

# A bibliometric analysis of biodiesel research during 1991–2015

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**Abstract** A bibliometric analysis based on the Science Citation Index Expanded (SCI-EXPANDED) from the Web of Science was carried out to provide insights into research activities and tendencies of the global biodiesel from 1991 to 2015. The document type and language, characteristics of publication outputs, Web of Science categories, journals, countries, institutions, author keyword and most cited articles were emphasized. The results indicated that annual output of the related scientific articles increased steadily. The top six categories focus on different aspects of biodiesel research. *Bioresource Technology* and *Fuel* were the two most frequent journals in the field of biodiesel research. The USA took a leading position and had the highest *h*-index (108) out of 122 countries/territories, followed by China and Brazil. Finally, author keywords and most cited articles were analyzed, indicating

that microalgae, *Jatropha curcas*, vegetable oil and waste cooking oil are the most general raw materials for biodiesel production.

**Keywords** Bibliometric analysis · Biodiesel · Research trend · Scientometrics

## Introduction

Alternative fuels for diesel engines are becoming increasingly important due to diminishing petroleum reserves and the environmental consequences of exhaust gases from petroleum-fuelled engines [1, 2]. Presently, biodiesel research is one of the most important areas in biofuels and its investment has dramatically increased in recent years [3, 4]. A number of papers presenting the latest research achievements have been published in the authoritative scientific journals such as *Nature*, *Science* and *Nature Biotechnology* [5–7]. The benefit of biodiesel as a promising energy source is that it produces few atmospheric pollutants and has a widely available raw material such as microalgae, *Jatropha curcas*, vegetable oil and waste cooking oil [8–10].

Though the biodiesel has experienced episodes of popularity throughout the twentieth century, the real biodiesel revival began in Europe in the early 1990s, spurred by mandatory alternative fuel utilization legislation and a liquid fuel market dominated by diesel fuel (66% of on-road, liquid fuel demand); also, the European Union has supported the biodiesel industry through tax exemptions, investment subsidies and, most importantly, consumption mandates. In 2003, biodiesel accounted for approximately 0.15% of total transport fuel; the target was established at a 1.44% share for biodiesel in transportation by 2010 [11].

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In 2004, Europe's biodiesel production has grown up to over 2.0 billion liters in comparison to that in USA (only 100 million liters per year) [12]. The European Union and the USA jointly account for over 95% of the global biodiesel demand. Also, Canada, Australia, South Africa, Japan, China, India, Brazil, Thailand, Malaysia, and Indonesia also have small commercial biodiesel programs and most of them are still in the research stage. In 2007, yearly total production of biodiesel in the world amounted to 7 billion liters [13]. From now on, the biodiesel production has rapidly increased in the last 8 years and the annual biodiesel production was 30.1 billion liters in 2015 [14], and its predictable biodiesel production could reach 61.6 billion liters in 2030.

The last decade was characterized by huge steps forward in terms of the development of biodiesel technologies and progress in the economic sustainability of small/large-scale biodiesel plants [15]. Numerous studies have been carried out on the various aspects of biodiesel research, such as catalyst [16], kinetics [17] and engine performance [18]. Suppes et al. described transesterification of soybean oil with zeolite and metal catalysts in 2004; it was the first study in heterogeneous catalysts and since then, many researches had been carried out. Boocock et al. work on fast one-phase oil-rich processes for the preparation of vegetable oil methyl esters in 1996 and propose transesterification kinetics in biodiesel research. Meanwhile, these studies were published in diverse journals of many subject categories and were written by researchers from a number of countries all over the world. However, no systematic analysis of the scientific research on biodiesel research has been carried out to date.

Bibliometric method is an effective research tool which has already been widely applied for the statistics of scientific production and research trends in many disciplines of science and engineering [19, 20]. Such as Ali Uzun et al., using bibliometric method, made a study of the national patterns of research output and priorities in renewable energy [21]. Yaoyang Xu et al. carried out a bibliometric evaluation to map research activities and tendencies of the global biofuel field [22]. Furthermore, the Science Citation Index Expanded (SCI-Expanded) from the Web of Science databases of the Institute for Scientific Information (ISI) are the most significantly and frequently used source database of choice for a broad review of scientific accomplishment in all studying fields [23, 24].

In this study, a comprehensive bibliometric analysis was used to trace global trends in biodiesel research from 1991 to 2015. Document types, languages, categories, journals, countries/territories, institutions, and *h*-index (*h*-index was defined by the *h* of the total publication (TP) having at least *h* citations each and the other (TP-*h*) papers having  $\leq h$  citations each) were analyzed to dissect publication patterns.

Further, author keywords in different periods and most cited articles by the years were analyzed to explore research tendencies and hotspots. Our results provide a basis for the comprehensive understanding of current biodiesel research, and serve as a potential guide for future directions.

## Data sources and methods

Information about scientific output was extracted from the Science Citation Index Expanded (SCI-EXPANDED) database and the 2014 Journal Citation Report (JCR) of Thomson Reuters, on the 23rd of March, 2016. The 2014 JCR indexes 11,149 journals across 237 scientific disciplines and 82 countries. In this study, “biodiesel” or “biodiesel” or “bio diesel” was used as a search phrase to search topics in SCI-EXPANDED for the period from 1991 to 2015.

Document type, language, output, subject category, journal, country, institute, author keyword, and *h*-index were all analyzed by Microsoft Excel 2010. Frequency analysis was conducted using BibExcel 1.0.0.0 [25] and word cloud (generated by <https://www.jasondavies.com/wordcloud/>). Data downloaded from Web of Science can be read by BibExcel and used for co-occurrence analysis and frequency analysis. Network diagrams for cooperation analysis were generated by Pajek 1.0.0.1 [26]. The reported journal impact factor (JIF) was obtained from the JCR Science Edition 2014. The new generation of the InCites platform provides enhanced JIF Quartile calculation, with a greater level of precision, and so, wherever quartile data differed between JCR on the Web of Science platform and JCR on the InCites platform, the latter record was used.

## Results and discussion

### Document type and language of publication

18,204 publications related to the biodiesel research were identified in SCI-EXPANDED between 1991 and 2015, which were categorized by 14 document types. Articles were the dominant document type comprising 15,560 (85%) of the total. The remaining publications were review (1258), meeting abstract (447), proceedings (472), news item (234), editorial material (74), letter (55), correction (52), book review (11), book chapter (6), software review (2), note (2) and reprint (1). On average, there were 12 articles per review and 32 articles per meeting abstract.

As the dominant type of document, 15,560 articles were then analyzed in the subsequent study. Of the 15,560 articles, 97% were published in English, followed by Portuguese (223), Polish (46), Chinese (45), Spanish (37),

German (32), Turkish (24), Japanese (18), French (10), Czech (4), Slovene (3), Italian (3), Serbo-Croatian (2), Korean (2), and only one article each in Estonian, Croatian, Serbian, Rumanian and Hungarian.

### Characteristics of publication outputs

As there are no publications about biodiesel prior to 1991, “biodiesel” or “bio-diesel” or “bio diesel” was used as a topic search phrase to obtain a general long-term trend. Figure 1 shows that the amount of biodiesel research continually grew by the years and the number of publications rose significantly from 2004.

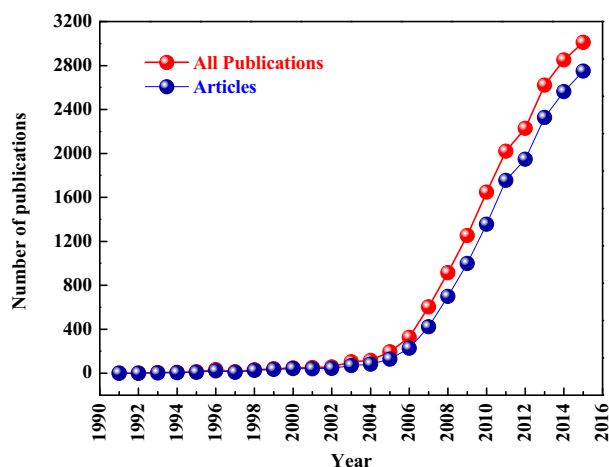
To obtain an overview of biodiesel research, the annual number of articles during 1991–2015 was displayed in Appendix Table 1 of online supplement. The number of biodiesel publications increased from only 1 in 1991 to 2749 in 2015. The most number of authors of a single article was 35, for an article published in *New Biotechnology*, 2013, which conducted research on sustainable production of biologically active molecules of marine-based origin in Ireland [27]. An increasing number of journals published research papers related with biodiesel. The average number of authors per biodiesel publication is 2 in 1991, which was steadily increased to 4.7 in 2015. Similarly, the number of references rose from 23 in 1994 to 38 in 2015. The progressive increase of publications and references indicated a growth trend and an increasing communication in the field of biodiesel research during the past 25 years.

### Web of Science categories and journals

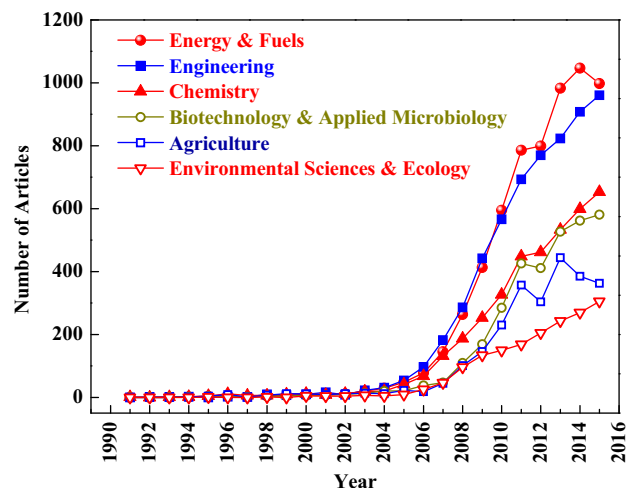
The 15,560 articles were published in 81 subject categories in SCI-EXPANDED and the number of categories

including more than 1% of total articles was 15. Among these categories, Energy & Fuels contributed the most with 6252 articles, followed by Engineering, Chemistry, Biotechnology & Applied Microbiology, Agriculture, and Environmental Sciences & Ecology (Fig. 2). The category of Engineering is in the leading position before the year of 2010, and then, the category of Energy & Fuels has a higher growth rate. The two most productive categories have been taking the lead, and are unlikely to be exceeded by the other categories in foreseeable future. According to the category description in the Web of Science, Energy & Fuels covers resources on the development, production, use, application, conversion, and management of non-renewable (combustible) fuels (such as wood, coal, petroleum, and gas) and renewable energy sources (solar, wind, biomass, geothermal, hydroelectric).

Top 30 most frequently used author keywords of the top six categories are listed in Appendix Table 2 of online supplement. The results show that “Biodiesel” ranked first in all of the six categories, which was used as keywords for searching. “Transesterification” ranked second in the five categories, except Biotechnology & Applied Microbiology, since Biotechnology & Applied Microbiology has high frequency with the keywords “Microalgae”, “Chlorella vulgaris”, “Oleaginous yeast” and “Photobioreactor”, indicating that the articles in this category focus on using algae as raw materials for biodiesel production [28]. Energy & Fuels and Engineering have similar high-frequency author keywords such as “Emission(s)”, “Diesel engine”, “Combustion”, “Engine performance”, “Exhaust emissions” and “Viscosity”. These words are related with the performance of biodiesel and biodiesel engine, as well as exhaust gas emission, which suggests that this category concentrates upon the practicability of biodiesel as a fuel,



**Fig. 1** Number of SCI publications on biodiesel research over the last 25 years



**Fig. 2** Publications of the top six productive Web of Science categories during 1991–2015

also the test of biodiesel performance [29]. Chemistry shows high-frequency keywords like “Glycerol”, “Heterogeneous catalyst”, “Kinetics” and “Immobilization”, suggesting that the articles in this category focus on processing the by-product of biodiesel and on optimizing the reaction conditions for biodiesel production [30, 31]. Compared with other categories, the Environmental Sciences & Ecology look eye on unique high-frequency keywords such as “LCA”, “Sustainability” and “Renewable energy”, and some keywords with relatively higher frequency like “Vegetable oil”, “*Jatropha curcas*” and “Waste cooking oil”, indicating that the articles in this category focus on the evaluation methods of economic and environmental influence [32].

The 15,560 articles were published in 1308 journals. Among these journals, 1091 (83%) journals contained less than 10 articles. Among the top 10 most productive journals ( $TP > 250$ ), accounting for approximately 32% of the articles (Appendix Table 3 of online supplement), *Biore-source Technology* published the most articles with 1198 articles (7.7%), while *Fuel* ranked second with 1029 articles (6.6%). The articles published in the rest of the journals are much less than these top 2 journals. It is worth noting that *Biore-source Technology* has the highest  $h$ -index value (92) among these 10 journals. Thus, both *Biore-source Technology* and *Fuel* are among the most influential journals on biodiesel research. It is noticeable that the 6th place *Applied Energy* had a high impact factor of 5.613, but showed a relatively low  $h$ -index of 49 in biodiesel research. The journals with the highest impact factor were *Nature Biotechnology* with two articles ( $IF = 41.514$ ), followed by *Nature* with one article ( $IF = 41.456$ ), and *Science* with two articles ( $IF = 33.611$ ).

### Contribution of country/territory and institution

The contribution of different countries/territories and institutes can be estimated according to the author's addresses. 15,500 articles with author address information published between 1991 and 2015 were analyzed, covering 122 countries/territories. 7922 (51.1%) were independent articles and 7578 (48.9%) were internationally collaborative articles.

The top 20 countries/territory, taking 97%, are listed in Appendix Table 4 of online supplement with five indicators: total articles, total number of single-country and internationally collaborative articles, the percentage of single-country articles of total articles, the percentage of internationally collaborative articles of total articles, and the  $h$ -index of countries/territories are analyzed. One Oceania country, three American countries, seven European countries, nine Asian countries/territory were ranked in the top 20 of publications. There were no African

countries in the top 20. The seven major industrialized countries (G7: Canada, France, Germany, Italy, Japan, the UK, and the USA) are all in the top 16 list, producing 33.3% of all articles over the years. This comes as no coincidence, since the earliest biodiesel research occurred in these industrial countries and they conducted the earliest and the most relative research performances [33]. The USA showed the greatest counts of article publications, and also the highest  $h$ -index (108), followed by China and Brazil. France had the highest internationally collaborative ratio which accounted for 56.11% of the total articles.

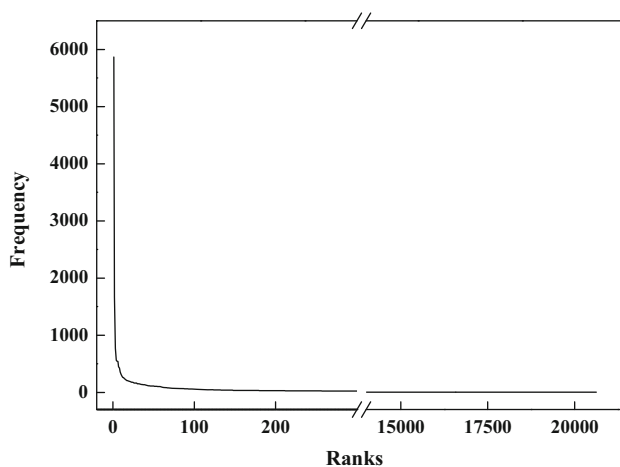
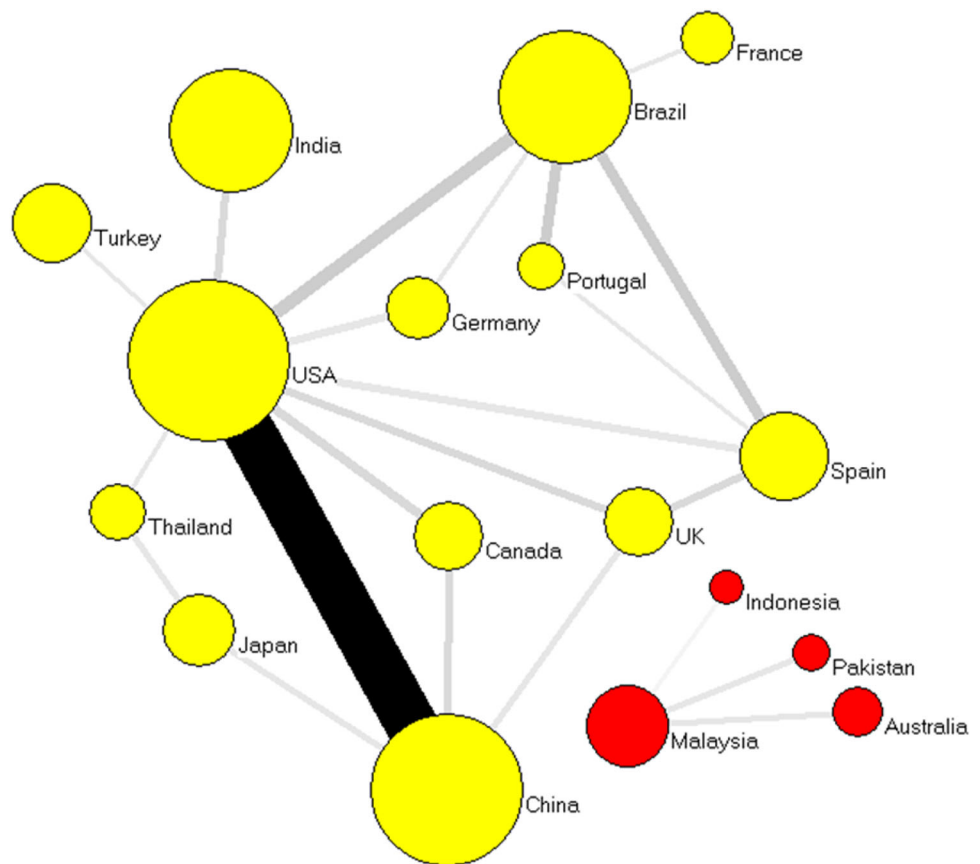
Figure 3 shows that there are two regional groups varying in size of countries and articles. The largest and most complicated country is USA with 9 countries, followed by the Brazil-centered group (5) and the China-centered group (4). It can be noticed that India is the fourth productive country with only a small number of international collaborations. USA–China collaborations ranked first, with 221 cooperative articles, which is far more than other countries' collaboration, followed by USA–Brazil (52), Brazil–Portugal (45), Brazil–Spain (44), and USA–South Korea (41). Collaborative countries tend to be geographically correlated, which is mirrored by findings in other scientific fields [34, 35].

At the institution level, 15,505 articles came from 6722 institutes and form the top 20 most productive institutions (Appendix Table 5 of online supplement). The *Chinese Academy of Sciences*, the first-ranked national-level research institution, has published 367 papers on biodiesel during the past 25 years. The *Indian Inst Technol (India)* and the *Univ Malaya (Malaysia)* ranked 2nd and 3rd accomplishing 196 and 194 publications, respectively, and followed by *Univ Sains Malaysia (Malaysia)* and *Univ Sao Paulo (Brazil)*. Among the top 20 most productive institutions, 4 institutions were located in the China Mainland, a direct reason for explaining the leading and dominant role of China in biodiesel research. While the biodiesel research was centralized in two national institutions in the USA, it was more equally distributed among research institutions and universities in China. And it can be noticed that the *Indian Inst Technol (India)*'s major collaborator was the *King Fahd Univ Petr & Minerals (Saudi Arabia)* which is also found in industrial wastewater research [36].

### Author keywords analysis

Bibliometric reviews with keywords analysis have been recently published to analyze research trends and identify research “hotspots” [37]. Among the 15,560 peer-reviewed research articles, 13,166 articles (84.6%) had recorded information of author keywords. The 13,166 articles had 20,625 unique keywords, which appeared 66,033 times. The frequency of keywords and their ranks follows the

**Fig. 3** Network diagram showing cooperation between countries with a minimum of 20 articles (The circles size represents the article's number, two different colors represent the presence of significant connection of two groups of countries, the thickness of connecting lines means the number of the collaboration articles) (color figure online)



**Fig. 4** The power relationship between the frequencies of keywords and their ranks

power-law distribution (Fig. 4). Most of the keywords were not employed frequently, whereas there was a small group of keywords that were widely used. There were 15,011 keywords which appeared only one time each and 19,841 keywords which each appeared in less than 10 articles, accounting for 72.8 and 96.2% of these 20,625 keywords, respectively. However, the 30 (0.15%) most frequent keywords appeared 15,938 times and were responsible for

24.1% of total keyword occurrences. The temporal evolution for the 30 most frequently used keywords was presented by the summaries of frequency and rank (Appendix Table 6 of online supplement) and the intellectual connections of scientific knowledge were shown by the co-words network (Fig. 5).

Ranking first, the keyword “Biodiesel” was the search terms in the data retrieval process and occupied the core position in the co-words network. The ranking of “Transesterification” was in a steady position which reflects that transesterification-relevant topics have been the hotspot for the past 25 years and a continued high rank is expected in the future [38, 39]. It is not surprising that “biofuel” was the keyword with the third highest rank and clearly linked to the core position of co-words network (shown in Appendix Table 6 of online supplement, and Fig. 6), due to biodiesel being one of the most important biofuels. Biological feedstock is of fundamental importance to biodiesel life cycle; the 8 keywords related to feed stock and production were not solidified until the recent 10 years, including “Microalgae”, “Chlorella”, “Jatropha”, “Waste cooking oil”, “Soybean oil”, “Sunflower oil”, “Palm oil” and “Vegetable oil”. Among these 8 keywords, “Microalgae” ranked the highest and its rank increased from 195th in 2001–2005 to 16th in 2006–2010, and to 4th in





word network of biodiesel, because research on sustainability aims to provide a rational decision for the application of biofuels [47]. As one of sustainability-based methods, “LCA”, which did not even appear before 2000, ranked the 70th during 2006–2010 and the 36th during 2011–2015 (not shown in the Appendix Table 6 of online supplement). LCA can be used as a holistic decision-support technique to qualify and quantify the economic, environmental and societal implications of various bio-refinery process, feedstock, and integration options [22]. The present rank and position of the keyword “LCA” also confirmed that LCA is an ever-increasingly popular method for biodiesel research during recent years.

Algae, *Jatropha curcas*, Vegetable oil and Waste cooking oil are the most common raw materials for biodiesel production [48, 49]. Figure 6 shows that research relating to these four raw materials has increased up to the year of 2012. Then after, Algae and Waste cooking oil show a continued increase, while *Jatropha curcas* shows stability over the following years. However, the research of Vegetable oil has declined by the years because the use of vegetable oils for biodiesel production results in the shortage of edible oils and leads to the food versus energy conflict [50].

A word cloud (Fig. 7) was created to visualize the counted frequency more than 100 times the author keywords. This word cloud gives greater prominence (reflected by text size) to author keywords that appear more frequently [51, 52] and, thus, serves as a visualization method to display the identified research focus and trend in biodiesel research.

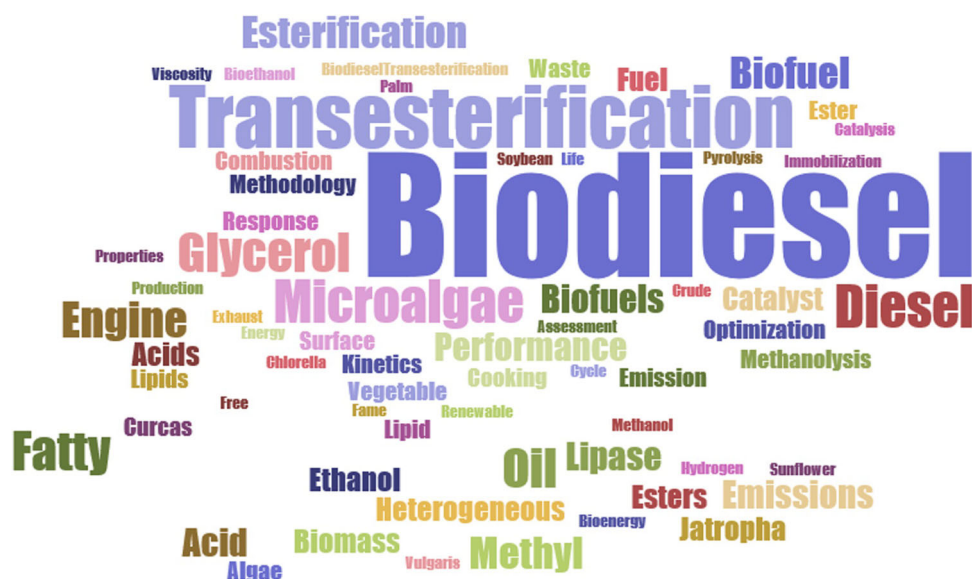
In conclusion, transesterification is the central topic in biodiesel research receiving dominant and increasing scientific attention over the past 25 years. The use of *Jatropha curcas*, Waste cooking oil and Algae as raw material for

biodiesel production increased in the recent years. Researches have paid great focus on biodiesel engine performance to verify the alternative of diesel oil. Also, LCA is achieving practical applications in biodiesel production.

### Most cited articles

The most frequently cited articles proved to be the pioneers of research for the publication of these papers and worked as the watershed of research history and created lots of follow-on papers [53]. Appendix Table 7 of online supplement shows the most frequently cited articles of biodiesel in each year since 1991 through 2015. One was published in *Nature* (IF = 41.456 in 2010) and *Nature Biotechnology* (IF = 41.514 in 2012), respectively, Six in *Bioresource Technology*. Among the most frequently cited articles each year, twelve articles included authors from the USA, three from Spain, and each one from Austria, Czech Republic, France, Canada, Australia, Germany, Italy, UK, South Africa, Turkey and China, respectively. From 1991 to 2015, the most frequently cited article was “Biodiesel production: a review”, which was published in *Bioresource Technology* by Ma and Hanna from USA in 1999 and had been cited 2273 times with the highest average citation 134 time/year by 2015. And it can be noticed that microalgae was a hotspot in recent years. Among the 25 most cited articles, thirteen were about different raw materials for biodiesel production. Two were about reaction kinetics research and two about biodiesel engine performance. “Microalgae for oil: strain selection, induction of lipid synthesis and outdoor mass cultivation in a low-cost photobioreactor” had the second average number of citations by 2015, indicating the focus of microalgae as raw material for biodiesel production, consistent with the previous

**Fig. 7** Word cloud of author keywords frequency more than 100 times during 1991–2015 (the size of keywords represents the frequency of occurrence)



results. “Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels” had the third average number of citations by 2015, indicating that environmental and economic analysis is also a hotspot in biodiesel research.

## Conclusions

Based on 18,204 biodiesel publications dealing with SCI-EXPANDED, this bibliometric study provides an overview of research in biodiesel and identifies some significant points in the research throughout the investigation period from 1991 to 2015. The following conclusions were drawn from this study:

1. Biodiesel-related researches and communication in the research field have significantly increased in the last 25 years. The average number of authors per biodiesel publication is 2 in 1991, which was steadily increased to 4.7 in 2015. Similarly, the number of references rose from 23 in 1994 to 38 in 2015.
2. There were totally 1308 journals distributed in the 81 subject category. *Bioresour Technol* and *Fuel* are among the most influential journals. The top six categories focus on different aspects of biodiesel research; the majority research on biodiesel was in Energy & Fuels and Engineering.
3. The G7, with a longer tradition in research in this field, accounted for 33.3% of total world production. The USA, with the highest *h*-index of 108, also had the largest and most complicated country collaborations with 9 countries (more than 20 articles collaborations). France had the highest internationally collaborative ratio which accounted for 56.11% of the total articles.
4. According to the analysis of the author keywords about the biodiesel-related research: “Transesterification” was the central topic; more and more different raw materials were used for biodiesel production; and researching on biodiesel engine performance was a hotspot; and also LCA getting more applications in biodiesel research.

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