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TRENDS AND PERFORMANCES OF THE ALGAL BIOFUEL: A BIBLIOMETRIC APPROACH

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Highlights

- The literature on algal biofuel from 1980 to 2019 analyzed via bibliometric techniques including analysis of publication outputs and citation, subject categories and journals, characteristics and collaboration of countries/regions and keywords.
- Algal biofuel was classified: algae selection, cultivation, harvesting, extraction, conversion, and bioproducts.
- A historical review about algal biofuel gives a global view on historical trends to future research.

Abstract. The paper systematically presents a survey of the literature on algal biofuel by a bibliometric assessment. Based on 10,201 articles extracted from the Science Citation Index Expanded database during 1980–2019, a knowledge-generating system about algal biofuel has been established through analysis of publication performance, social networks, citations analysis and keywords analysis. Annual publication output in algal biofuel research has rapidly increased, particularly over the past decade. "Bioresource Technology" is the most outstanding journal when all analysis indices have been taken into account. The USA ranks 1st with 2,151 publications and has a high supremacy in international research collaborations. Through the analysis of keywords, the research trends of algae biofuel in algae selection, cultivation, harvesting, extraction, conversion and bioproducts are reviewed. The future of algal biofuel is quite promising, however, for its commercial production, several technical challenges like large-scale algal biomass production, cheap harvesting technology, etc. have to be met a-priori.

Keywords: algae, biofuel, bibliometric, social network analysis, timeline analysis, research hotspots, eco-energy.

Introduction

With development of the global economy, increase in population growth, and resource consumption per capita, people are facing significant challenges relating to both energy and the environment. Unlike fossil fuel, biofuel is renewable energy derived from different resources of biological origin (Mao et al., 2015). Depending on advancement of origin of biofuel, scientists categorized them as first generation, second generation and third generation biofuels. While first generation biofuels are produced from edible feedstock such as corn, soybeans, sugarcane and rapeseed, second generation biofuels have been prepared from waste and dedicated lignocellulosic feedstocks and finally, third generation biofuels have been derived from algae feedstock (Montingelli et al., 2015). Several advantages of algae like high photosynthetic efficiency, high lipid content, non-requirement of farmland, ability to grow in wastewater and utilizing pollutants as growth nutrient make the third generation biofuel a strong contender among others (Borowitzka & Moheimani, 2013; Zhu & Ketola, 2012). Furthermore, algae can be considered as versatile feedstock since its biomass can be used to produce different types of biofuel, such as biodiesel, bioethanol, biogas, and biohydrogen (Suganya et al., 2016; Zhu, 2015).

Algal biofuel has been receiving global attention for last few years. Recently there have been many publications

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in academic journals covering various aspects of algal biofuel. Most of these studies have focused on the merits of algal strains, cultivation methods, harvesting and extraction techniques, different conversion technologies, as well as life cycle assessment and policy implications (Adenle et al., 2013; Bahadar & Khan, 2013; Brennan & Owende, 2010; Harun et al., 2010; Montingelli et al., 2015; Piloto-Rodriguez et al., 2017; Pragya et al., 2013; Razzak et al., 2013; Sambusiti et al., 2015; Suali & Sarbatly, 2012; Suganya et al., 2016; Tian et al., 2014; Zeng et al., 2011; Zhu, 2015). Therefore, it is necessary to assess the overall development and trends of research related to algal biofuel.

Bibliometric study is a powerful tool for assessing the overall development and advancement in algal biofuel research (Fu et al., 2013). Bibliometric reviews apply quantitative analyses and statistics to describe distribution patterns of articles by topic, field, institution, and country as well as providing more elaborate analyses to indicate the changing trends and orientations of investigation trend in each research field (Zhang et al., 2017). To date, however, only a few bibliometric studies have been undertaken in biomass energy (Chen & Ho, 2015; Mao et al., 2015). Such gap calls for a timely study to implement bibliometric analytical techniques to evaluate the advancement of knowledge on algal biofuel.

The objectives of this study are to systematically evaluate the development of algal biofuel from 1980 to 2019, to determine the publication pattern of research outputs, to capture the collaboration pattern between countries/institutions, and to identify research trends and frontiers in this field. In addition, potential research directions are identified to promote the practical applications of algal biofuel. Similarly, the findings will be valuable for research landscape mapping and technology forecasting. Some critical questions are posed to facilitate observations of this study based on the keyword analysis such as "what are the most important papers about the algal biofuel?", "which country and institution have made the greatest contribution to algal biofuel?", "what are the main research fields in the past", "what will be focused on in the future?" etc.

In the present study, the methodology applied in searching for existing studies on algal biofuel in the SCI-Expanded database have been described in detail. Bibliometric analyses of the latest research on algal biofuel have been conducted and statistics of publication outputs, subject categories and journals, countries/regions, institutions, funding agencies, and article citations have been included. The research hotpots for algal selection, cultivation, harvesting, extraction, conversion, and bioproducts obtained by keyword frequency analysis have been discussed and summarized. Finally, some concluding remarks on future aspect have been provided.

1. Methodology

Figure 1 shows the research framework and procedures applied in the present paper. This consists of three parts: data collection, bibliometric analyses and literature review. A summary of algal biofuel research was established through performance analysis, social network analysis, citation analysis and literature review based on keyword analysis. The first step was defining proper search terms, followed by retrieval of literature then collecting and refining the search results. Further details about the methodology were discussed below.

1.1. Data sources

Publication outputs related to algal biofuel were carried out up to Dec 12, 2019. A broad collection was conducted in the field "Topic" based on the SCI-Expanded database of Web of Science Core Collection (Thomson Reuters, USA). SCI-Expanded was considered the most valuable and efficient for publication (Falagas et al., 2008) by journals which met the highest standards (Marzi et al., 2017). In order to study the developmental history and current state of algal research for the third generation biofuel production, articles published starting from 1980, when the first paper in this field came out, up to the end of 2019 were included.

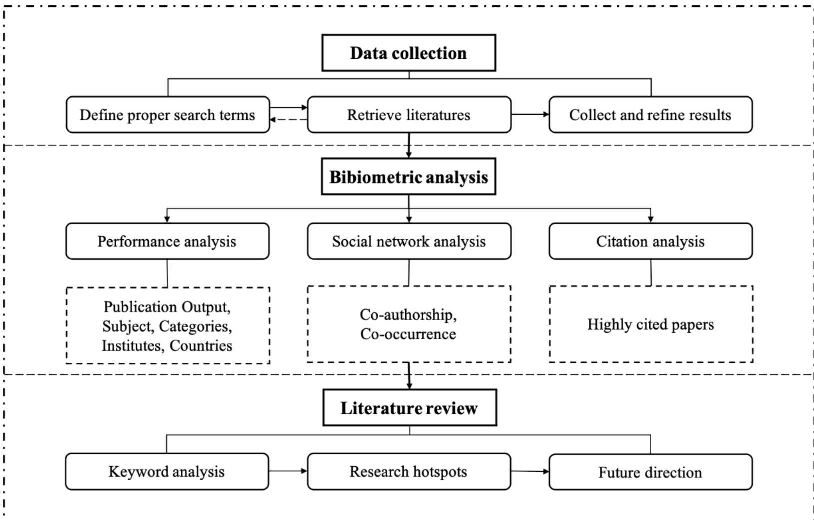

Figure 1. The research framework and procedures implemented in this paper

1.2. Inclusion and exclusion criteria

Due to the extensive literature on algal biofuel, an in-depth analysis for synthesis of knowledge in the field is essential. Inclusion criteria were established based on keywords provided by author(s). Proper selection of keywords was a crucial step to define the screening process and the accuracy of research (Palomo et al., 2017). In order to improve the accuracy of search results while excluding irrelevant articles as many as possible, the search terms selected were "alga*", "microalga*", "macroalga*", "micro-alga*", "macro-alga*", "seaweed*", "biofuel", "bio-fuel", "biogas", "bio-gas", "biooil", "bio-oil", "biohydrogen", "bio-hydrogen", "bioelectricity", "bio-electricity", "biodiesel", "bio-diesel", "biomethane", "bio-methane", "bioethanol", "bio-ethanol", "biobutanol", "bio-butanol", "bioenergy" and "bio-energy". In order to preferentially select the highest-quality publications, and to perform reliable bibliometric analyses, the search results were refined by screening document types and languages (Fahimnia et al., 2015). Finally, article, review, proceeding paper, and book chapter published in English were included in this research. Articles classified as letters, editorial material, news items, meeting abstracts, corrections, notes and retracted publications were all eliminated. Although the exclusion criteria could understate the contribution of researchers in this field, the reliability and quality of the documents used in these analyses should be ensured. Finally, all essential information including titles, abstracts, keywords, affiliations, journals, funding agencies and references were downloaded for further analysis.

1.3. Statistical analysis

The raw data were computed using the SCI-Expanded analysis tool and Incites of Web of Science. Further, statistical multivariate analyses for all the characteristics of the collected data were performed using the software Bibexcel designed by Olle Persson. The attributes, authors, year of publication, journal name, geographic location of authors' affiliations, total number of citations and keyword frequency were extracted. Continuous variables were calculated with descriptive statistics, while category variables were presented in terms of frequency and percentage (Nadri et al., 2017). ArcGIS 10.1 (Environmental Systems Research Institute, USA) was used to provide the geographical distribution of publications and share location-based insights. Additionally, the *h*-index was widely used in the bibliometric analysis, and the *h* values of paper indicated that it was cited at least *h* times (Hirsch, 2005). In contrast to traditional indicators, the *h*-index was good for evaluating the citation frequency of authors, institutes, and countries. It was assumed that citation frequency beard a positive statistical relationship to research quality.

1.4. The social network analysis

Social network analysis was applied to measure the degree of cohesion of interactional units. The networked structures were characterized in terms of nodes represented as circles and ties represented as lines. In this study, the data network of co-occurrence was visualized through VOSviewer (Leiden University, Netherlands), which provided the ability to produce easy-to-interpret graphical representations of bibliometric maps (van Eck & Waltman, 2010). In order to emphasize the historical hotspots and important topics in the field of algal biofuels, Citespace 5.7.R.1 (Chen Chaomei) was used to draw a timeline view and analyze the burst of keywords (Chen, 2017).

2. Performance of publication

2.1. Publication outputs

After data collection and refinement procedures, a total of 10,201 English-language publications were obtained from the SCI-Expanded database. Among them, 8668 cases were research articles (84.97%), followed by 1169 reviews (11.46%), 346 conference-proceedings papers (3.39%) and 18 book chapters (0.18%). For an overview of publication outputs, Figure 2 shows the annual trend in quantity of publications and citations over a 40-year period. During this time period, two stages can be identified: the first one was from 1980 to 2007 with few annual publications, and the second one beginning in 2008 had a significant increase in the quantity of publications and citations. Affected by rising oil prices and global warming, the project of the aquatic biological species plan in the

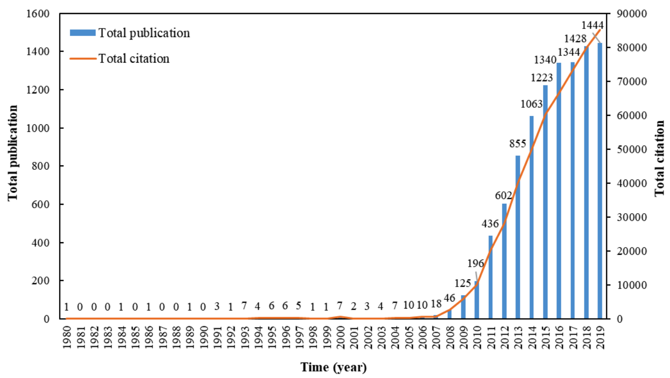

Figure 2. The annual trend in quantity of publications and citations from 1980 to 2019

USA was restarted in 2007 (Cheng et al., 2020), and United Kingdom also launched a project to encourage the algal biofuel in 2009 (Singh & Cu, 2010). The trend in the number of publications was consistent with the global research on algal biofuel, which has become a hotspot garnering extensive interest and promoting further research.

2.2. Subject categories and journals

All of the documents considered were classified into 116 subject categories by Web of Science. Figure 3 presents the publication distribution of the top 20 most productive subject categories. Within the top group, "Biotechnology & Applied Microbiology" and "Energy & Fuels" stood out, with 4,677 (45.8%) and 4,184 (41.0%) documents respectively. The next subjects were "Agricultural Engineering" (19.0%), "Chemical Engineering" (16.6%) and "Environmental Sciences" (12.6%).

In total, 10,201 documents were published in 905 different journals and more than 50.9% of the algal-biofuel related publications were published in the top 20 journals. As shown in Table 1, "Bioresource Technology" took the top position with 1,674 publications and 69,698 citations, far beyond that of any other journals,

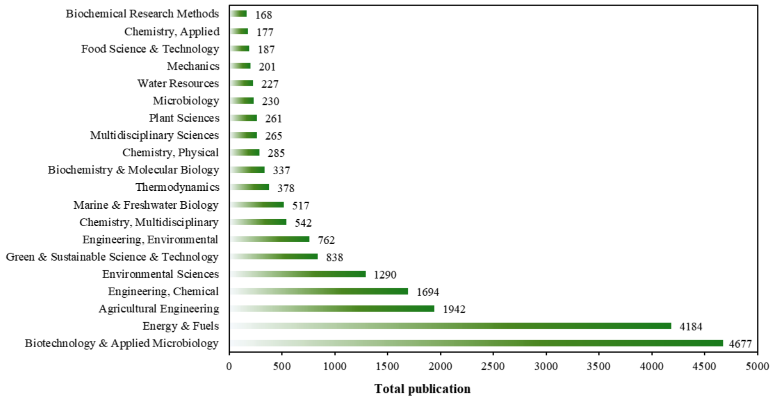

Figure 3. The publications distribution of the top 20 most productive subject categories

Table 1. The top 20 most productive journals

Journal	TP	TC	TC/TP	5 year IF	IF	Country
Bioresource Technology	1674	69698	41.6	6.589	6.669	Netherlands
Algal Research-Biomass Biofuels and Bioproducts	750	12157	16.2	4.474	3.723	Netherlands
Journal of Applied Phycology	370	8879	24.0	2.828	2.635	Netherlands
Renewable & Sustainable Energy Reviews	251	19596	78.1	11.239	10.556	USA
Biomass & Bioenergy	212	6828	32.2	4.062	3.537	England
Biotechnology for Biofuels	205	4526	22.1	6.343	5.452	England
Energy Conversion and Management	183	5133	28.0	6.722	7.181	England
Renewable Energy	171	3570	20.9	5.257	5.439	England
Applied Energy	170	10763	63.3	8.558	8.426	England
Fuel	155	4593	29.6	5.223	5.128	England
International Journal of Hydrogen Energy	130	2402	18.5	3.969	4.084	England
Energy	129	2787	21.6	5.747	5.537	England
Journal of Cleaner Production	110	1755	16.0	7.051	6.395	USA
Energy & Fuels	108	4078	37.8	3.554	3.021	USA
Applied Biochemistry and Biotechnology	103	3089	30.0	2.094	2.140	USA
Energies	99	2129	21.5	2.990	2.707	Switzerland
Energy Sources Part A-Recovery Utilization and Environmental Effects	98	740	7.6	0.789	0.894	USA
Applied Microbiology and Biotechnology	96	5728	59.7	3.889	3.670	Germany
Bioprocess and Biosystems Engineering	93	1116	12.0	2.277	2.371	Germany
Scientific Reports	81	888	11.0	4.525	4.011	England

Notes: TP – total publications; TC – total citations; TC/TP – average citations per article; IF – impact factor.

while the average number of citations per article was at an intermediate level (41.6). "Renewable & Sustainable Energy Reviews" performed best in terms of citations per article, with an average of 78.1, followed by "Applied Energy" (63.3) and "Applied Microbiology and Biotechnology" (59.7). Impact factor (IF), a useful indicator to evaluate the number of citations per paper for each journal, was obtained based on the Journal Citation Reports (JCR) of the Institute for Scientific Information published on 20 June 2019. The six most influential journals, with IF more than 5 were "Renewable & Sustainable Energy Reviews" (10.556), "Applied Energy" (8.426), "Energy Conversion and Management" (7.181), "Bioresource Technology" (6.669), "Journal of Cleaner Production" (6.395), "Energy" (5.537), "Biotechnology for Biofuels" (5.452), "Renewable Energy" (5.439) and "Fuel" (5.128).

2.3. Countries/regions

2.3.1. Characteristics of countries/regions

Figure 4 shows that the USA and China ranked 1st with 2,151 publications and 2nd with 2,127 publications among the 114 countries/regions contributing to this field, respectively. This emphasized their public interest and specific focusing on algal biofuel. Among European countries/regions, Spain was most prominent (436), followed by England (382), Germany (298), Italy (297), France (286) and the Netherlands (161). In addition, considering the effort of the European Union in its entirety, it had an outstanding performance in research output with a total of 2,117 publications in algal biofuel and an above-average citation impact of 34.4. As indicated in Figure 4, New Zealand, Ireland and Portugal had relatively fewer publications (95, 89 and 145) with greater citation impacts of 107.4, 68.9 and 55.9, respectively.

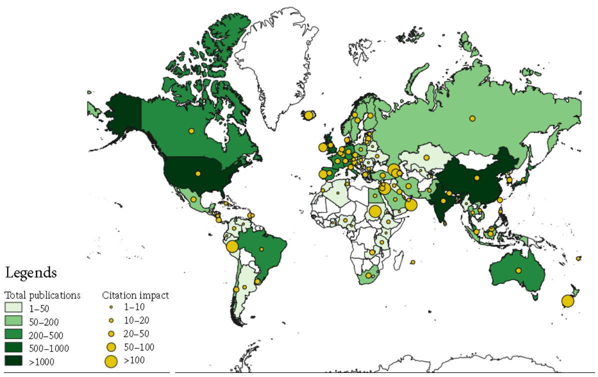

Figure 4. The geographical distribution of publications and citation impacts

The primary characteristics of the top 20 most productive countries/regions are showed in Figure 5. With regard to the percentage of international collaborations, Germany, the Netherlands and France had the outstanding performance in a leading position. The Netherlands ranked 1st in the proportion of highly cited papers, while the USA ranked 1st in terms of the number of highly cited papers (86).

2.3.2. Collaboration of countries/regions

The social network of international cooperation among countries is constructed using VOS viewer as shown in Figure 6. Each node represents a country/region and the size of the node corresponds to the quantity of publications of each country/region. There are seven clusters in total and countries/regions belonging to the same cluster are strongly associated within a specific research topic. For instance, the USA, China, New Zealand, the United Arab Emirates, Iran, Egypt, Tunisia, Pakistan, Iceland, and Nigeria in the sky-blue cluster, show strong association in algal biofuel research. Each line between two nodes represents the collaboration between two countries/regions and the thickness of the line indicates the link strength. The top 20 cooperative relationships between countries/regions are presented graphically in Figure 6. The USA is in the center of countries/regions with hundreds of lines connecting with other countries, indicating a high centrality in international collaboration. Moreover, the cooperative relationship between the USA and China is the closest with a link strength of 309, which is far beyond that of other countries/regions. South Korea, India, Canada, Brazil, Australia, Germany and England also have a relatively

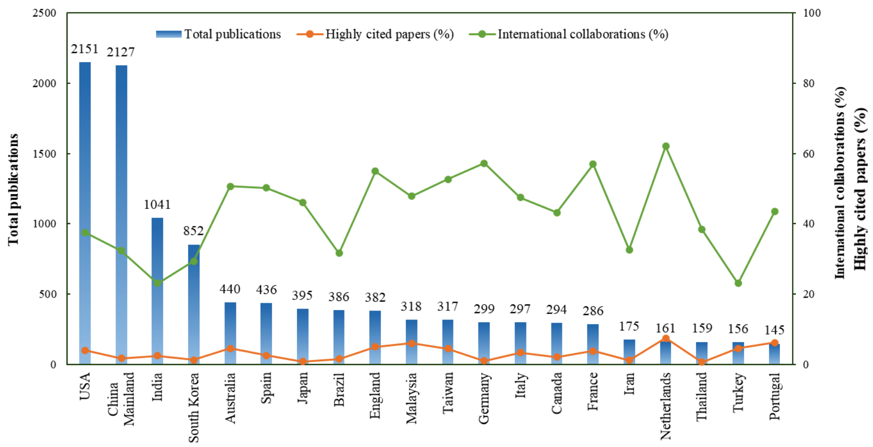

Figure 5. The primary characteristics of the top 20 most productive countries/regions

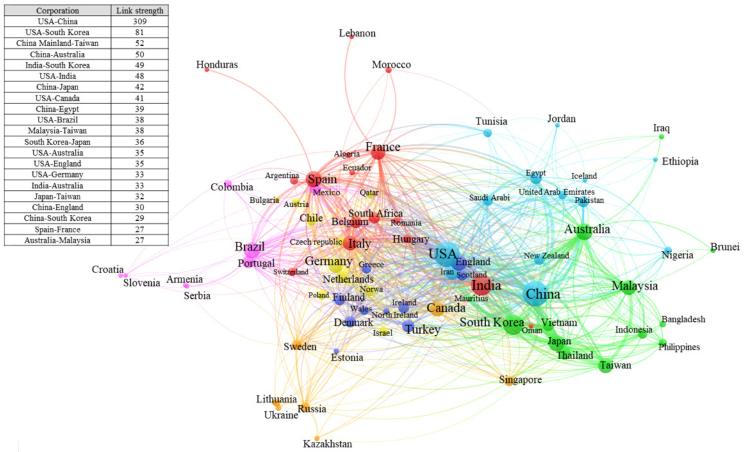

Figure 6. The social network of international cooperation across countries visualized by VOSviewer

close collaboration with the USA. China ranked second in international collaboration, mainly cooperating with the USA, Australia and Japan. In addition, several European (Spain, Germany, England and France) and Asian (South Korea, India and Japan) countries had a wide variety of international collaboration partners.

2.4. Institutions

Table 2 illustrates the primary characteristics of the top 20 most productive institutions in algal biofuel research. The Chinese Academy of Sciences was the largest contributor with the greatest number of total publications (476) and international collaborative publications (139), followed by the United States Department of Energy with a total of 282 publications. Two American institutions, the National Renewable Energy Laboratory and Arizona State University, which contributed dozens of papers, showed distinguished citation impacts of 92.9 and 69.6 citations/paper, respectively. The United States Department of Energy had the highest *h*-index of 59, followed by the Chinese Academy

Table 2. The top 20 most productive institutes

Institutes	Country	TP	TC	TC/TP	*h*-index	CP (%)	HP (%)
Chinese Academy of Sciences	China Mainland	476	12921	27.1	57	139 (29.2)	11 (2.3)
United States Department of Energy	USA	282	14703	52.1	59	65 (23.0)	17 (6.0)
Indian Institute of Technology System	India	281	5182	18.4	38	60 (21.4)	6 (2.1)
Council of Scientific & Industrial Research	India	225	6094	27.1	38	42 (18.7)	6 (2.7)
Korea Advanced Institute of Science & Technology	South Korea	208	4509	21.7	38	49 (23.6)	2 (1.0)
University of California System	USA	184	8883	48.3	49	68 (37.0)	12 (6.5)
University of Chinese Academy of Sciences	China Mainland	180	4360	24.2	34	49 (27.2)	3 (1.7)
National Cheng Kung University	Taiwan	172	7430	43.2	45	107 (62.2)	9 (5.2)
Centre National de la Recherche Scientifique	France	163	5810	35.6	37	81 (49.7)	5 (3.1)
Tsinghua University	China Mainland	142	7500	52.8	38	43 (30.3)	6 (4.2)
University of Minnesota System	USA	109	4973	45.6	36	65 (59.6)	3 (2.8)
University of Minnesota Twin Cities	USA	107	4740	44.3	35	63 (58.9)	2 (1.9)
Japan Science & Technology Agency	Japan	103	1824	17.7	23	35 (34.0)	–
Arizona State University	USA	101	7029	69.6	35	55 (54.5)	6 (5.9)
Harbin Institute of Technology	China Mainland	99	1760	17.8	22	55 (55.6)	0 (0.0)
Qingdao Institute of Biomass Energy and Bioprocess Technology	China Mainland	98	4050	41.3	33	18 (18.4)	5 (5.1)
Pukyong National University	South Korea	89	1737	19.5	24	17 (19.1)	–
Korea Institute of Energy Research	South Korea	87	1736	20.0	22	3 (3.4)	1 (1.1)
Wageningen University & Research	Netherlands	85	4159	48.9	30	58 (68.2)	7 (8.2)
National Renewable Energy Laboratory	USA	84	7803	92.9	37	18 (21.4)	8 (9.5)
Zhejiang University	China Mainland	84	1944	23.1	27	20 (23.8)	1 (1.2)

Notes: TP – total publications; TC – total citations; TC/TP – average citations per article; CP – the number of international collaboration papers; HP – the number of highly cited papers; % – the percentage of articles of institutes in total articles.

of Sciences (57), the University of California System (49), and National Cheng Kung University (45). Comparing the degree of international cooperation, National Cheng Kung University, University of Minnesota System, University of Minnesota Twin Cities, Arizona State University, Harbin Institute of Technology and Wageningen University & Research stood out with the percentage of international collaborative publications exceeding 50%. Institutions from the USA and China made a greater contribution in highly-cited papers.

2.5. Funding agencies

Generally, research funding agencies had important impacts on the development of both research subject and national science foundations from governments, engaging in strategies of knowledge transfer and decision making, provided most of the financial support (Lavis et al., 2003). In USA, since the Energy Independence and Security Act of 2007 was implemented, which mandated increased use of biofuels in gasoline under the Renewable Fuel Standard (RFS2) (Gallinaro, 2014), over 450 million dollars were invested in scientific research on seaweed energy. And a number of projects on algal energy have been funded by the Ministry of Science and Technology of China (MSTC), National Natural Science Foundation of China (NSFC), State Oceanic Administration, and Municipal People's Government since 2009, which greatly promoted the rapid development of this field domestically. In Europe, more than 100 million Euros were invested in the research and development of algal biofuel since 2008 (Su et al., 2017). These projects were exploring critical techniques in enhancing the production efficiency of algal biofuels and industrial demonstration. In order to have a better understanding of the history of research on algal biofuel, a diverse distribution of funding agencies in this research field was extracted. A total of 8,019 agencies were acknowledged as funding the research on algal biofuel. Table 3 lists the top 20 most productive funding agencies in detail. Among them, China mainland had 6 funding agencies with the most varied grant programs to support the research. To the best of our knowledge, the Australian Research Council was the first to fund the research in algal biofuel. The first paper titled "Second Generation Biofuels: High-Efficiency Microalgae for Biodiesel Production" supported by the Australian Research Council was published in 2008. Since then, more and more studies on algal biofuel have been funded by governments, research institutes, organizations and academies. Publications supported by the majority of the top 20 most productive funding agencies were published firstly in 2009 or 2010. The National Natural Science Foundation of China was the most highly published funding agency with 1,167 articles.

2.6. Citation analysis

It was significant to analyze the highly cited papers, which not only provided a historic perspective on the development of a specific subject but also revealed the scientific advances through useful and valuable insights (Baltussen

Table 3. The top 20 most productive funding agencies

Funding Agency	Country	Start Time	TP
National Natural Science Foundation of China	China Mainland	2009	1167
United States Department of Energy (DOE)	USA	2008	443
National Science Foundation (NSF)	USA	2009	397
National Council for Scientific and Technological Development (CNPq)	Brazil	2010	206
European Union (EU)	EU	2009	194
Fundamental Research Funds for the Central Universities	China Mainland	2011	181
National Basic Research Program of China (973 Program)	China Mainland	2009	174
Council of Scientific & Industrial Research (CSIR)	India	2009	167
National High Technology Research and Development Program of China (863 Program)	China Mainland	2009	150
Coordenacao de Aperfeicoamento de Pessoal de Nivel Superior (CAPES)	Brazil	2010	149
Natural Sciences and Engineering Research Council of Canada (NSERC)	Canada	2009	134
Department of Biotechnology (DBT)	India	2009	133
Engineering & Physical Sciences Research Council (EPSRC)	UK	2009	119
China Postdoctoral Science Foundation	China Mainland	2013	113
Department of Science & Technology	India	2010	109
Ministry of Education,Culture,Sports,Science and Technology, Japan(MEXT)	Japan	2009	104
Consejo Nacional de Ciencia y Tecnologia (CONACyT)	Mexico	2009	102
Chinese Academy of Sciences (CAS)	China Mainland	2009	98
National Science Council of Taiwan	Taiwan	2009	97
University Grants Commission	India	2010	96

Note: TP – total articles.

& Kindler, 2004; Ohba et al., 2007; Smith, 2008). In total, there were 274 highly cited papers in field among the 10,201 publications and some papers were cited highly but not recorded as highly cited papers in this field as analyzed from Web of Science Core Collection. The top 20 most highly cited papers based on citation numbers are presented in Table 4. It included 8 articles and 12 reviews published from 2006 to 2012. Among them, all papers ranking in the top 5 obtained large the total citations (>1000) and annual citations (>100). The paper written by Yusuf Chisti (2007) ranked 1st in both total (5,071) and annual citations (390.1), which emphasized that the oil productivity of microalgae greatly exceeded that of any agricultural crops greatly pushing forward the development of algal-biofuel research (Chisti, 2007). Some papers gave overviews of the development and application of algal

Table 4. The top 20 highly cited papers

Year	F & C authors	Title	Journal	TC	TC/TY
2007	Chisti, Yusuf	Biodiesel from microalgae	Biotechnology Advances	5071	390.1
2010	Mata, Teresa M.	Microalgae for biodiesel production and other applications: A review	Renewable & Sustainable Energy Reviews	2549	254.9
2010	Brennan, Liam	Biofuels from microalgae-A review of technologies for production, processing, and extractions of biofuels and co-products	Renewable & Sustainable Energy Reviews	2150	215.0
2008	Hu, Qiang; Darzins, Al	Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances	Plant Journal	2088	174.0
2009	Rodolfi, Liliana; Tredici, Mario R.	Microalgae for oil: Strain selection, induction of lipid synthesis and outdoor mass cultivation in a low-cost photobioreactor	Biotechnology and Bioengineering	1589	144.5
2008	Schenk, Peer M.	Second Generation Biofuels: High-Efficiency Microalgae for Biodiesel Production	Bioenergy Research	1181	98.4
2008	Chisti, Yusuf	Biodiesel from microalgae beats bioethanol	Trends in Biotechnology	1169	97.4
2011	Nigam, Poonam Singh	Production of liquid biofuels from renewable resources	Progress in Energy and Combustion Science	1035	115.0
2006	Kapdan, I. K.; Kargi, F.	Bio-hydrogen production from waste materials	Enzyme and Microbial Technology	959	68.5
2011	Chen, Chun-Yen; Chang, Jo-Shu	Cultivation, photobioreactor design and harvesting of microalgae for biodiesel production: A critical review	Bioresource Technology	884	98.2
2009	Lardon, Laurent	Life-cycle assessment of biodiesel production from microalgae	Environmental Science & Technology	840	76.4
2009	Griffiths, Melinda J.; Harrison, Susan T. L.	Lipid productivity as a key characteristic for choosing algal species for biodiesel production	Journal of Applied Phycology	830	75.5
2006	Miao, X. L.; Wu, Q. Y.	Biodiesel production from heterotrophic microalgal oil	Bioresource Technology	805	57.5
2011	Pittman, Jon K.	The potential of sustainable algal biofuel production using wastewater resources	Bioresource Technology	742	82.4
2012	Hoekman, S. Kent	Review of biodiesel composition, properties, and specifications	Renewable & Sustainable Energy Reviews	740	92.5
2012	Atabani, A. E.	A comprehensive review on biodiesel as an alternative energy resource and its characteristics	Renewable & Sustainable Energy Reviews	714	89.3
2009	Gouveia, Luisa	Microalgae as a raw material for biofuels production	Journal of Industrial Microbiology & Biotechnology	690	62.7
2009	Sialve, Bruno	Anaerobic digestion of microalgae as a necessary step to make microalgal biodiesel sustainable	Biotechnology Advances	663	60.3
2009	Converti, Attilio	Effect of temperature and nitrogen concentration on the growth and lipid content of Nannochloropsis oculata and Chlorella vulgaris for biodiesel production	Chemical Engineering and Processing	663	60.3
2006	Munoz, Raul; Guieysse, Benoit	Algal-bacterial processes for the treatment of hazardous contaminants: A review	Water Research	660	47.1

Notes: F & C authors – first & corresponding authors; TC – total citations; TC/TY – annual citations.

biofuel (Li et al., 2008a, 2008b; Mata et al., 2010; Nigam & Singh, 2011; Schenk et al., 2008), while others focused on the particular processes such as algal cultivation (Chen et al., 2011; Converti et al., 2009; Li et al., 2008), lipid production or accumulation (Griffiths & Harrison, 2009; Hu et al., 2008; Meng et al., 2009), anaerobic digestion (Sialve et al., 2009), and life cycle assessment (Clarens et al., 2010; Lardon et al., 2009).

3. Research tendencies and future trends

3.1. Keyword analysis

Keywords are placed in publications to draw attention as the most salient research topics. Novel insights and implications of the research were elicited from the network of keywords by metrics (Choi et al., 2011). Therefore, the number of occurrences of each keyword served as an indicator to identify the research themes of the greatest interest. In the current study, the frequency of each keyword was extracted by Bibexcel software. Among 10,201 publications, a total of 14,412 keywords were recorded. However, keywords appearing only once accounted for approximately 72.8% of all the keywords, while keywords used more than 5 and 10 times accounted for only 1,256 (8.7%) and 613 (4.3%), respectively.

Based on the 1,256 keywords with a frequency over 5, a density view was created by VOSviewer. Labels are shown for frequently used keywords only in order to prevent overlapping labels, and the size of the keyword labels is proportional to their frequency in Figure 7. This revealed co-occurrence of the keywords, their density and centrality. The term microalgae had a dark red indicating its importance. Biodiesel took the second place, followed by biofuel, algae, biomass, lipid, *Chlorella vulgaris*, anaerobic digestion, wastewater, hydrothermal liquefaction, photobioreactor, biogas, bio-oil, bioethanol, bioenergy, wastewater treatment, transesterification and macroalgae, which strongly suggested the research hotspots and the important topics in this field.

3.2. Historical hotspots analysis

Hotspots rely on the connection of keywords. The review and analysis of keywords were investigated in the algal biofuel research. In order to identify the specific hotspots and give a detailed review throughout the process of algal biofuel production, 1,256 keywords occurring more than 5 times were categorized into six groups: Algal selection, Cultivation, Harvesting, Extraction, Conversion, and Bioproducts. A flow chart about algal biofinery combined with the keyword frequency is shown in Figure 8. Keywords that differed slightly were combined for the frequency calculation and unified in a standard form. Only the most frequent keywords in specific processes were provided.

Total 200 author keywords that appeared most frequently each year were selected for analysis by Citespace 5.7.R.1. Since there were few publications between 1980–1990, a timeline view of author keywords of publications from 1991 to 2019 was drawn (Figure 9). Each node represented a keyword, and the location of the node represented the time when the keyword first became a research hotspot. The size of the node corresponded to the total frequency of the keyword. The links between nodes indicated that these keywords co-occurred in the same article. The nodes on one axis were the same cluster. According to the timeline view as shown in Figure 9, the

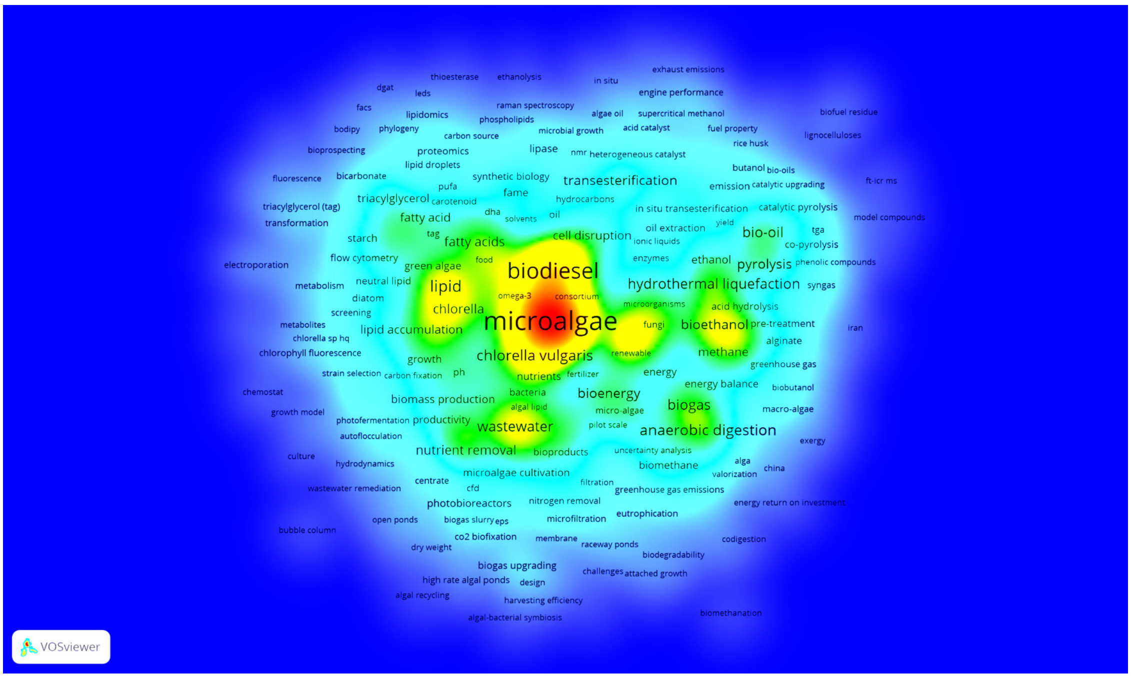

Figure 7. Density view of the keywords with a frequency over 5 times created by VOSviewer

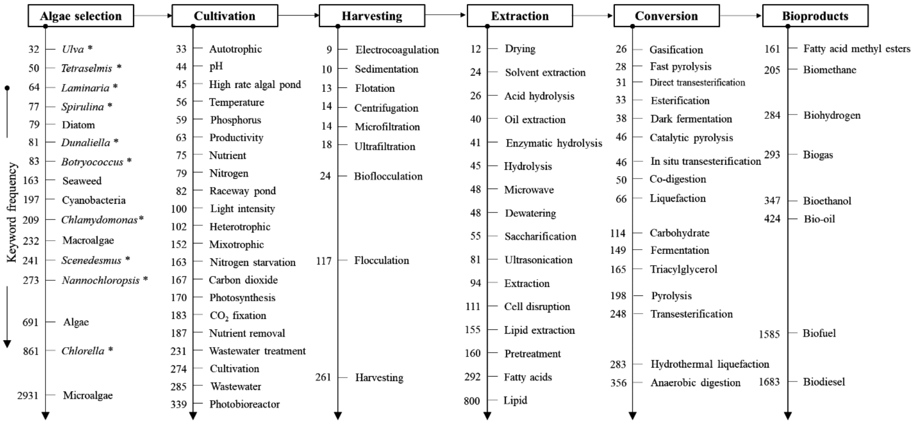

Figure 8. Flow chart of algae biorefinery combined with keyword frequency

Notes: Similar keywords were combined for frequency calculation and unified in a standard form. E.g., keywords such as diatom and diatoms were sorted as "Diatom"; The generic name of algae with * means the combination of various algae in the same genera. E.g., keywords such as Tetraselmis subcordiformis, Tetraselmis suecica, Tetraselmis and Tetraselmis sp. were sorted as "Tetraselmis *".

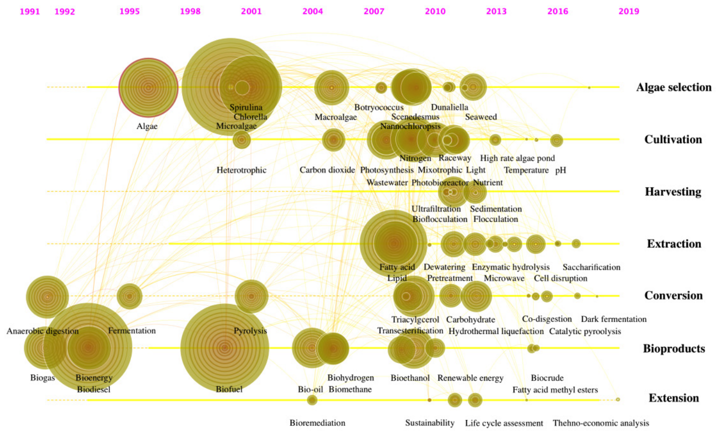

Figure 9. A timeline visualization of keyword during 1991 to 2019

research on Algae selection, Conversion and Bioproducts started earlier, while Cultivation, Harvesting and Extraction mainly were focused after 2007.

3.2.1. Algal selection

Algae were able to photosynthetically convert atmospheric carbon dioxide (CO_2) into a wide range of metabolites and compounds including proteins, polysaccharides and/or lipids (Sambusiti et al., 2015). The keyword "microalgae" ranked first with a frequency of 2,931 while "macroalgae" had a much lower frequency of 232 (Figure 8). This indicated that microalgae occupied the core position in the production of biofuels (Chen et al., 2015). Since 2001, the research on *Chlorella* and *Spirulina* as the production of biofuels has begun as shown in Figure 9. After 2007, a large number of studies on *Chlamydomonas* (209), *Nannochloropsis* (273), *Scenesmus* (241), *Dunaliella* (81), and *Diatom* (79) emerged. *Botryococcus* (83) and *Seaweed* (163) in macroalgae became the research hotspots in 2007 and 2012, respectively.

The major components of microalgae are protein, lipids, and carbohydrates. The lipid content of biomass in algae depended on the algal strain and strain selection affected the chemical composition of algal biofuel (Ahmad et al., 2011). The primary need for algal biofuel was to identify algal species with higher oil content and growing quickly to produce biodiesel, bio-crude fuels (Singh & Cu, 2010). *Chlorella,* with the highest lipid yields, was applied commercially among microalgae (Liang et al., 2009; Nascimento et al., 2013). *Nannochloropsis* with higher oil content was extensively grown as a robust industrial algae in outdoor ponds and photobioreactors for aquaculture (Kilian et al., 2011; Pal et al., 2011). *Chlamydomonas* led to the development of molecular tools for strain selection and engineering for green algae (Scranton et al., 2015). *Scenedesmus* presented the most adequate fatty acid profile, however, *Dunaliella* was also used if associated with other microalgal oils (Chen et al., 2011; Ho et al., 2012).

Compared with microalgae, macroalgae are multicellular plants. Moreover, they are richest in carbohydrates, rather than proteins or lipids (Jung et al., 2013). A net energy of 11,000 MJ/t generated by dry macroalgae compared to 9,500 MJ/t from microalgae according to a life cycle assessment (Chen et al., 2015). Macroalgae have more potential for bioethanol and biogas (Ramachandra & Hebbale, 2020). The first article on the application of *Ulva* for biofuels as higher lipid and sugar content than red algae and brown algae in 1996. At the same time, *Ulva* was suitable for co-cultivation with marine aquaculture to increase sugar content, and was considered a very promising feedstock for bioethanol (Chia et al., 2018) and biobutanol (Potts et al., 2012).

3.2.2. Algal cultivation

The choice of algal cultivation systems depended on algal characteristics, geological environment and target products (van Beilen, 2010). The emergence of hotspots in algae cultivation was concentrated after 2007. In the early days, there was a lot of research on "carbon dioxide" (167), "light intensity" (100), "nitrogen" (79), "nutrients" (75), and "phosphorus" (59). After 2013, more research of pH (44) and temperature (56) on algae culture appeared. In the cultivation process, light was the decisive factor (Singh & Singh, 2015). In general, there were two primary avenues of carbon fixation in algal culture. The first was autotrophic cultivation which corresponded to photosynthetic growth and fixation of inorganic carbon through the Calvin-Bensen cycle. CO_2 was bubbled into the medium to maintain dissolved gas concentration and pH at the constant levels. The second was heterotrophic cultivation, which referred to assimilation of organic carbon in the absence of light. Furthermore, some algae persisted in mixotrophic conditions (Lowrey et al., 2015). Based on keyword frequency, "mixotrophic" was the most frequent culture method with 152 publications. Some algal species surviving in the extreme environments were cultivated by adjusting pH and temperature. Extreme temperature or pH gave the microalgal strains an advantage against the contamination by the competing microbial species during the cultivation process (Enamala et al., 2018). Thus, algal cultivation systems could effectively be controlled and optimized by monitoring CO_2 concentration, temperature, pH, nitrogen, phosphorus, nutrient and light intensity (Zeng et al., 2011).

Several technologies have been developed for algal culture, from open ponds and raceways to closed photobioreactor, column, and tubular systems (Clarens et al., 2010; Greenwell et al., 2010). The keyword "photobioreactor" attracted much attention (339 papers), and "raceway pond" stood out with 82 publications due to its ease of maintenance and operation (Chisti, 2007). However, the disadvantage of open system could not be ignored because of microbial contamination. Currently, the cultivation techniques, including open pond reactors and photobioreactors, in pilot or demonstration-scale have been proven to be immature for commercial application. The biggest barriers to translate lab-scale experiment results (high yields) to large-scale production was lack in understanding the biology of optimal biomass production (White & Ryan, 2015).

The consideration of wastewater/effluents as potential nutrient sources for low-cost production of lipids was also of great interest among researchers. Further, algae could also reduce biochemical oxygen demand during cultivation in wastewater. After 2012, high rate algae ponds attracted wide attention from researchers. It was usually used as a part of Advanced Pond System, which combined BOD removal and algae cultivation in sewage (del Rosario Rodero et al., 2018). Therefore, it had broad application and great potential owing to win-win situation for wastewater treatment and production of algal biofuel (Suali & Sarbatly, 2012) with the frequency of the keywords, "wastewater" (285) and "wastewater treatment" (231).

3.2.3. Algal harvesting

Harvesting algae is a crucial step in the production of algal biofuel. Harvesting cost has come about 20% to 30% of the cost of total algal biomass and 90% of the equipment costs for algal biomass production from harvesting and dehydration (Milledge & Heaven, 2012). The steps of cultivation and harvesting consume 25–70% of the energy produced in the whole process as well as the post-processing demands 15–30% (van Beilen, 2010). However, the hotspots in this field appeared relatively late until after 2010 (Figure 9). The most common method is still flocculation (117) in Figure 8. The mechanism of flocculation was to neutralize or reduce the negative charge on the algal surface to aggregate algal cells in suspension (Wang et al., 2008). Flocculation and flotation were widely used for bulk separation. Flotation depended on trapping algae by dispersed micro-air bubbles. Centrifugation and filtration were the most commonly used technologies for further concentrating and thickening the algae (Brennan & Owende, 2010). The harvesting technologies of centrifugation (14), ultrafiltration (18), and flotation (13) were limited because of high operating costs. Sedimentation (10) required clear algae species, best suited to dense non-motile cells. The separation speed of sedimentation was slow as well as low concentration obtained. Bioflocculation (24) was costly but energy efficient alternative harvesting method. However, this technology affected by pH and temperature was not suitable for pre-harvesting and further research would be needed (Milledge & Heaven, 2012).

Since 2013, research on algae harvesting technology has greatly increased. The challenge of harvesting is to take the very low algal cell density and concentrate them. Therefore, reducing harvest costs is a key issue for the commercialization of algal biofuel. It will have a huge impact on the production process of algal biofuel.

3.2.4. Extraction

Lipid extraction is one of the important steps to obtain biodiesel from algae. Lipid extraction mainly includes chemical extraction and mechanical extraction. The Folch method and Bligh and Dyer method were the most studied chemical extraction methods. They were established methods for extracting lipids, but they had the disadvantages that the solvents in extraction were not friendly to the environment and the extraction process was laborious (Enamala et al., 2018). Among the mechanical methods, hydrolysis (46), microwave (50) and ultrasonication (41) were studied more frequently. Compared with other mechanical methods, ultrasonication had the advantage of not requiring high temperature or adding other substances (Lee et al., 2012). It was an economical and environment friendly extraction method. The microwave was another promising method because it took a short time and had low operating costs (Hemwimon et al., 2007). Ultrasonication and microwave have been extensively studied. Hydrolysis included enzymatic hydrolysis and acid hydrolysis since 2012. The research on acid hydrolysis was focused on 2013–2016, and gradually decreased in the past two years. The research on enzymatic hydrolysis gradually increased after 2012, but its effect was greatly affected by enzyme activity and the price of enzyme was relatively high (Liang et al., 2012). Pretreatment of concentrated algae, such as drying and cell disruption, was proven to aid in extraction of lipids and fatty acids (Zeng et al., 2011). After 2009, it became another hotspot in this field.

As discovered in this study, the keyword "lipid" with a frequency of 800 first appeared as a keyword in 2000, and became a hotspot in this field after 2007. "Pretreatment" and "lipid extraction" were the two other major areas with appearance of 160 and 155 number of times. In the pretreatment process, "cell disruption" (111) and "dewatering" (48) were of the most common.

3.2.5. Conversion of algal biomass and production of bioproducts

Conversion and Bioproduct of algal biomass developed almost simultaneously (Figure 9). Algal biomolecule could be extracted and converted into biodiesel through transesterification process and the waste biomass was used to produce different types of biofuel such as biomethane, bioethanol, and biohydrogen through other types of conversion processes such as anaerobic digestion, fermentation, etc. Conversion process involving anaerobic digestion (356) was the most frequent and the earliest keyword from 1991. The research on fermentation (149) and pyrolysis (198) began before 2000. After 2007, hydrothermal liquefaction (290) and transesterification (248) were extensively studied. Conversely, less attention was devoted to "gasification" (26) and "esterification" (33), which only appeared in a few publications.

The algal lipid was converted to biodiesel through transesterification process (Suali & Sarbatly, 2012). Algal lipid was initially hydrolyzed to form fatty acids and glycerol. Fatty acids were esterified with methanol to form fatty acid methyl ester called biodiesel. The selection of suitable medium for hydrolysis of algal lipid and proper choice of catalyst for transesterification of hydrolyzed fatty acid with methanol were the topics of research interest. Anaerobic digestion converted the residual biomass after lipid extraction, and recycles nitrogen and phosphorus which were added as nutrient for growth of algal culture. Algae was also used as feedstock for bioethanol production through fermentation (Pragya et al., 2013). The liquefaction and pyrolysis products of algae were mainly affected by the algae composition, temperature, pressure, residence time, and catalyst (Suali & Sarbatly, 2012). For pyrolysis, "catalytic pyrolysis" and "catalytic co-pyrolysis" had the greatest keywords frequency.

The largest node in the axis of bioproduct was "Biodiesel" (1683). The research on biodiesel could be traced back to the early 1990s and exploded after 2007. Biodiesel was the most concerned product because the biodiesel from algae could provide the highest net energy and be directly applied to existing diesel engines (Singh & Cu, 2010). The algae nodes connected to biodiesel were *Chlorella*, *Spirulina*, and *Nannochloropsis*. Lipid rich algae were better choice than other algal species for sustainable production of algal biodiesel. However, the production of algal biodiesel faced the problem of higher algae planting and harvesting costs (Lee, 2016).

The earliest hotspot keyword in bioproducts is biogas in Figure 9. The extraction of biogas from seaweeds through anaerobic digestion was studied in 1980 (Rao et al., 1980). Brown seaweeds had low content of protein and high content of carbohydrates (high C/N ratio) in their biomass, therefore they were considered more suitable for anaerobic digestion in comparison to green algae (Nielsen & Heiske, 2011). The main components of biogas were methane, carbon dioxide and a small amount of N_2, H_2, H_2S and water vapor. There were many studies on biomethane produced by algae and the content of biomethane was increased by pretreatment of algae after 2004. However, the efficiency of pretreatment varied with algal species (Bruhn et al., 2011).

More attention was paid to production of biohydrogen as a potential alternative energy source from 2005 to 2012. The early development of biohydrogen focused on pyrolysis and photosynthetic by various microorganisms. However oxygen was produced in the process of producing biohydrogen through pyrolysis, which inhibited the production of hydrogen (Lakaniemi et al., 2011). The development of subsequent dark or heterotrophic fermentation could produce hydrogen under anaerobic conditions without light. Dark fermentation required less space for hydrogen production and it was not affected by the light of the external environment. The produced hydrogen containing carbon dioxide, methane and other gases and the conversion rate of algal biomass to produce hydrogen was still low, so further exploration was needed (Show et al., 2018). The increasing trend of publications on biohydrogen from 2012 to 2017 was flat, but a large number of publications broke out during 2018–2019.

In the past decade, bioethanol become another hotspot in algal biofuel. Especially, there were 260 publications on bioethanol during 2018–2019. Lignin-free, high-sugar macroalgae such as *Brown algae*, *Ulva*, *Seaweed*, etc., had great potential to produce bioethanol (Sun & Cheng, 2002). Fermentation converted sugar, starch or cellulose in biomass into ethanol. However, both the pretreatment of algae and the process of converting ethanol required high costs (Dave et al., 2019).

3.3. Future trends

The burst detection algorithm was proposed by Kleinberg in 2002. Burst keywords referred to a sudden increase during a short term. Through the burst detection, the content did not reach the frequency threshold, but it had the development of informatics significance in the academic process. The frontier fields by analyzing the keywords burst out so far (Chen, 2017). Four keywords namely "co-culture", "sludge", "climate change" and "biocrude" burst out lasting until 2019 (Figure 10).

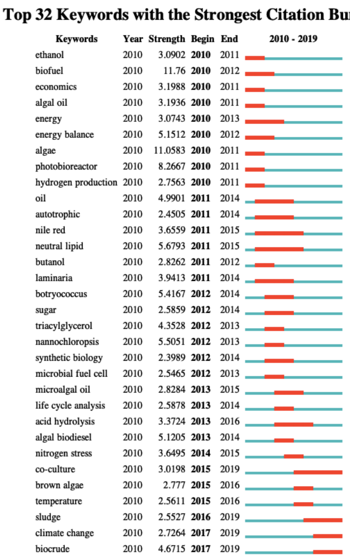

Figure 10. Top 32 keywords with the strongest citation bursts during 2010 to 2019

"Biocrude" was the keyword with the most explosive intensity, starting in 2017. It was a complex mixture of multiple compounds, including phenolic compounds, aromatic hydrocarbons, nitrogen-containing compounds, amides, fatty acids and esters. The content of various components largely depended on the type of algae and the process of extraction and transformation (Xu et al., 2018). Biocrude was obtained from wet algae through hydrothermal liquefaction or dehydrated algae by pyrolysis. Biocrude oil was produced by hydrothermal liquefaction with a higher energy recovery rate and a lower energy consumption (Faeth & Savage, 2016). Compared with biodiesel, the content of sulfur, nitrogen and total acid in biocrude was still higher. These components affected the storage and transportation of biocrude (Obeid et al., 2019).

The keyword with the longest burst duration was "co-culture" starting in 2015. Co-cultivation generally referred to the co-cultivation of algae and other microorganisms, such as bacteria, fungi or other algae species (Zhu, 2015). Co-cultivation not only increased the yield of biofuels, but also coupled sewage treatment and algae cultivation. When different algae were cultivated together, the dominant algae species increased the growth rate and lipid content (Sathish & Sims, 2012). When algae and bacteria were co-cultured, the algae used the carbon dioxide by the respiration of the bacteria for photosynthesis to produce oxygen. The bacteria released certain substances to promote the growth of the algae (Zhu et al., 2013). However, some bacteria also released substances to be harmful to algal cells (Zhang et al., 2012).

The keyword "sludge" began to explode in 2016. Anaerobic co-digestion was most closely related to sludge in the field of algal biofuel. High nitrogen content limited anaerobic digestion for algae. When algae and sludge were co-digested under anaerobic condition, the ratio C/N increased. Therefore, it can be stated that algae can increase the digestibility of the sludge, and the production of biogas will also be increased (Ajeej et al., 2015).

The key words of climate change have attracted widespread attention in this field since 2017. The emission of carbon dioxide and other greenhouse gases caused the global temperature to rise (Singh & Cu, 2010). In December 2015, the 21st United Nations Climate Change Conference passed the Paris Agreement, the long-term goal of the Paris Agreement was to control the global average temperature rise within 2 °C (Pires, 2017). This is also one of good chance for using algal biofuel to reduce the burning of fossil fuels.

All of these four words had a certain connection with wastewater treatment by analyzing the co-occurring keywords. Obviously, combining wastewater treatment with algae cultivation to produce biofuels is a promising process in the future because of the great reduction of costs and energy consumption theoretically (Bhatia et al., 2021). However, the process still faces some challenges, such as sludge management. How to deal with the algae-containing sludge produced by growing algae in sewage is a problem. When algae are co-cultured with other microorganisms in wastewater, how to screen the algae species or adjust cultivation conditions are worthy of in-depth exploration. In addition, the high sulfur and nitrogen content in wastewater and sludge makes it easier to cultivate high-protein algae, but how to reduce the sulfur and nitrogen content of biocrude produced by these algae is also a crucial issue. With the global sensitivity to climate change, the industrialization model is not yet mature, however algae biofuel is very attractive (Chamkalani et al., 2020). In the energy sector to overcome the crisis of the regular conventional fuel and global warming issues, new technological breakthroughs in algae energy are necessary to meet today's demand of energy without creating global warming issues.

Conclusions

Based on the SCI-Expanded database, characteristics of the algal-biofuel related literature from 1980 to 2019 were examined by bibliometric methods. A knowledge-generating system about algal biofuel was established through performance analysis, social network analysis, citation analysis, and keywords analysis. The total number of the annual articles and citations were increasing each year and a significant boost occurred in the quantity of publications and citations since 2007. Biotechnology & Applied Microbiology is the most productive subject with the highest number of algal biofuel publications. "Bioresource Technology" was the most outstanding journal taking into account all analysis indices, while "Renewable & Sustainable Energy Reviews" performed best with an average citation of 78.1 per article. The USA ranked 1st with 2,151 publications, showing its public interest and specific focus on algal biofuel, followed by China. Additionally, the USA had significant international research collaboration, connecting with numerous other countries. The Chinese Academy of Sciences was the key contributor to algal biofuels research (publishing 476 papers) among the top 20 most productive institutions.

Through the analysis of keywords frequency, *Chlorella* was the most widely studied algae for biofuel production. The results of timeline analysis and burst detection indicated that the optimization of algae cultivation and harvesting techniques to reduce costs and energy consumption will be focused on in the future, such as co-cultivating algae with other organisms and cultivating algae with municipal sludge. Moreover, biocrude, as a bioproduction, will attract more attention too. The efficient reduction of production costs and energy requirements are very complicated to maximize lipid productivity and biomass value. Although there are several technical challenges with large-scale algal biofuel production, the future of algal biofuel is quite bright. Finally, new technological breakthroughs and the government support in finance or policy-making are the main driving force of algal biofuel.

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Conflict of interest

The authors declare that they have no conflict of interest.

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