oxidation was one of the most discussed chemical treatment techniques. The S-curve of oxidation derived from articles would take longer to reach saturation stage compared with other technologies (Fig. 5), and the S-curve of oxidation derived from patents was still in the initial growth stage (Fig. 7). The results indicated that the academic research and innovation in both theory and application were critical for future oxidation technology development in the coming years. Advanced oxidation processes (AOPs) include photocatalysis, Fenton and Fenton-like processes, ozonation, UV ozonation, hydrogen peroxide and ozonation, ultrasound,

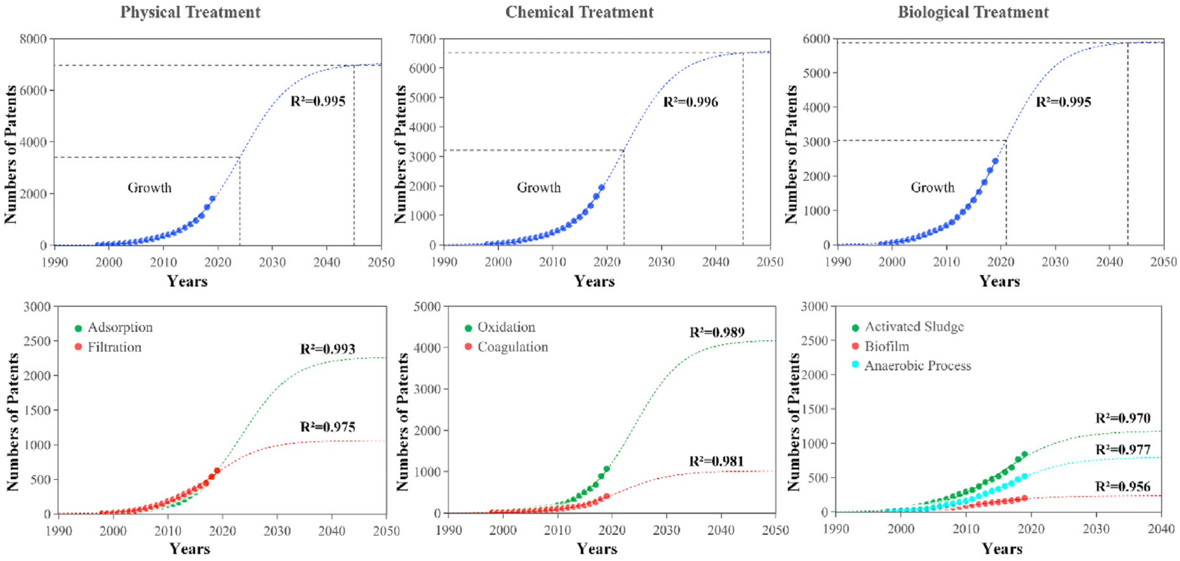

Fig. 7. The S-curves of different industrial wastewater treatment methods and technologies derived from patents.

to name a few. AOPs form hydroxyl radicals at room temperature and pressure to degrade organic pollutants. AOPs were superior to traditional chemical oxidation technologies because of higher reaction rates. Consequently, AOPs were recognized as an efficient treatment technology for wastewater containing refractory organic compounds (Shannon et al., 2008; Chong et al., 2010).

The keyword analysis showed that “ozone”, “photocatalysis”, and “TiO2″ were closely connected to advanced oxidation. Ozone was a key technology for the application of advanced oxidation in industrial wastewater treatment. It was widely used in the decolorization of dyes (Tabrizi et al., 2011; Turhan and Turgut, 2009), paper industrial wastewater treatment (Freire et al., 2000; Amat et al., 2005), and oil refinery wastewater treatment (Chen et al., 2014). Properties and concentration of oxidizing organic compounds, pH, ozone dose, competition between target compounds and biodegradable by-products and ozone mass transfer efficiency were the main factors that affect the performance of ozonation (Alvares et al., 2001). In application of ozonation, it was generally attached with high costs, strict technical requirements, and the risk of producing toxic by-products. Thus, it was usually combined with other technologies, e.g. electrochemistry (Bernal-Martinez et al., 2010), membrane aerated biofilm reactor (Tian et al., 2015), moving bed biofilm reactors (Gunnarsson et al., 2009), at the pre-treatment stage or intermediate stage of industrial wastewater (Oller et al., 2011). In addition to ozonation, photocatalysis has also attracted much attention. The keyword “photocatalysis” rose from 173rd (in 2003–2007) to 9th (in 2018–209). It can convert organic pollutants into short substances or even completely mineralized by producing highly reactive free radical oxidants. Especially, the more economical solar photocatalysis has great development prospects (Marcelino et al., 2015). TiO2, as the popular research topic, was a useful catalyst due to its high photochemical stability, low toxicity and low cost (Boroski et al., 2009; Subramonian et al., 2017; Stoller et al., 2015). In the keyword co-occurrence network, “TiO2″ presented some connections with “adsorption”, which combined with low-cost adsorbents to form composite materials so that high-efficiency treatment of heavy metals and dyes can be achieved simultaneously (Visa et al., 2015; Gao et al., 2014; Ahmad et al., 2017).

3.3.2.3. Biological treatment technology. Biological treatment methods utilize microorganisms to decompose and reduce or oxidize dissolved organic matter or colloids in sewage into stable inorganics, thereby purifying the sewage. Activated sludge or biofilms are commonly used. The biological treatment is more frequently used than physical methods.

Biotechnology is an economical, environmentally friendly and most promising treatment technology. Biological treatment methods are often used to treat paper and pulp wastewater and textile wastewater for further treatment of various nondegradable pollutants in a more economically reasonable way. Activated sludge has been studied deeply and is widely used in wastewater treatment with high frequency of 1288 (Fig. 6). There were many reactors based on the activated sludge process, such as the up-flow anaerobic sludge bed/blanket (USAB), sequencing batch reactor (SBR) and membrane bioreactor (MBR). In general, microbial granular sludge was more advantageous than a traditional flocculant in its mass concentration (30 kg/m^3), which was ten times of traditional flocculating sludge (approximately 3.0 kg/m^3). Another advantage was its rapid sedimentation capacity (settling velocity between 18 and 100 m/h), much larger than traditional flocculating sludge (less than 10 m/h) (Zheng et al., 2018). Sirianuntapiboon et al. (2016) successfully processed textile wastewater containing basic dyes using granular activated carbon-SBR (GAC-SBR) systems and found that adding organic matter (glucose) improved the removal efficiency (Sirianuntapiboon and Chairattanawan, 2016). Lin et al. (2017) proposed a conceptual model of a granular activated carbon-anaerobic digestion-microalgae biological treatment system, but its feasibility still needed to be tested in terms of its practical economic operation (Lin et al., 2017). Other treatment technologies, such as membrane filtration (nanofiltration (Ong et al., 2014), microfiltration, ultrafiltration (Avdicevic et al., 2017) and reverse osmosis) and membrane bioreactors (Hossain et al., 2016), can also be combined with the above techniques, which is worthy of further study.

Keywords analysis showed that “MBR” and “membrane fouling” were closely connected. After the membrane contacted industrial wastewater, the pore size of the membrane would become smaller or even blocked, thereby reducing the separation ability. Therefore, the optimization of membrane modules and pollution prevention have become important research points in industrial wastewater treatment. Many researchers were also devoted to the development of dynamic response models, the invention of new membrane modules and process improvement methods (Praveen and Loh, 2019; Charfi et al., 2017; Kim et al., 2014; Chai et al., 2016).

As biological treatment technology research was approaching to saturation stage, the development of circular economy provided the opportunities to explore new technologies for further development. Among them, microalgae and microbial fuel cells have received a lot of attention. The keyword “microalgae” did not appear until 2003, and its ranking rose from 631th (in 2003–2007) to 19th (in 2018–2019). The cultivation of microalgae in industrial wastewater can not only promote the performance of wastewater treatment, but also produce microalgae biomass which could be potentially used for the production of biofuels, fertilizers, and biochar. Researchers focused on the environmental impacts of bioproducts production from microalgal biomass (Castro et al., 2020), as well as the reactors and types of wastewater that can produce biomass (Wood et al., 2015). Another important keyword “microbial fuel cells” did not appear in 1998–2007, while ranked 31st in 2018–2019. Microbial fuel cells can operate efficiently at ambient temperature or even low temperature, and can achieve high conversion efficiency from substrate energy to electrical energy (Rabaey and Verstraete, 2005). However, it faced many challenges in practical applications. One important direction was to look for new materials or surface modification technologies to reduce cathode losses and other internal losses, as well as minimizing non-exogenous electrical reactions in the system, which should be enhanced in the future study (Cecconet et al., 2018). In addition, sludge was also one potential resource that can be recycled in the process of industrial wastewater treatment. Overall, through biological treatment technologies such as activated sludge and anaerobic digestion, valuable byproducts (biogas, electricity, biochar, etc.) can be generated (Jaria et al., 2017; Pradel et al., 2016). And for biological treatment, technologies and materials innovation would be of great importance, which plays an important role in the sustainable development in the future.

3.4. Patent analysis of treatment technology

Compared with the article analysis, patents can better reflect the practical application of the technologies to a certain extent. Therefore, we used patent analysis by extracting patents related to the industrial wastewater treatment from the Derwent database from 1998 to 2019, and fitted the S-curve for the three types of wastewater treatment technologies (Fig. 7). The results showed that physical, chemical and biological treatment methods were all still in the growth stage, much slower than that in the article analysis (all in mature stage, Fig. 5). However, biological treatment method was closer to the mature stage than physical and chemical treatment methods, and for the specific technologies, i.e. activated sludge, biofilm, and anaerobic processes, have all entered the mature stage, indicating that biological treatment was currently at a critical time for commercial application and promotion. Physical and chemical treatment technologies got more attention in the laboratory scale and scientific analysis, but the practical engineering applications and patent protection are rather limited due to limitations in experimental facilities, longer time span, higher cost, etc. These results indicated the large development space and huge development potential for physical and chemical treatment technologies in terms of the practical application, especially adsorption and oxidation, whose saturated K values were much higher than other technologies.

Technological innovations and applications did not generally occur at the same pace. For engineering applications, it was necessary to consider the complicated pollutants in wastewater, the treatment scale, and the economic benefits. Such a large problem requires solutions that comprise of several technologies. Currently, industrial wastewater pollution was produced by an industrial system and was often not integrated into urban centers (Xu et al., 2010). Many studies have achieved good results for industrial wastewater through integration and optimization of technology mix and enterprises within industrial parks (Long et al., 2019). Artificial intelligence would be helpful to classify and identify pretreat technologies for industrial wastewater. It should be possible to build a bridge between industrial wastewater and domestic sewage treatments by reorganizing the links among various infrastructure systems, and the integration of the two is still a question worthy of further consideration.

4. Conclusion

4.1. Summary

We performed a bibliometric analysis to analyze 9413 publications that report research on industrial wastewater treatment from 1998 to 2019. International cooperation networks and keyword co-occurrence networks were obtained by social network analysis, revealing the country development status in the field and five research hotspots in “technology category”, “pollutant type”, “industrial application”, “theory” and “process”. China, USA and India published 19.66%, 9.78%, 7.98% of the global research articles, respectively, while UAS got higher academic influence internationally. To further analyze research hotspots, we applied the S-curve to simulate the technology development stage for physical, chemical and biological wastewater treatment technologies derived from both literature database and patent database, to identify the research potential from both academic research and practical application aspects. These outputs are useful for academic researchers, practitioners, policy makers, as well as who are interested in this research area. The future research directions in technologies, commercialization applications and resource reuse in the wastewater treatment field are as followed. Then, the methodology limitations and research opportunities are presented.

4.2. Future perspectives

4.2.1. Research characteristics and future directions of technology

Among industrial wastewater treatment technologies, adsorption, oxidation and activated sludge were mostly studied technologies according to the keyword frequency. For the three major methods, dominate connections indicated the major research focus: (1) As for physical treatment method, adsorption and filtration were currently popular technologies. “Heavy metals”, “activated carbon” and adsorption were the main co-occurrence keywords, while the large-scale application cost of commercial activated carbon, the accumulation of foulants and retarded diffusion in filtration were the challenges of physical technologies (Joseph et al., 2019; Kim et al., 2018; Renu and Singh, 2017). Important research opportunities for researchers would be to consider other low-cost materials that can effectively remove heavy metals, as well as the viability at the pilot scale. (2) The co-occurrence of the keywords “ozone”, “photocatalysis”, “TiO2″ and advanced oxidation revealed the main research focus of chemical treatment method. Although the advanced oxidation processes had high degradation efficiency, there were also many limitations in economy and large-scale application. For instance, the short half-life of ozone and the additional investment for ozone generation on site may lead to uneconomical applications (Amor et al., 2019); the application of photocatalysts was still limited to dilute (chlorophenol) solutions, and very little information was available on the stability and the possibility of handling the contaminants and impurities (inhibitors, competitors, poisons) in wastewater (Descorme, 2017). (3) Activated sludge was the most frequently studied technology and widely applied in the practical biological treatment. The main keywords are "MBR", "membrane fouling" and activated sludge. The laboratory-scale research of the activated sludge was in-depth, but these studies with controllable parameters could not fully represent the environmental conditions. The presence of co-contaminants, competition from other microbial participants in the wastewater, and membrane fouling during operation may become challenges for successful biodegradation (Zhang et al., 2017). The optimization of membrane modules, the development of dynamic response models for membrane fouling prediction, and the simulation of pilot scale have become important research directions for biological treatment in the future.

4.2.2. Towards commercialization and integrated system of technology

The challenges faced by industrial wastewater treatment technologies in commercial applications included the complicated environmental conditions and the cost-benefit effectiveness, which could not be well reflected in laboratory-scale experiments. Important considerations for the commercial application of one technology include pollutant removal efficiency, energy consumption, operation complexity, secondary pollutants generation, and so on (Arroyo and Molinos-Senante, 2018). Due to the environmental-friendly and economical characteristics, biological treatment such as activated sludge was currently one of the most accepted wastewater treatment technologies in the industry (Yadav et al., 2019). However, some industrial wastewater contained compounds with low biodegradability and high toxicity that require pretreatment or advanced treatment. Physical and chemical treatment technologies such as adsorption, filtration, and advanced oxidation (photocatalysis, ozone) were widely applied to integrate with biological treatment technology to form an integrated treatment system (Avdicevic et al., 2017; Kumar and Pal, 2013; Laera et al., 2012). For the integrated treatment system in actual applications, it was a very complicated task to choose the best treatment methods, which required the consideration of the wastewater type, contaminants, wastewater amount, desirable treatment efficiency, recycling feasibility, minimum reasonable cost and other factors (Piadeh et al., 2018a). For example, the position of the technical unit in the integrated system may also lead to changes in the final removal efficiency and reliability (Piadeh et al., 2018b). The above challenges highlighted the importance of collecting empirical results and operation experience, and establishing a sustainability evaluation model for integrated systems in future research.

4.3. Resource reuse and circular economy in industrial wastewater treatment

As the requirements for sustainable development become more prominent, the resource reuse and circular economy has become a direction that the industrial wastewater treatment industry should consider. New paradigms of circular economy require the adoption of new technological methods to replace traditional, energy-consuming technologies. For example, the microalgae cultivation and microbial fuel cells are innovative ecological technologies that are worth to be further studied. The former technology can produce potentially useful bioproducts, and the latter one can realize electricity recovery. They will bring great interest to future sustainability-oriented applications. To realize the best environmental performance and least economic cost, researcher could apply different qualitative models, e.g. LCA analysis, cost-benefit analysis (CBA) to conduct environmental impact assessments for their practical applications.

4.3.1. Limitations and research opportunities of the methodologies

The combination of bibliometric analysis with patent analysis can quantitatively study the development of technologies in academic research and practical applications at the same time, revealing the distribution of technology hotspots and the relationships between topics. Our research focused on structured information such as keywords and international classification numbers, while the use of unstructured information and the exploration of blank technologies were limited. Based on our work, future researchers can use artificial intelligence combined with citation networks or information maps to explore technology development path and promising technologies in the field of industrial wastewater treatment.

Credit author statement

Guozhu Mao: Conceptualization, Methodology, Supervision, Project administration. **Haoqiong Hu:** Methodology, Formal analysis, Investigation, Data Curation, Writing - Original Draft. **Xi Liu:** Validation, Formal analysis, Writing - Review & Editing. **John Crittenden:** Methodology, Writing - Review & Editing. **Ning Huang:** Visualization, Writing - Review & Editing.

Compliance with ethics guidelines

All authors (Guozhu Mao, Haoqiong Hu, Xi Liu, John Crittenden, Ning Huang) declare that they have no conflict of interest or financial conflicts to disclose.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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