Environmental Science and Pollution Research (2021) 28:25339–25348
https://doi.org/10.1007/s11356-021-12348-4

RESEARCH ARTICLE

The scientometric analysis of the research on microalgae-based wastewater treatment

Zhuo Li[1] · Liandong Zhu[1,2]

Received: 22 September 2020 / Accepted: 2 January 2021 / Published online: 17 January 2021

Abstract

This study explores the characteristics of the literature on microalgae-based wastewater treatment during the past 20 years, based on the Web of Science Core Collection database and its scientometric techniques. The results reveal that the literature on microalgae-based wastewater treatment has grown rapidly with 2621 publications and 54,388 citations in total. Most of the document types are journal articles, constituting 80.7% of the total records. China and the USA are the two most active countries, regarding the publications and cooperation in this filed from the viewpoint of the number of publishing papers, total number of citations, and the number of multinational author papers. The Chinese Academy of Sciences is the largest institutional contributor, publishing 2.3% of the papers, followed by the Indian Institute of Technology (2.2%) and Council of Scientific & Industrial Research (2.1%). The most publishing author is Ruan (35 papers) with the highest number of citation (2460 times). "Bioresource Technology" is the most publishing journal with 365 published papers, while 36.2% of the total sample is published in the subject area of "Environmental Sciences Ecology." The most cited paper in the past 20 years is a review of the status of phosphorus removal in wastewater by de-Bashan in 2004. Bibliometric analysis has systematically combed the development system of microalgae-based wastewater treatment in the past 20 years and has a great potential to gain valuable insights for the future development, which provides a supplement to the common content analysis.

Keywords Microalgae · Wastewater treatment · Bibliometric analysis · Biofuels · Publication

Introduction

The water resource system is an indispensable part of the ecological civilization system. In the last few decades, the existence of emerging contaminants in the aquatic environment has become a worldwide issue (Luo et al. 2014; Li et al. 2020). An efficient sewage treatment system is one of the important ways to protect water resources.

Recent advances in microalgae wastewater treatment have offered ample opportunities to develop next-generation water treatment processes. A variety of microalgae, including *Chlorella*, *Chlamydomonas*, and *Spirulina*, have a good removal effect on organic matters (Mujtaba and Lee 2017; Mujtaba et al. 2017; Zhu et al., 2020), heavy metal ions (Wang et al. 2010; del Rosario Martinez-Macias et al. 2019), phenolic compound (Surkatti and Al-Zuhair 2018), and possible medical waste (Xiong et al. 2016) in sewage. On the other hand, microalgae after sewage treatment have strong potential economic value. Lipid in microalgae is easily converted into biofuels by biological/thermochemical methods (Zhu et al. 2018; Zhu et al. 2019), expected to alleviate the energy crisis to a certain extent. Certain food additives can also be produced by microalgae such as carotene, astaxanthin, EPA, and so on (Polishchuk et al. 2015). All of these are the unparalleled competitiveness of other conventional methods.

In brief, research in the field of microalgae wastewater treatment is expanding from depth to breadth. Here, we present a systematic review and bibliometric analysis on the application of microalgae for wastewater treatment.

Responsible Editor: Philippe Garrigues

✉ Liandong Zhu
ldzhu@whu.edu.cn

[1] School of Resource and Environmental Sciences, Hubei Key Laboratory of Biomass-Resources Chemistry and Environmental Biotechnology, and Hubei International Scientific and Technological Cooperation Base of Sustainable Resource and Energy, Wuhan University, Wuhan 430079, People's Republic of China

[2] Faculty of Technology and Vaasa Energy Institute,, University of Vaasa, P.O. Box 700, FI-65101 Vaasa, Finland

Bibliometric is a branch of information science and philology, which refers to the quantitative analysis of all knowledge carriers using mathematical and statistical methods (Zupic and Cater 2015). It analyzes the number of papers, the frequency of citations, the country of publication, and other literature information, to compare the research differences between countries and regions at various time periods, and reveal the development law, research status, and future trends of the field (Bornmann and Mutz 2015; Du et al. 2014; Wang et al. 2018).

This study comprehensively examines the current status and the future of this research field through detailed review and large-scale bibliometric analysis, providing a certain basis for the optimization of future research directions. The contribution of this study lies in the provision of valuable insights for the future development of microalgae-based wastewater treatment through the bibliometric analysis of publications on the topic during the recent 20 years.

Material and methods

This search was carried out through the Web of Science Core Collection using the "ISI Web of Knowledge" database of Web of Science, in April 2020.

The search terms used were [TS = (microalga* OR alga*) AND TI = (effluent OR wastewater OR waste*water OR wasted water OR sewage OR biogas slurry)] in the Advanced Search. Until 2020 April 10, 2954 records were retrieved. Three hundred thirty-three invalid records focusing on toxicological analysis were eliminated after manual screening. The remaining 2621 documents are valid samples for the analysis, with an effective rate of 88.7%.

These search terms were determined by the expectation of locating the most relevant papers for the special issue on wastewater treatment by microalgae. These terms have a limit that the title must include one or more possible pending sewage, while microalgae were kept broad to give a complete picture of the research in this area as much as possible.

The scientometric analysis was firstly carried out by using the "analyze the results" tool of the Web of Science database. The basic information was downloaded as "document type," "author," "publication year," "countries/regions," "organizations-enhanced," "source title," and "subject area."

As a second step, supplementary information was manually retrieved for the articles used like the total citation numbers pear year, the numbers and countries of multinational author papers, *h* index of authors, publishing dates and citation numbers of certain papers, and so on. Some data had undergone basic calculations such as average citation numbers pear year. If an article had multiple authors or countries, the article would be considered as the literary work of all authors and countries.

Finally, the most cited papers were analyzed, and the relevant information was summarily recorded to measure the impact of the original research found in the former steps. This article discussed the most relevant parts of these results, rather than posting full information in tables.

Results and discussion

Document types

Through keyword search and manual selection, a total of 2621 articles were obtained. Table 1 lists the types, numbers, and proportions of these documents. It is notable that the sum of all types of documents is greater than 2621, since some documents occupy multiple document types in the database. A representative example is that the conference paper "Progress in the biological and chemical treatment technologies for emerging contaminant removal from wastewater: A critical review" at the 14th International Conference on Environmental Science and Technology can be counted as both an article and a proceeding paper. After excluding all duplicate documents, the total number is still 2621.

According to the distribution of documents listed in Table 1, 80.7% of the references were articles, followed by proceeding papers and reviews, accordingly accounting for 10.4% and 5.9%. The proportion of all the other literature types of references was notably small (2%). In this article, a comprehensive analysis of all the abovementioned literature types was carried out.

Historical development of the field

It is an important clue on the underlying supporting structures and incentives by analyzing the data on the historical development of a research field. In this part of investigation, the following items were discussed: (1) the number of published

Table 1 The distribution of the references by the type of the document

Document type	Number	Number (excluded)	Percentage
Article	2258	2114	80.7
Proceeding paper	274	273	10.4
Review	155	155	5.9
Meeting abstract	49	49	1.9
Early access	13	13	0.5
Correction	6	6	0.2
Editorial material	5	5	0.2
News item	3	3	0.1
Letter	2	2	0.1
Book chapter	1	1	0
		2621	

papers according to the length of time, which reflected the development of research in this field to a certain extent; (2) the number of citations for published papers (Cn1), which reflected the degree of attention paid to the field; and (3) the number of citations of the papers published each year (Cn2), which reflected the quality of the papers of the year. The distribution of the papers by the publication year is shown in Table 2. The analysis of publication year showed that the number of papers on microalgae-based wastewater treatment exponentially increased during the last 20 years.

Although there had been some research on the treatment of wastewater by microalgae before 2010, both the number of studies and their impact were stabilized in a low level. However, as from 2010, research in this field emerged in an endless stream, and the number of publications surged. The literature in the past 5 years (2015–2019) accounted for 63.1% of the total. At the same time, the number of citations for published papers also surged in around 2010, which showed that the application of microalgae in sewage treatment attracted more attention. Table 2 describes that there was still a strong development space for the research on microalgae-based wastewater treatment because the number of papers and citations has not reached the highest point around 2019.

Table 2 The distribution of the papers by the publication year

	Publication year	Paper numbers	Cn1	Cn2
	2019–2015	1655 (63.1%)	41,472	16,724
	2014–2010	624 (23.8%)	10,611	26,287
	2000–2010	342 (13.1%)	2305	15,444
1	2019	437	12,262	1073
2	2018	371	9391	2265
3	2017	318	8002	3623
4	2016	308	6699	4730
5	2015	221	5118	5033
6	2014	200	3772	5000
7	2013	167	2782	6054
8	2012	106	1743	5143
9	2011	87	1410	6593
10	2010	64	904	3497
11	2009	48	718	1985
12	2008	41	554	1706
13	2007	46	354	2858
14	2006	29	268	1437
15	2005	33	174	1259
16	2004	32	122	1858
17	2003	38	72	1199
18	2002	27	27	1459
19	2001	25	13	454
20	2000	23	3	1229

It is also notable that papers published between 2010 and 2014 held the highest number of citations. Especially in 2011, the total number of citations of published papers reached the highest number of 6593. The average citations of the literature in that year were also the highest in the past 20 years, reaching 75.8 times. Table 3 lists the most cited papers in 2011. Through a brief analysis of the article, all of the five papers were related to bioenergy without exception, which reflected that the high attention was paid to the coupled wastewater treatment with biofuel production by microalgae in that period.

However, the citation frequency and average citation frequency of papers published since 2015 were not as high as 2010–2014. On one hand, the number of citations of the papers was a long-term accumulation process, and excellent papers also needed time accumulation to receive a higher frequency of citations. On the other hand, the quality of a paper is determined by not only the number of citations but also its specific research value and direction.

Most active countries

An analysis of the number of papers and citations on a national scale was carried out to determine the most active countries. Due to the existence of exchanges and cooperation between countries, some papers will be calculated multiple times.

Table 4 shows that the most publishing single country was the China with 581 papers, comprising 22.2% of the sample, followed by the USA (386, 14.7%), India (286, 10.9%), Spain (187, 7.1%), and Korea (144, 5.5%). It also reflects that the USA held the highest citation number up to 12,667. The next four countries were China (11110), India (8066), Spain (5485), and Mexico (3636). It is notable that although South Korea ranked fifth in the number of published papers, its total citations were lower than Mexico during the investigation time.

Table 4 also shows sufficient research investment and incentive policies in this field of China, the USA, and India, without which it would be impossible for researchers to actively publish high-quality papers in related fields. However, it seemed that these three countries still have a long way to improve the overall level of articles.

Table 3 The most cited papers in 2011

	Paper reference	Published date	Total no. of citations
1	Pittman et al.	2011.01	752
2	Christenson and Sims	2011.11	594
3	Park et al.	2011.01	531
4	Rawat et al.	2011.10	461
5	Li et al.	2011.03Bashan	370

Table 4 The most publishing countries

	Country	Paper numbers	Percentage	Total no. of citations	Average citations
1	China	581	22.2	11,110	19
2	USA	386	14.7	12,667	33
3	India	286	10.9	8066	28
4	Spain	187	7.1	5485	29
5	Korea	144	5.5	3211	22
6	Malaysia	133	5.1	1667	13
7	Brazil	122	4.6	1728	14
8	Australia	115	4.4	2524	22
9	Canada	89	3.4	3331	37
10	Egypt	75	2.9	2284	30
11	Mexico	72	2.7	3636	50
12	Italy	71	2.7	1190	18
13	New Zealand	59	2.2	2158	37
14	England	57	2.2	2002	35
15	Iran	55	2.1	522	9
16	Netherlands	53	2.0	1543	29
17	Japan	50	1.9	981	20
18	Germany	49	1.9	2056	42
19	Portugal	46	1.8	972	21
20	Sweden	45	1.7	833	19

The published papers and citations are only one reference when discussing active countries. Adequate cooperation not only has a positive effect on the promotion of research capabilities, but also reflects international influence in a certain country. Table 5 lists the top 20 number of papers completed by scholars from multiple countries. It shows that China was the country with the largest number of cooperation with other countries in the world, reaching 151 times.

Among these multinational author papers, China and the USA had the most frequent exchanges, with 73 times, accounting for 24.3%, and tripled the second place (the USA and Korea). Based on the fact that these two countries held the highest number of published documents and the highest frequency of citations in the world, these close exchanges between China and the USA not only promoted the development of microalgae-based wastewater treatment research but also enhanced the international reputation of both parties. It also reflected the lack of international exchanges in India, although its number of published papers ranked third.

Table 5 Multinational author papers top 20

	Cooperation countries	Paper numbers	Percentage
1	China-USA	73	24.3
2	USA-Korea	20	6.7
3	China-Malaysian	18	6.0
4	China-Australia	17	5.7
5	USA-Canada	17	5.7
6	China-Japan	14	4.7
7	India-Korea	13	4.3
8	China-England	12	4.0
9	China-Finland	12	4.0
10	USA-India	12	4.0
11	China-Egypt	11	3.7
12	Korea-Egypt	11	3.7
13	USA-Mexico	10	3.3
14	Brazil-Portugal	10	3.3
15	New Zealand-Spain	9	3.0
16	Italy-Spain	9	3.0
17	China-Canada	8	2.7
18	Mexico-Spain	8	2.7
19	Spain-France	8	2.7
20	USA-Australia	8	2.7

Distribution of research institutions

One certain aspect of research may be carried out simultaneously by multiple research institutions in one country, and thus, it is necessary to evaluate the papers published by research institutions. A total of 2157 research institutions had been screened from 2621 documents. The top 20 research

Table 6 The most publishing research institutions

	Research institutions	Paper numbers	Percentage
1	Chinese Academy of Sciences	61	2.3
2	Indian Institute of Technology System	58	2.2
3	Council of Scientific & Industrial Research	55	2.1
4	Harbin Institute of Technology	48	1.8
5	The National Institute of Water and Atmospheric Research	41	1.6
6	University of Minnesota	41	1.6
7	University of Illinois	35	1.3
8	China Agricultural University	33	1.3
9	University of Illinois Urbana-Champaign	32	1.2
10	United States Department of Energy	30	1.2
11	Universidad de Valladolid	29	1.1
12	Shandong University	28	1.1
13	Tsinghua University	28	1.1
14	Polytechnic University of Catalonia	27	1.0
15	Nanchang University	25	1.0
16	Tongji University	24	0.9
17	University Technologic Petronas	23	0.9
18	University of California	23	0.9
19	Consejo Superior de Investigaciones Cientificas	22	0.8
20	National Cheng Kung Universit	22	0.8

institutions with the number of published articles and the citations of their published papers are listed one by one in Table 6.

It was found that the Chinese Academy of Sciences was the most publishing institution (2.3%), followed by India Institute of Technology (2.2%), Council of Scientific & Industrial Research (2.1%), Harbin Institute of Technology (1.8%), and The National Institute of Water and Atmospheric Research with University of Minnesota (1.6%).

These results suggest that the research in this area concentrated in main national research centers and institutions of higher education. As the highest academic institution of natural sciences in China, the Chinese Academy of Sciences had a leading role in the development of this field in China, while the other 7 Chinese universities on the Table 6 had made indelible contributions. It is notable that a total of 15 institutions (75%) in Table 6 are affiliated to China, the USA, and India, which proves that these three countries have made irreplaceable contributions to the development of microalgae-based wastewater treatment.

Author distribution

Research institutions are composed of a certain number of researchers. Based on the sample of the papers, Table 7 shows that the top 20 publishing authors.

The most publishing authors were Ruan R (35 papers) publishing mostly in the area of energy fuels and the application in agriculture of microalgae, followed by Munoz R (29 papers), Craggs RJ (28 papers), Chen P (27 papers), Zhang YH, and Zhou WG (24 papers). It is notable that Ruan R was the author with the most number of citations, while Min M possessed the highest average citations per paper. What they had in common was that both their research concentrated in the area of biodiesel production from microalgae dealing with sewage. However, it turned out to be that not all high-level research must be related to bioenergy. For example, the research of Craggs RJ mostly focused on water resources and engineering.

It is admitted that there is still certain possibility that some authors working in the fields related to microalgae-based wastewater treatment were not included for some reasons. So it should be cautious in interpreting findings of this table.

Most influential journals

The data from journals where researches on microalgae-based wastewater treatment were published are also important. From 2000 to 2019, 578 journals published papers related to microalgae wastewater treatment. The titles of the top 20 most publishing journals and their 5-year impact factors were listed, as shown in Table 8.

Table 7 The most publishing authors

	Authors	Paper numbers	Total no. of citations	Average citations	*h* index
1	Ruan R	35	2460	70	19
2	Munoz R	29	968	33	16
3	Craggs RJ	28	1422	51	16
4	Chen P	27	2311	86	19
5	Zhang YH	24	614	26	11
6	Zhou WG	24	1657	69	16
7	Garcia J	21	866	41	14
8	Chang JS	20	630	32	14
9	Pei HY	19	255	13	10
10	Liu YH	18	1057	59	10
11	Min M	17	2027	119	17
12	Perales JA	17	669	39	14
13	Zhang YL	17	522	31	11
14	Zhao YJ	17	194	11	9
15	Arbib Z	16	667	42	14
16	Kim HS	16	385	24	11
17	Jeon BH	15	659	44	11
18	Lu HF	15	83	6	5
19	Bux F	14	799	57	10
20	Ferrer I	14	562	40	12

"Bioresource Technology" was the most publishing journal with 365 published papers, followed by "Water Science and Technology" (138 papers), "Algal Research-Biomass Biofuels and Bioproducts" (119 papers), "Water Research"

Table 8 The most publishing journals on the topic

	Journal title	Paper numbers	Total no. of citations	Five-year impact factor
1	Bioresource Technology	365	15,468	6.589
2	Water Science and Technology	138	1425	1.541
3	Algal Research-Biomass Biofuels and Bioproducts	119	1861	4.474
4	Water Research	82	4462	8.424
5	Journal of Applied Phycology	73	2084	2.828
6	Desalination and Water Treatment	62	251	1.290
7	Ecological Engineering	48	1578	3.617
8	Environmental Technology	44	330	1.848
9	Science of the Total Environment	38	951	5.727
10	Environmental Science & Technology	36	373	7.874
11	Journal of Environmental Management	35	1631	4.962
12	Journal of Cleaner Production	34	486	7.051
13	Chemical Engineering Journal	34	670	7.610
14	Journal of Hazardous Materials	30	2138	7.336
15	Applied Biochemistry and Biotechnology	27	1312	2.094
16	Chemosphere	27	602	5.089
17	Journal of Chemical Technology and Biotechnology	24	299	2.891
18	International Journal of Phytoremediation	23	260	2.290
19	Applied Energy	22	1868	8.558
20	Water Environment Research	22	215	0.991

(82 papers), and "Journal of Applied Phycology" (73 papers). The subject heading of Biotechnology lists the first and the third journals of the table, suggesting that the field of bio-energy finds a firm place in researches related to microalgae-based wastewater treatment. Table 8 also shows that the impact factors of "Bioresource Technology" and "Water Research" in the past 5 years were accordingly 6.589 and 8.424, which indicated that the research of microalgae-based wastewater treatment had been well spread in these two journals.

In addition, the journals in Table 8 covered a variety of basic sciences, such as chemistry, biology, management, and applied sciences including biotechnology, chemical engineering, and energy, demonstrating that this field was an interdisciplinary combination research. At the same time, areas frequently appeared like engineering and energy also implied that researchers had an increasing interest in the application of the field.

Most published subject areas

The Web of Science database assigns one or more research fields to each journal in order to use a more systematic subject analysis and highlight the differences between disciplines. The literature retrieved in this article was divided into 55 fields. Table 9 lists the top 20 research fields assigned to the largest number of journals.

Table 9 shows that "Environmental Sciences Ecology" was the area where 36.2% of the sample was published, followed by "Engineering" (34.2%), "Biotechnology Applied Microbiology" (32.0%), "Energy Fuels" (22.6%), and "Agriculture" (16.1%). Although it had not entered the top five, "Water Resources" was still the last field with a proportion of more than 10% (15.8%), only 0.3% lower than "Agriculture."

Ecology, engineering and biotechnology ranked top three in Table 9, fully demonstrating that microalgae-based sewage treatment could not only be deeply explored by a theoretical basis, but also be close to practical applications. And Energy and agriculture ranked the fourth and fifth, which pointed out the close aforementioned connection between the microalgae wastewater treatment and bio-energy with aquaculture.

Twenty most-cited papers

The data on the most cited papers provide important information on the development of the field. By reading such articles, the depth of research in this field and the hot issues of peer concern could be quickly obtained. The most-cited 20 papers were determined, and the citation details for these papers were given in Table 10 with the references of these papers listed in refs.

Table 10 shows that de-Bashan's review (2004) of the status of phosphorus removal in wastewater has been most

Table 9 The subject area of the papers

	Subject area	Paper numbers	Percentage
1	Environmental Sciences Ecology	948	36.2
2	Engineering	896	34.2
3	Biotechnology Applied Microbiology	839	32.0
4	Energy Fuels	592	22.6
5	Agriculture	422	16.1
6	Water Resources	415	15.8
7	Science Technology Other Topics	214	8.2
8	Marine Freshwater Biology	189	7.2
9	Chemistry	175	6.7
10	Biochemistry Molecular Biology	65	2.5
11	Microbiology	41	1.6
12	Plant Sciences	40	1.5
13	Materials Science	39	1.5
14	Toxicology	37	1.4
15	Fisheries	32	1.2
16	Thermodynamics	31	1.2
17	Food Science Technology	25	1.0
18	Life sciences Biomedicine Other Topics	17	0.6
19	Mechanics	17	0.6
20	Public Environmental Occupational Health	17	0.6

Table 10 The most cited papers

	Paper reference	Year of publication	Total no. of citations	Total no. of citations (before 2019)	Average citations per year
1	De-Bashan and Bashan	2004	846	815	51
2	Ahluwalia and Goyal	2007	827	804	62
3	Pittman et al.	2011	752	732	73
4	Christenson and Sims	2011	594	574	64
5	Ali et al.	2012	537	518	65
6	Park et al.	2011	531	514	57
7	Cai et al.	2013	512	476	68
8	Wang et al.	2010	490	469	47
9	Rawat et al.	2011	461	440	49
10	Mehta and Gaur	2005	406	395	26
11	Chinnasamy et al.	2010	403	390	39
12	Abdel-Raouf et al.	2012	378	349	44
13	Li et al.	2011	370	349	39
14	Aslan and Kapdan	2006	360	347	25
15	Holkar et al.	2016	340	276	69
16	Margot et al.	2013	328	300	43
17	Saha and Orvig	2010	319	306	31
18	Ruiz-Marin et al.	2010	305	289	29
19	Pant and Adholeya	2007	301	291	22
20	Mallick	2002	286	282	17

frequently cited, up to 846 times. This paper was followed by Ahluwalia (2007, 827 times) on microbial removal of heavy metals in wastewater and the collection of biomass. It is worth noting that three of the five articles are related to biodiesel. Most of the highest-cited 5 papers maintained a high average annual citation number (greater than 60); however, there were still two articles that reached a number higher than 60. One is Cai (2013, 68 times per year) on status about nutrient recovery from wastewater by microalgae, while the other one is Holkar (2016, 69 times per year) on possible approaches on textile wastewater treatments.

In addition, Table 10 also shows that the most cited papers are concentrated between 2010 and 2013, accounting for 65%. Only one highly cited document was published in 2016, and the research content of this article was the method of textile wastewater treatment, only mentioning the use of algae in biological methods to treat wastewater. This phenomenon reflects that there is a possibility that no widely recognized work in this field was found recently, due to factors such as technical bottlenecks, research enthusiasm, and social evaluation.

Comparative discussion

Until April 2020, there has been no published scientometric study of research on the algae and wastewater treatment in the scientific community, but only one publication about the bacterial algae symbiosis system on the sewage treatment (Qi et al. 2019). It investigated the research activities and tendencies of algae-bacteria symbiotic wastewater treatment technology by bibliometric method from 1998 to 2017 based on SCI-EXPANDED database, and concluded that China and the USA had the largest amount of publications, and the cooperation between them is the closest in the world, which is consistent with the conclusion of this paper. It also utilized VOSviewer as manifestations instead of a diagram in some cases to illustrate its opinions. Meanwhile, a critical review and bibliometric analysis about microalga-derived biodiesel was also analyzed by Ma et al. (2018).

In addition, there was still a part of bibliometric literature related to sewage treatment although it had nothing to do with microalgae. Some documents were related to what kind of wastewater was treated. Zheng et al. evaluated industrial wastewater treatment research from 1991 to 2014, based on the Science Citation Index Expanded (SCIE) database and applied a method named "word cluster analysis" to trace the research hotspots (Zheng et al. 2015). Qian et al. carried out a bibliometric analysis based on the science citation index expanded from Web of Science to assess the research pattern and tendencies of pharmaceutical wastewater treatment from 1994 to 2013 (Qian et al. 2015). Other documents focused on the method of wastewater treatment including nanomaterials (Zhao et al. 2018), electrochemical technology (Zheng et al. 2017), biosorption technology (Ho 2008), etc.

Among all the few bibliometric analysis literature, the discussed topics covered annual output, mainstream journals, WOS categories, major countries, institutions, and a small number of paper discussed title analysis, author keyword analysis, and keywords plus analysis. In terms of presentation form, tables were the most common form to visually display data and some articles had graphs to enhance the contrast effect at the same time.

In general, although this article was slightly single in form of expression (only tables), the content of the discussion was comprehensive and detailed, and comprehensively showed the development and possible future research directions of the field of microalgae-based wastewater treatment from 2000 to 2019.

Conclusion

Microalgae wastewater treatment is one of the most common and highly potential wastewater treatment methods. A metrological analysis of the literature on microalgae wastewater treatment in the past 20 years provided helpful insights into the research in this field. The results showed that the research on microalgae wastewater treatment had grown exponentially during the last two decades especially with the development of the research on algae and bio-energy. China and the USA played an essential role in the directions, depths, and contents of this field. The results also provided valuable information on the citations of the research on microalgae wastewater treatment, which had significant impacts and further incentives for the researchers, their institutions, and their countries to do more influential research in this area. In addition, the literature on microalgae wastewater treatment concentrated in ecology, engineering, and biotechnology, which was also proved by the most cited papers. The development of interdisciplinary fields has a side promotion effect on the development of other basic sciences. It is also important to note that bibliometric research was a supplement to the other types of qualitative research such as content analysis. It intuitively provides a more complete research picture in the form of data within a certain time frame with large number of references. Finally, it should be admitted that due to the single source of the literature and the continuous updating of the database, the conclusions of this article will have certain limitations.

Acknowledgments The author respectfully and gratefully acknowledges the kind editorial support and help provided by Prof. Dr. Liandong Zhu during the editorial processing of this paper. The authors would also like to thank the two anonymous reviewers for their helpful comments and suggestions that greatly improved the manuscript.

Authors' contributions Zhuo Li designed and finished this survey, Liandong Zhu supervised the work.

Funding This work was supported by the National Key R&D program of China (2019YFC1803405; 2019YFD1101300).

Data availability Not applicable.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

References

Abdel-Raouf N, Al-Homaidan AA, Ibraheem IBM (2012) Microalgae and wastewater treatment. Saudi J Biol Sci 19. https://doi.org/10.1016/j.sjbs.2012.04.005

Ahluwalia SS, Goyal D (2007) Microbial and plant derived biomass for removal of heavy metals from wastewater. Bioresour Technol 98: 2243–2257. https://doi.org/10.1016/j.biortech.2005.12.006

Ali I, Asim M, Khan TA (2012) Low cost adsorbents for the removal of organic pollutants from wastewater. J Environ Manag 113:170–183. https://doi.org/10.1016/j.jenvman.2012.08.028

Aslan S, Kapdan IK (2006) Batch kinetics of nitrogen and phosphorus removal from synthetic wastewater by algae. Ecol Eng 28:64–70. https://doi.org/10.1016/j.ecoleng.2006.04.003

Bornmann L, Mutz R (2015) Growth rates of modern science: a bibliometric analysis based on the number of publications and cited references. J Assoc Inf Sci Technol 66:2215–2222. https://doi.org/10.1002/asi.23329

Cai T, Park SY, Li Y (2013) Nutrient recovery from wastewater streams by microalgae: status and prospects. Renew Sust Energ Rev 19:360–369. https://doi.org/10.1016/j.rser.2012.11.030

Chinnasamy S, Bhatnagar A, Hunt RW, Das KC (2010) Microalgae cultivation in a wastewater dominated by carpet mill effluents for biofuel applications. Bioresour Technol 101:3097–3105. https://doi.org/10.1016/j.biortech.2009.12.026

Christenson L, Sims R (2011) Production and harvesting of microalgae for wastewater treatment, biofuels, and bioproducts. Biotechnol Adv 29:686–702. https://doi.org/10.1016/j.biotechadv.2011.05.015

De-Bashan LE, Bashan Y (2004) Recent advances in removing phosphorus from wastewater and its future use as fertilizer (1997-2003). Water Res 38:4222–4246. https://doi.org/10.1016/j.watres.2004.07.014

Del Rosario Martinez-Macias M, Correa-Murrieta MA, Villegas-Peralta Y, Eduardo Devora-Isiordia G, Alvarez-Sanchez J, Saldivar-Cabrales J, Sanchez-Duarte RG (2019) Uptake of copper from acid mine drainage by the microalgae Nannochloropsis oculata. Environ Sci Pollut Res 26:6311–6318. https://doi.org/10.1007/s11356-018-3963-1

Du H, Li N, Brown MA, Peng Y, Shuai Y (2014) A bibliographic analysis of recent solar energy literatures: the expansion and evolution of a research field. Renew Energy 66:696–706. https://doi.org/10.1016/j.renene.2014.01.018

Ho Y-S (2008) Bibliometric analysis of biosorption technology in water treatment research from 1991 to 2004. Int J Environ Pollut 34:1–13. https://doi.org/10.1504/ijep.2008.020778

Holkar CR, Jadhav AJ, Pinjari DV, Mahamuni NM, Pandit AB (2016) A critical review on textile wastewater treatments: possible

approaches. J Environ Manag 182:351–366. https://doi.org/10.1016/j.jenvman.2016.07.090

Li Y et al (2011) Characterization of a microalga Chlorella sp well adapted to highly concentrated municipal wastewater for nutrient removal and biodiesel production. Bioresour Technol 102:5138–5144. https://doi.org/10.1016/j.biortech.2011.01.091

Li SX et al (2020) Influence of polystyrene microplastics on THE growth, photosynthetic efficiency and aggregation of freshwater microalgae Chlamydomonas reinhardtii. Sci Total Environ 714:8. https://doi.org/10.1016/j.scitotenv.2020.136767

Luo Y et al (2014) A review on THE occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment. Sci Total Environ 473:619–641. https://doi.org/10.1016/j.scitotenv.2013.12.065

Ma X, Gao M, Gao Z, Wang J, Zhang M, Ma Y, Wang Q (2018) Past, current, and future research on microalga-derived biodiesel: a critical review and bibliometric analysis. Environ Sci Pollut Res 25:10596–10610. https://doi.org/10.1007/s11356-018-1453-0

Mallick N (2002) Biotechnological potential of immobilized algae for wastewater N, P and metal removal: a review. Biometals 15:377–390. https://doi.org/10.1023/a:1020238520948

Margot J, Kienle C, Magnet A, Weil M, Rossi L, de Alencastro LF, Abegglen C, Thonney D, Chèvre N, Schärer M, Barry DA (2013) Treatment of micropollutants in municipal wastewater: ozone or powdered activated carbon? Sci Total Environ 461:480–498. https://doi.org/10.1016/j.scitotenv.2013.05.034

Mehta SK, Gaur JP (2005) Use of algae for removing heavy metal ions from wastewater: Progress and prospects. Crit Rev Biotechnol 25:113–152. https://doi.org/10.1080/07388550500248571

Mujtaba G, Lee K (2017) Treatment of real wastewater using co-culture of immobilized Chlorella vulgaris and suspended activated sludge. Water Res 120:174–184. https://doi.org/10.1016/j.watres.2017.04.078

Mujtaba G, Rizwan M, Lee K (2017) Removal of nutrients and COD from wastewater using symbiotic co-culture of bacterium Pseudomonas putida and immobilized microalga *Chlorella vulgaris*. J Ind Eng Chem 49:145–151. https://doi.org/10.1016/j.jiec.2017.01.021

Pant D, Adholeya A (2007) Biological approaches for treatment of distillery wastewater: a review. Bioresour Technol 98:2321–2334. https://doi.org/10.1016/j.biortech.2006.09.027

Park JBK, Craggs RJ, Shilton AN (2011) Wastewater treatment high rate algal ponds for biofuel production. Bioresour Technol 102:35–42. https://doi.org/10.1016/j.biortech.2010.06.158

Pittman JK, Dean AP, Osundeko O (2011) The potential of sustainable algal biofuel production using wastewater resources. Bioresour Technol 102:17–25. https://doi.org/10.1016/j.biortech.2010.06.035

Polishchuk A et al (2015) Cultivation of Nannochloropsis for eicosapentaenoic acid production in wastewaters of pulp and paper industry. Bioresour Technol 193:469–476. https://doi.org/10.1016/j.biortech.2015.06.135

Qi Y, Chen X, Hu Z, Song C, Cui Y (2019) Bibliometric analysis of algal-bacterial Symbiosis in wastewater treatment. Int J Environ Res Public Health 16. https://doi.org/10.3390/ijerph16061077

Qian F, He M, Song Y, Tysklind M, Wu J (2015) A bibliometric analysis of global research progress on pharmaceutical wastewater treatment during 1994-2013. Environ Earth Sci 73:4995–5005. https://doi.org/10.1007/s12665-015-4183-3

Rawat I, Kumar RR, Mutanda T, Bux F (2011) Dual role of microalgae: Phycoremediation of domestic wastewater and biomass production for sustainable biofuels production. Appl Energy 88:3411–3424. https://doi.org/10.1016/j.apenergy.2010.11.025

Ruiz-Marin A, Mendoza-Espinosa LG, Stephenson T (2010) Growth and nutrient removal in free and immobilized green algae in batch and semi-continuous cultures treating real wastewater. Bioresour Technol 101:58–64. https://doi.org/10.1016/j.biortech.2009.02.076

Saha B, Orvig C (2010) Biosorbents for hexavalent chromium elimination from industrial and municipal effluents. Coord Chem Rev 254:2959–2972. https://doi.org/10.1016/j.ccr.2010.06.005

Surkatti R, Al-Zuhair S (2018) Microalgae cultivation for phenolic compounds removal. Environ Sci Pollut Res 25:33936–33956. https://doi.org/10.1007/s11356-018-3450-8

Wang L et al (2010) Cultivation of green algae Chlorella sp in different wastewaters from municipal wastewater treatment plant. Appl Biochem Biotechnol 162:1174–1186. https://doi.org/10.1007/s12010-009-8866-7

Wang B, Liu Y, Zhou Y, Wen Z (2018) Emerging nanogenerator technology in China: a review and forecast using integrating bibliometrics, patent analysis and technology roadmapping methods. Nano Energy 46:322–330. https://doi.org/10.1016/j.nanoen.2018.02.020

Xiong J-Q, Kurade MB, Abou-Shanab RAI, Ji M-K, Choi J, Kim JO, Jeon B-H (2016) Biodegradation of carbamazepine using freshwater microalgae Chlamydomonas mexicana and Scenedesmus obliquus and the determination of its metabolic fate. Bioresour Technol 205:183–190. https://doi.org/10.1016/j.biortech.2016.01.038

Zhao L et al (2018) Nanomaterials for treating emerging contaminants in water by adsorption and photocatalysis: systematic review and bibliometric analysis. Sci Total Environ 627:1253–1263. https://doi.org/10.1016/j.scitotenv.2018.02.006

Zheng T, Wang J, Wang Q, Nie C, Smale N, Shi Z, Wang X (2015) A bibliometric analysis of industrial wastewater research: current trends and future prospects. Scientometrics 105:863–882. https://doi.org/10.1007/s11192-015-1736-x

Zheng T, Wang J, Wang Q, Meng H, Wang L (2017) Research trends in electrochemical technology for water and wastewater treatment. Appl Water Sci 7:13–30. https://doi.org/10.1007/s13201-015-0280-4

Zhu L, Li Z, Hiltunen E (2018) Microalgae *Chlorella vulgaris* biomass harvesting by natural flocculant: effects on biomass sedimentation, spent medium recycling and lipid extraction. Biotechnol Biofuels 11. https://doi.org/10.1186/s13068-018-1183-z

Zhu L, Li S, Hu T, Nugroho YK, Yin Z, Hu D, Chu R, Mo F, Liu C, Hiltunen E (2019) Effects of nitrogen source heterogeneity on nutrient removal and biodiesel production of mono- and mix-cultured microalgae. Energy Convers Manag 201:112144. https://doi.org/10.1016/j.enconman.2019.112144

Zhu L, Li S, Hu T, Nugroho YK, Li B, Cao J, Show PL, Hiltunen E (2020) Effects of operating parameters on algae *Chlorella vulgaris* biomass harvesting and lipid extraction using metal sulfates as flocculants. Biomass Bioenergy 132:105433. https://doi.org/10.1016/j.biombioe.2019.105433

Zupic I, Cater T (2015) Bibliometric methods in management and organization. Organ Res Methods 18:429–472. https://doi.org/10.1177/1094428114562629