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Mapping biofuel field: A bibliometric evaluation of research output

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ABSTRACT

Among sustainable and renewable energies, biofuels appear to be the most promising and attractive, and related research has been expanding along with an exceptional growth of scientific knowledge. Based on the Science Citation Index Expanded from the Web of Science, a bibliometric evaluation of research output was carried out to map research activities and tendencies of the global biofuel field. The results indicate that annual output of scientific articles rocketed during the past decade (2003–2012). The United States of America (USA) is leading biofuels research and collaborated mainly with other productive countries (China, United Kingdom, Germany, Canada and South Korea). In general, international collaborative publications resulted in more citations than single country publications. Institutional collaborations became increasingly prevalent over time and the 15 most productive institutions of USA tended to collaborate more with each other. Most research publications on biofuels appeared in the journals *Biomass and Bioenergy* and *Bioresource Technology*. Furthermore, biofuels research was based on combinations of multi-subject categories including "Energy and fuels", "Biotechnology and applied microbiology", "Chemical engineering", "Environmental sciences" and "Agricultural engineering". The keyword analysis confirmed the production of biodiesel from microalgae as the mainstream of recent biofuels research. Biorefinery was the most common technology for conversions of biological feedstock and life cycle assessment was the most popular tool of decision support to evaluate the sustainability of biofuel development.

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Contents

1. Introduction

Mitigation of changing climate and meeting increasing energy needs are quickly becoming two of the most important challenges all over the world in this 21st century [1]. It has been commonly recognized by governments, commercial organizations and academic communities that the only way to face these two global challenges is to develop economically rational, environmentally friendly, sustainable and renewable energy [2]. Among various alternatives, biomass-derived fuel appears to be the most promising and attractive, and it is expected to grow in the foreseeable future [3]. Government responses to those global concerns include policies which promote the production and use of biofuels. Such policies have been established by more than 35 countries including the United States of America (USA), members of European Union, China and Brazil [4]. The ambitious goal from USA Department of Energy is to derive 20% of the transportation fuel from biomass by 2030 [5]. With incentives

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from governmental policies and commercial benefits, new companies with great enthusiasm for biofuel have sprung up almost overnight and most of major oil companies (e.g. ExxonMobil and Chevron) are also researching and investing in biomass-derived fuel [6]. Many important and challenging research areas have the potential to bring significant positive outcomes for our future needs of sustainable energy [7]. Thus, a thorough review of the science behind biofuels is urgently needed to improve our understanding of biomass-derived fuel.

Considering that many studies of biofuel have already been published, a bibliometric evaluation of publications could serve as an alternative and innovative way of connecting various aspects of scientific finding and revealing global trends of biofuel research. Bibliometric studies are based on the research methodology employed in the science of library and information, and it includes a series of quantitative and visual procedures to generalize the patterns and dynamics of publications [8]. The focus of specific research fields could be reflected by the publication of scientific findings which is a critical part of the research process [9]. Bibliometric methods have already been widely performed in many disciplines of science and engineering, and could be considered as a common research tool to interpret the scientific production and research trends of a specific topic [10,11]. One of the major sources for bibliometric information is the Web of Science database (Institute for scientific information, ISI), and more than 10,000 high-impact journals are indexed in this multidisciplinary database of sciences, social sciences, arts and humanities [12]. Based on publication outputs by countries, institutes, journals and research fields, the temporal bibliometric analysis aims to analyze the development of research fields across different periods [13]. While the conventional bibliometric analysis centers around numbers and citations of articles, some of the newly-developed bibliometric methods aim to display the intellectual connections of changing scientific knowledge or the structural and dynamic aspects of scientific research as well [14]. Furthermore, geographic analyses can elucidate spatial pattern and identify geographic areas in which most of the research activity occurs [15]. Network analysis allows us to understand the interrelationships among research disciplines, helps us to visualize the collaborative patterns among countries and institutions, and can identify the hot issues of a research field [16].

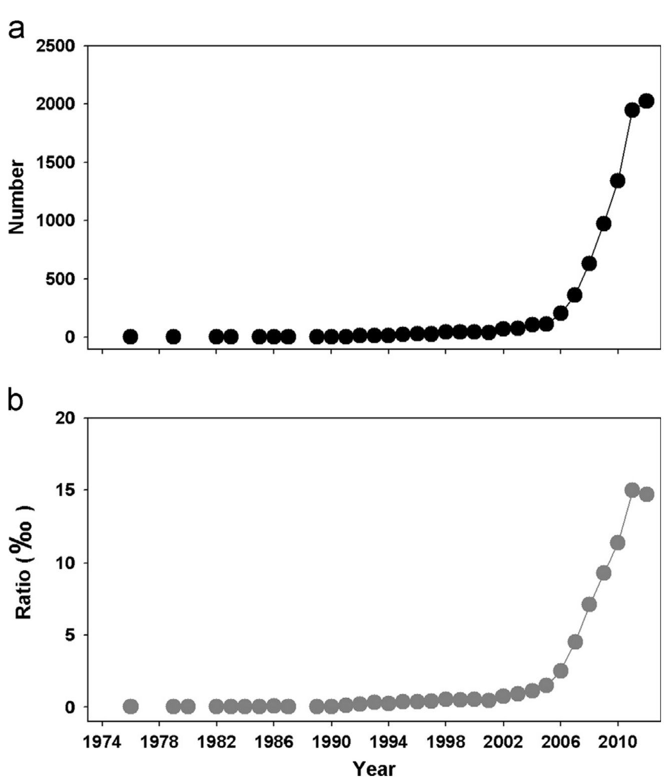

Fig. 1. The dynamics of total research articles (a) and standardized index (b).

Based on the ISI web of Science information during the period of 1979–2012, the present bibliometric evaluation combined traditional and innovative methods to examine the temporal, spatial, structural and current aspects of biofuel research. More specifically, the present article involves in the following four aspects: (1) Analysis of temporal trends of annual outputs and performances of biofuel research, using numbers of publications, authors, pages, citations and references as response variables; (2) Geographic analysis of contact addresses to display the global distribution of biofuel research and focus on outputs and performances of the 20 most productive countries and institutions. The geographic analysis was combined with a network analysis to show collaborative patterns among countries and institutions at international and inter-institutional scales; (3) Ranking of most commonly cited journals by outputs and performances of publications. Network and temporal analysis helped to visualize the connections of multidisciplinary research and dynamics of core scientific categories; (4) Extraction of the most frequent keywords to demonstrate the evolution of research focus. A co-words network of the 50 most frequently used keywords was formed to identify the hot issues of biofuel research. This article will provide additional insights into the current hotspots and future projections of biofuel research.

2. Data and methods

The bibliometric information of biofuel publications was downloaded from the Scientific Citation Index (SCI) databases of the web of Science (Thomson Reuters) which is maintained by the Institute of Scientific Information (USA). We searched for “biofuel*”among documents published between 1900 and 2012, but the earliest publication related to this topic was indexed by the SCI database in 1976. The downloaded record of individual document included the following fields: Authors (AU), Document Title (TI), Language (LA), Document Type (DT), Author Keywords (DE), Keywords plus (ID), Author Address (C1), Reference count (NR), Times

Table 1
Characteristics of publications outputs from 1991 to 2012.

Year	TP	PG	PG/TP	TC	TC/TP	AU	AU/TP	NR	NR/TP
1991	4	60	15.0	54	13.5	7	1.8	74	18.5
1992	14	200	14.3	148	10.6	31	2.2	386	27.6
1993	13	82	6.3	109	8.4	36	2.8	101	7.8
1994	12	139	11.6	113	9.4	42	3.5	130	10.8
1995	23	189	8.2	709	30.8	63	2.7	376	16.3
1996	27	284	10.5	782	29.0	85	3.1	590	21.9
1997	26	260	10.0	991	38.1	68	2.6	669	25.7
1998	45	458	10.2	1287	28.6	115	2.6	1317	29.3
1999	44	413	9.4	1626	37.0	112	2.5	1033	23.5
2000	46	479	10.4	1832	39.8	166	3.6	1220	26.5
2001	39	424	10.9	1950	50.0	186	4.8	1235	31.7
2002	69	613	8.9	2802	40.6	228	3.3	1777	25.8
2003	76	942	12.4	4025	53.0	354	4.7	2306	30.3
2004	106	1036	9.8	5463	51.5	440	4.2	3357	31.7
2005	114	1070	9.4	4329	38.0	418	3.7	3767	33.0
2006	204	1637	8.0	7868	38.6	692	3.4	5473	26.8
2007	361	3019	8.4	9400	26.0	1,259	3.5	10,563	29.3
2008	632	5779	9.1	16,601	26.3	2,446	3.9	21,264	33.6
2009	974	8966	9.2	14,173	14.6	3,905	4.0	34,502	35.4
2010	1342	13,084	9.7	13,489	10.1	5,684	4.2	53,485	39.9
2011	1946	18,789	9.7	9890	5.1	8,480	4.4	77,818	40.0
2012	2024	19,484	9.6	1796	0.9	9,441	4.7	84,011	41.5
Average			10.0		27.3		3.5		27.6

TP=number of publications, PG=Page count, TC=Times Cited, AU=number of Authors and NR=Reference count; PG/TP, TC/TP, AU/TP and NR/TP are average numbers of pages, citations, authors and references per article, respectively.

Cited (TC), Year Published (PY), Page count (PG), Subject category (SC) and Journal name (JN). Following the SCI database, these two-character field tags identified the abbreviations of fields. After the duplicated records were eliminated, a total of 11,396 publications were identified as being related to biofuel.

Among the total of 11,396 publications, fifteen document types were found. The document type with the most number of publications was "Peer-reviewed research articles" (8158) which accounted for 71.6% of total publications. A significant portion of total publications comprised six other document types which included "Reviews" (1143, 10.0%), "New items" (608, 5.3%), "Proceedings papers" (550, 4.8%), "Editorial materials" (396, 3.5%), "Meeting abstracts" (329, 2.8%), and "Letters" (125, 1.1%). Other, less significant document types included "Book chapters" (50), "Corrections" (20), "Book reviews" (8), "Reprints" (3), "Biographical items" (2), "Notes" (2), "Software Reviews" (2) and "Bibliography" (1). As consistent with bibliometric analyses of other fields, the present study focused on the analysis of "Peer-reviewed research articles" (71.6%) and further analyses excluded all documents of other types (28.4%). There were seventeen types for the publishing language, but 7907 of the 8158 Peer-reviewed research articles (96.9%) were published in English. Other major publishing languages included Portuguese (45), German (44), French (36), Polish (36), Spanish (30), Chinese (16), Czech (15), while Japanese (7), Russian (7), Finnish (4), Turkish (3), Swedish (3), Croatian (2), Lithuanian (1), Serbo-Croatian (1), Rumanian (1) were minor publishing languages in biofuel research that were indexed by the SCI database.

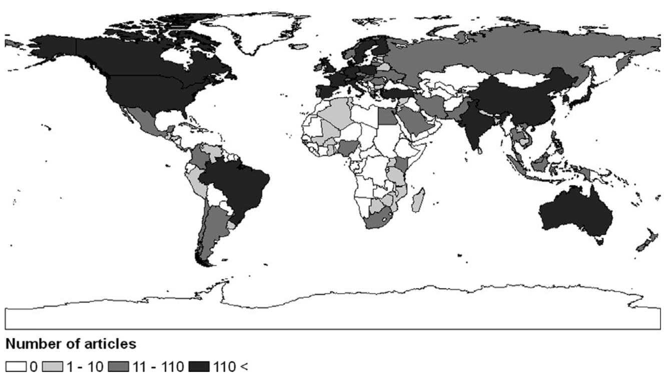

Fig. 2. Global geographical distribution of biofuel research outputs.

The articles published by England, Scotland, Northern Ireland, and Wales were reclassified as being published by the United Kingdom (UK), and the articles from Hong Kong were included in publications from China. According to the number of articles, we used Arc GIS 9.0 software to map global distribution of biofuel research and classify all countries into several groups [17]. The collaborations among countries or institutions were determined by the addresses of the authors based on the following strategies: the term "single country article" was assigned to the article where co-authors were from the same country, while the term "internationally collaborative article" was assigned when researchers were from multiple countries [18]. Similarly, we defined publications where all co-authors were from the same institution as "single institution article", while the term "inter-institutionally collaborative article" was assigned when authors were from different institutions [19]. The 20 most productive countries (institutions) in biofuels research were characterized by total publications, total citations, h-index, single country (institution) articles and citations, and international (inter-institutional) collaborative articles and citations. Citation is defined as the number of an article which has been cited as a reference by other articles, and the analysis of citation is based on the assumption that the number of citations represents the article quality [20]. According to the citation, the h-Index was calculated to measure the research importance of a country/institution. Among the articles (N) from a country/institution, there are h articles having at least h citations for each article, while the other articles (N - h) have less than h citations each article [21]. Using the author addresses of publications, the science mapping of international (institutional) collaborations were built for the 20 most productive countries (institutions) of biofuel research by the software of Bibexel and Pajek following the procedure of co-occurrence analysis [14,22].

The 20 most popular journals were ranked by the number of articles, impact factor, h-index and positions in Web of science categories. The impact factor and positions in Web of science categories were taken from Journal Citation Reports (JCR) published in 2011. Using the software of Bibexel and Pajek [14,22], we performed the procedures of co-occurrence analysis

Table 2
The 20 most productive countries in biofuels research.

Country	All				Single country				International collaboration			
	TP	TC	TP/TC	h-index	SP	TC	TC/SP	SP (%)	CP	TC	TC/CP	CP (%)
USA	3009	45978	15.3	89	2298	34117	14.8	76.4	711	11861	16.7	23.6
China	729	8742	12	41	463	4828	10.4	63.5	266	3914	14.7	36.5
UK	460	5861	12.7	38	255	2832	11.1	55.4	205	3029	14.8	44.6
Germany	452	7229	16	42	234	2179	9.3	51.8	218	5050	23.2	48.2
Sweden	407	5380	13.2	34	247	3043	12.3	60.7	160	2337	14.6	39.3
Brazil	350	2416	6.9	27	262	1637	6.2	74.9	88	779	8.9	25.1
France	299	4080	13.6	32	161	1395	8.7	53.8	138	2685	19.5	46.2
Japan	282	3538	12.5	31	176	2162	12.3	62.4	106	1376	13	37.6
India	276	3228	11.7	31	186	1708	9.2	67.4	90	1520	16.9	32.6
Netherlands	273	4660	17.1	35	153	2301	15	56	120	2359	19.7	44
Canada	245	2719	11.1	26	135	878	6.5	55.1	110	1841	16.7	44.9
Spain	238	2471	10.4	24	141	1223	8.7	59.2	97	1248	12.9	40.8
Turkey	207	4257	20.6	38	192	4091	21.3	92.8	15	166	11.1	7.2
Italy	199	2008	10.1	25	115	941	8.2	57.8	84	1067	12.7	42.2
South Korea	173	1909	11	22	92	1014	11	53.2	81	895	11	46.8
Finland	161	1769	11	21	92	738	8	57.1	69	1031	14.9	42.9
Australia	150	1879	12.5	22	85	754	8.9	56.7	65	1125	17.3	43.3
Denmark	145	1235	8.5	18	63	536	8.5	43.4	82	699	8.5	56.6
Austria	120	2631	21.9	25	35	740	21.1	29.2	85	1891	22.2	70.8
Poland	119	585	4.9	14	85	228	2.7	71.4	34	357	10.5	28.6

TP=Total publications, TC=Total citations, SP= single country publications, CP=International collaboration publications.

on Web of science categories to map the bibliometric coupling of multidisciplinary research. The title and author keywords provide a considerable overview of an article's theme. Although the title is readily available from articles, the meaning of a single word within the title might be more obscure [18]. Despite of the possible lack of keywords for few articles, the keywords analysis can provide a relatively comprehensive overview of research trends [23], because the authors' keywords are typically more indicative of the context of the article [24]. Based on each article's citations and references, the SCI database produces keywords plus, but they are often somewhat unconnected to the actual article [11]. Thus, we only performed the analysis of author keywords to demonstrate the tendencies and hotspots of biofuel research. We used SPSS 13.0 software to conduct frequency analysis to define the most frequent keywords [25]. According to annual compositions of the 200 most frequent keywords, several periods of biofuel research were determined by hierarchical cluster analysis (HCA) with the software of PC-ORD 4.0 [26]. Following the procedure of co-words analysis [14], the co-words network of the 50 most frequent keywords were mapped to explore research hotspots.

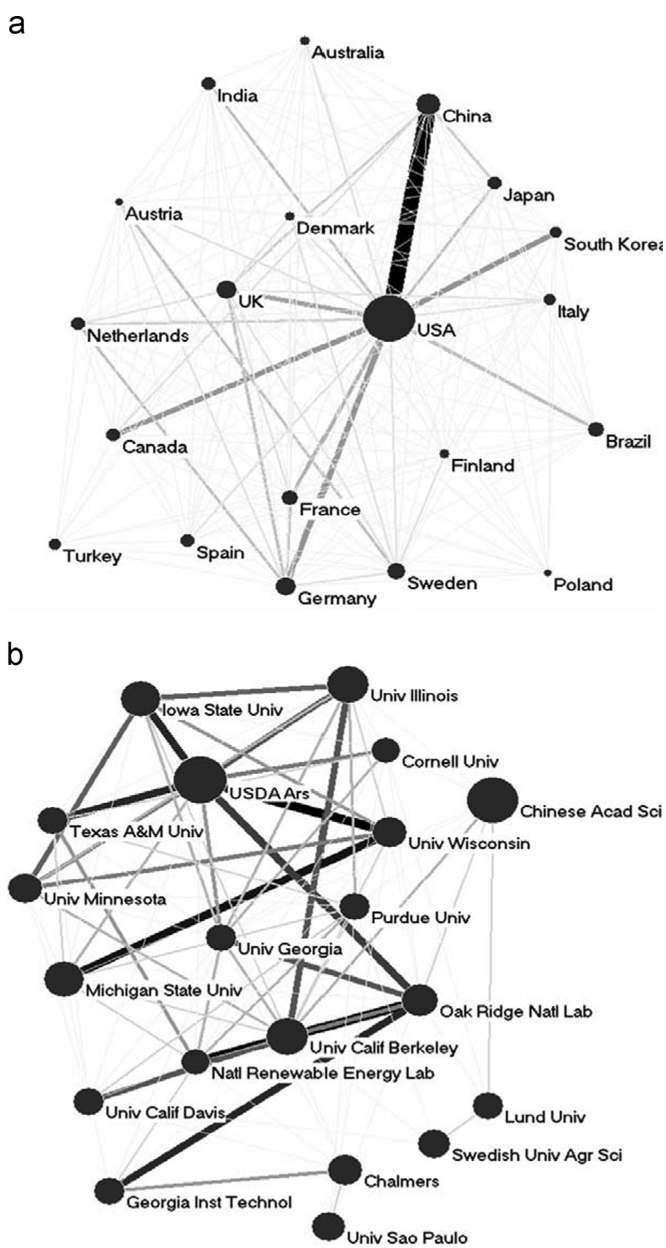

Fig. 3. The collaboration networks of the 20 most productive countries (a) and institutions (b).

3. Results and discussions

3.1. Publication outputs

Number of articles per year started to increase in 1991 and then rocketed from 76 to 2024 during the last decade (2003–2012, Fig. 1a). Considering that the observed growth of scientific articles was partly attributed to the increasing amount of total SCI-indexed publications, we applied a standardized index to assess relative outputs of biofuels publications. This index is defined as the ratio of annual number of publications on biofuels to annual amount of SCI-indexed publications. The standardized index of biofuels publications also sharply increased from 0.92‰ to 14.68‰ during the last decade (Fig. 1b). Therefore, a clear research focus on biofuels was also found by controlling for the increasing number of publications being indexed in the SCI database.

Major scientific productivity descriptors are summarized for the period of 1991–2012 in Table 1. With an overall average of 10 pages, the average length of articles per year (PC/NP) fluctuated

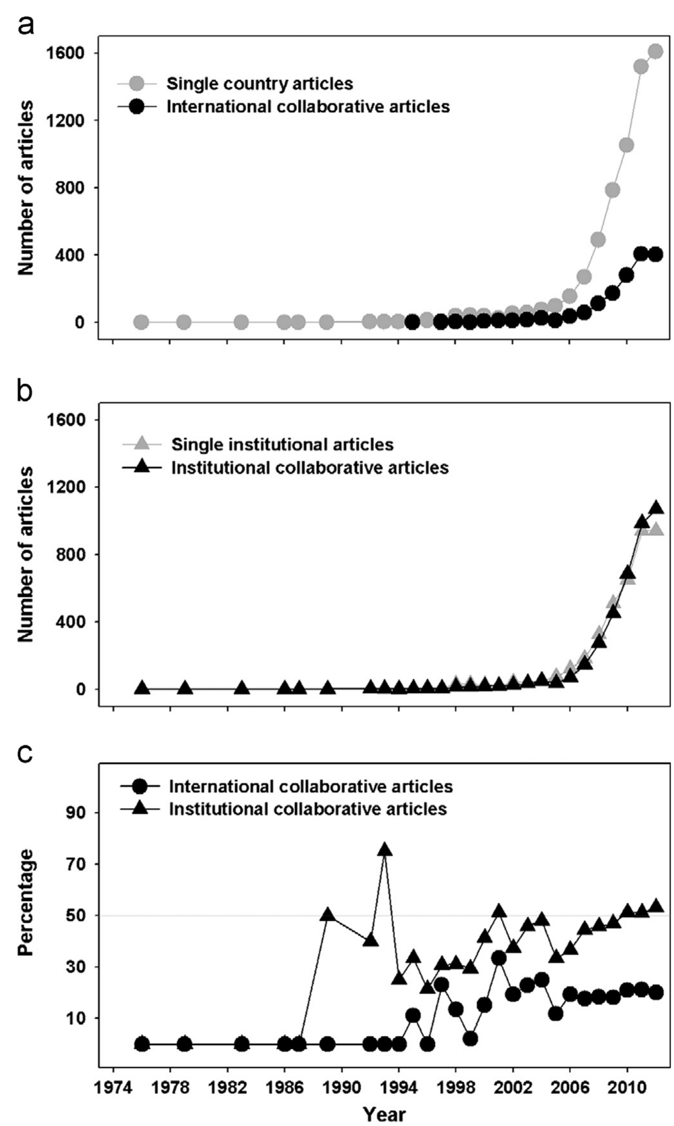

Fig. 4. The number (a, international collaborative and single country; b, Institutional collaborative and single institution) and percentage (c) of articles.

between 6.3 and 15; however, there was no increasing or decreasing trend over time. The average number of authors per publications was defined as the collaboration index which increased from 1.8 to 4.7 during 1991–2012. This increasing collaboration index suggested that biofuels research became more collaborative during the last couple of decades. An expanding accumulation of knowledge about biofuels was indicated by the average number of references which grew to 41.5 in 2012 (Table 1). The increasing collaboration and accumulating knowledge revealed a solid progress in the biofuel research field.

3.2. Country, institution and collaborations

The global distribution of published articles for biofuels shows a broad geographical coverage; a total of 104 countries/territories are involved in biofuel research (Fig. 2). Based on the number of articles, the 104 countries were classified into three groups. The first group with 1–10 articles comprised 50 countries; the second group with 11–110 articles totaled 34 countries; and the third group with over 110 articles included the 20 most productive countries. Out of these countries, 12 were from Europe, 4 from Asia, 2 from North America,

Table 3
The 20 most productive institutions in biofuels research.

Institution	All				Single institution				Institutional collaboration			
	TP	TC	TP/TC	h-index	SP	TC	TC/SP	SP (%)	CP	TC	TC/CP	CP (%)
Agricultural Research Service, USDA, USA	213	1882	8.8	23	62	588	9.5	29.1	151	1294	8.6	70.9
Chinese Academy of Sciences, China	195	3101	15.9	30	67	1226	18.3	34.4	128	1875	14.6	65.6
University of California (Berkeley), USA	138	3023	21.9	24	39	1217	31.2	28.3	99	1806	18.2	71.7
University of Illinois, USA	127	1323	10.4	18	50	470	9.4	39.4	77	853	11.1	60.6
Michigan State University, USA	119	1774	14.9	22	55	1021	18.6	46.2	64	753	11.8	53.8
Iowa State University, USA	117	1578	13.5	15	54	190	3.5	46.2	63	1388	22.0	53.8
Oak Ridge National Laboratory, USA	104	1471	14.1	16	21	275	13.1	20.2	83	1196	14.4	79.8
Chalmers University of Technology, Sweden	95	1247	13.1	20	41	571	13.9	43.2	54	676	12.5	56.8
University of Minnesota, USA	95	3238	34.1	19	35	840	24.0	36.8	60	2398	40.0	63.2
University of Wisconsin, USA	91	1185	13.0	19	27	364	13.5	29.7	64	821	12.8	70.3
Swedish University of Agriculture Sciences, Sweden	81	891	11.0	17	43	496	11.5	53.1	38	395	10.4	46.9
University of São Paulo, Brazil	80	567	7.1	12	22	168	7.6	27.5	58	399	6.9	72.5
Lund University, Sweden	76	1269	16.7	22	20	314	15.7	26.3	56	955	17.1	73.7
Purdue University, USA	76	755	9.9	14	34	368	10.8	44.7	42	387	9.2	55.3
Texas A&M University, USA	74	543	7.3	13	23	173	7.5	31.1	51	370	7.3	68.9
University of Georgia, USA	74	556	7.5	14	17	73	4.3	23.0	57	483	8.5	77.0
University of California (Davis), USA	73	864	11.8	13	37	519	14.0	50.7	36	345	9.6	49.3
Georgia Institute of Technology, USA	70	1371	19.6	19	22	153	7.0	31.4	48	1218	25.4	68.6
Cornell University, USA	67	1256	18.7	20	25	475	19.0	37.3	42	781	18.6	62.7
National Renewable Energy Laboratory, USA	67	1017	15.2	19	27	433	16.0	40.3	40	584	14.6	59.7

TP=Total publications, TC=Total citation, SP= Single institution publications, CP=Institutional collaboration publications.

Table 4
The most commonly used journals with the number of articles, impact factor, h-index and category of journal in its position.

JR	TP	TP (%)	TC	TC/TP	IF	h-index	WSC (position)
1	405	4.95	5828	14.39	3.646	37	A(13/81); B(32/157); J(2/12)
2	373	4.56	3762	10.09	4.98	29	A(8/81); B(20/157); J(1/12)
3	211	2.58	2350	11.14	2.723	27	A(23/81); D(46/205)
4	145	1.77	1725	11.90	3.248	25	A(19/81); E(13/133)
5	142	1.73	1532	10.79	2.721	24	A(24/81); E(18/133)
6	141	1.72	3302	23.42	5.228	31	C(3/45); D(8/205)
7	133	1.62	1510	11.35	5.106	23	A(7/81); E(7/133)
8	128	1.56	2502	19.55	_	30	–
9	96	1.17	414	4.31	3.617	12	A(15/81); K(2/79)
10	88	1.08	1995	22.67	5.602	24	B(14/157); F(9/74); G(4/73); I(1/27); L(14/66)
11	87	1.06	753	8.66	3.562	12	A(17/81); D(24/205)
12	87	1.06	1488	17.10	3.946	21	B(28/157)
13	81	0.99	627	7.74	4.738	13	A(10/81); B(21/157)
14	77	0.94	709	9.21	3.487	16	A(18/81); H(4/52)
15	74	0.90	2784	37.62	9.681	28	M(3/55)
16	73	0.89	312	4.27	4.092	10	N(12/84)
17	71	0.87	315	4.44	6.088	10	B(12/157)
18	68	0.83	1342	19.74	3.829	19	B(29/157)
19	66	0.81	974	14.76	3.425	17	B(39/157)
20	65	0.79	1649	25.37	4.859	27	I(2/27)

Journals rank (JR): 1=Biomass and Bioenergy; 2=Bioresource Technology; 3=Energy Policy; 4=Fuel; 5=Energy and Fuels; 6=Environmental Science and Technology; 7=Applied Energy; 8=Energy Education Science and Technology Part A-Energy Science and Research; 9=Global Change Biology Bioenergy; 10=Biosensors and Bioelectronics; 11=Bioenergy Research; 12=Biotechnology and Bioengineering; 13=Biofuels Bioproducts and Biorefining-Biofpr; 14=Energy; 15=Proceedings of The National Academy of Sciences of The United States of America (PNAS); 16=PloS ONE; 17=Biotechnology for Biofuels; 18=Applied and Environmental Microbiology; 19=Applied Microbiology and Biotechnology; 20=Electrochemistry Communications.

Web of Science categories (WSC): A=Energy & Fuels; B=Biotechnology and Applied Microbiology; C=Engineering, Environmental; D=Environmental Sciences; E=Engineering, Chemical; F=Biophysics; G=Chemistry, Analytical; H=Thermodynamics; I=Electrochemistry; J=Agricultural Engineering; K=Agronomy; L=Nanoscience and Nanotechnology; M=Multidisciplinary Sciences; N=Biology.

TP =Total publications, TC=Total citation, TC/TP=average of citations per article, IF=Impact factor (2011)

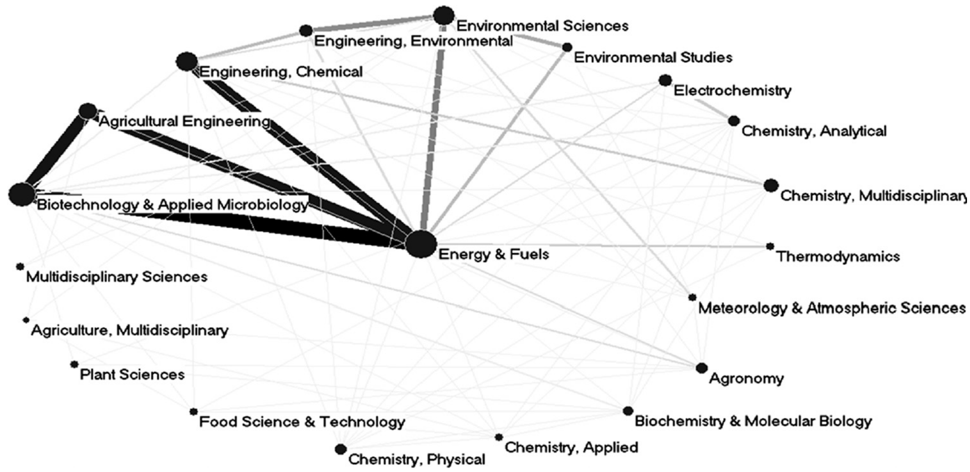

Fig. 5. The interdisciplinary network of the 20 most productive Web of Science categories.

1 from South America, and 1 was from Oceania. USA headed the article ranking of countries with the highest citations and h-index (Table 2), and was responsible for the most single-country (2298) and internationally collaborative articles (711). China published the second highest number of articles (729), followed by UK (460) and Germany (452). There were 3250 single country articles from the four most productive countries which accounted for 51.0% of total 6372 single country articles, and they published more single country articles than internationally collaborative articles. Turkey published 207 articles with the highest percentage of single country articles (92.8%), while Austria published 120 articles with highest percentage of internationally collaborative articles (70.8%). Network centrality suggested that USA took the central positions in the international collaboration network of these 20 most productive countries (Fig. 3a), and it was the principal collaborator with other five major productive countries (China, UK, Germany, Canada and South Korea). Internationally collaborative articles generally drew more citations than those produced by individual countries (Table 2), although the number of internationally collaborative articles has never exceeded single country articles (Fig. 4a).

A total of 4376 institutions participated in biofuels research and the 20 top institutions were ranked by the number of articles (Table 3). Among the top 20 institutions, there were 15 in USA, 3 in Sweden, and one each in China and Brazil. USA Department of Agriculture, Agricultural Research Service (USDA ARS) led the institutional productivity with 213 articles, but the institution had relatively low citations and h-index. Ranking 2nd with 195 articles, Chinese Academy of Sciences had the highest h-index, followed by the University of California, Berkley. The most cited institution was University of Minnesota with a total of 3238 citations and an average of 34.1, although this institution ranked 9th with less than 100 articles. Of the 8158 peer-reviewed research articles, there were 4028 single-institutional articles (49.4%) and 3914 inter-institutional articles (48.0%), and we were unable to identify the institutional information for 216 articles (2.54%). In the last three years, the number of institutional collaborative articles exceeded the number of single institution articles (Fig. 4b). Compared to international collaborations, institutional collaborations became more and more prevalent (Fig. 4c). Among the 20 most productive institutions (Table 3), 18 institutions were characterized by the percentage of institutional collaborative articles with more than 50%, while only 2 institutions (Swedish University of Agriculture Sciences and University of California-Davis) had a greater number of single-institution articles than inter-institutionally collaborative articles. Following network centrality, we identified a core group of institutions in the collaboration network of the 20 most productive institutions (Fig. 3b). The 15 most productive institutions in USA tended to collaborate more with each other, and USDA ARS occupied the central position in the collaboration network. In contrast, the edge of the collaboration network was distributed by the 5 most productive institutions in other countries (Sweden, China and Brazil) which showed the weakest links with the central position.

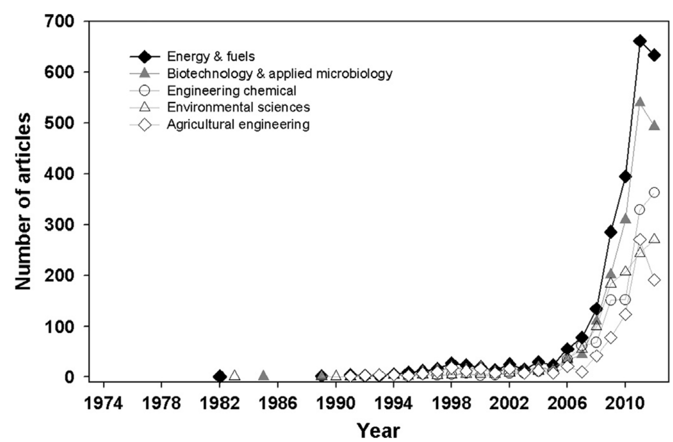

Fig. 6. The number of articles for the 5 most productive Web of Science categories.

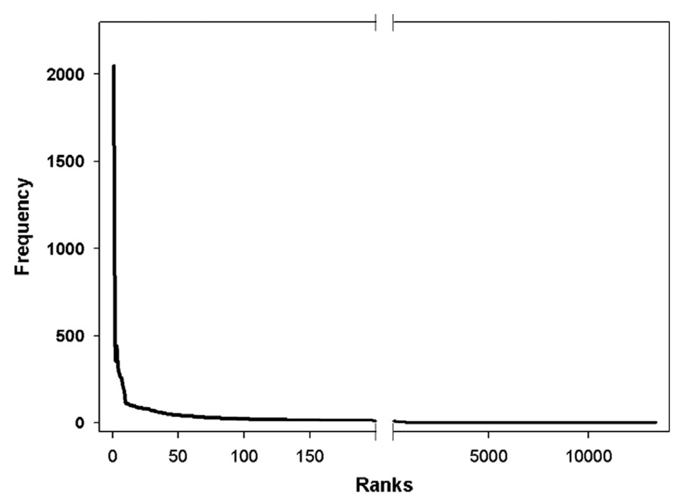

Fig. 7. The power relationship between the frequencies of keywords and their ranks.

3.3. Popular journals, science categories and interdisciplinary

The 8158 articles analyzed in our study were published in 1281 journals from various scientific fields. Among these journals, 1229 journals (95.9%) contained less than 10 articles, while the most commonly used 20 journals published 2611 articles on biofuel research, accounting for more than 30.0% of total articles (Table 4). According to the titles and themes of these commonly used journals, "technology" ("biotechnology") was identified as the focus of biofuels research. The percentages of most commonly used journals were not high, indicating the breadth of publication distribution as well as the broad interest in biofuels research from various angles. Most articles of biofuels (405, 4.95%) were published by *Biomass and Bioenergy* which had the highest h-index with 37, while *Bioresource Technology* published 373 articles (4.56%) and ranked second with an h-index of 29. In the category of agricultural engineering (J), *Bioresource Technology* and *Biomass and Bioenergy* ranked first and second with the impact factor of 4.980 and 3.646, respectively. With an average citation of 37.63 and the highest impact factor of 9.681, *PNAS* published 74 articles and ranked third in the category of multidisciplinary sciences (M).

The published articles of biofuels research belonged to 147 ISI identified subject categories in the SCI database and the number of categories including more than 1% of total articles was 30. The number of articles with two or more subject categories was 5017 and accounted for 61.5% of total articles. Biofuel research can thus be considered an interdisciplinary field which commonly includes two or more academic disciplines. In the interdisciplinary network of those 30 major subject categories (Fig. 5), we visualized a core group of subject categories following network centrality which measures the relative importance of nodes within networks. The category of energy and fuels is contributing the most with 2475 articles (accounting for 30.3% of total articles) took the central position in the interdisciplinary network. It was closely related to other four common categories which included biotechnology and applied microbiology (1901 articles, 23.3%), chemical engineering (1231 articles, 15.1%), environmental sciences (1184 articles, 14.5%) and agricultural engineering (871 articles, 10.7%). Among the four other common categories, biotechnology and applied microbiology was also closely related to agricultural engineering.

A lag-phase of publications was observed during a long period from 1976 to 2004, and there were no clear differences in the number of articles among five categories (Fig. 6). Since 2005, the number of articles in energy and fuels and biotechnology and applied microbiology grew quickly and consistently ranked 1st and 2nd. Based on the category descriptions, energy and fuels covers resources on the development, production, use, application, conversion, and management of nonrenewable fuels (such as coal, petroleum, and gas) and renewable energy sources (solar, wind, biomass, geothermal, hydroelectric), but does not include resources dealing with nuclear energy and nuclear technology (Web of Science, 2011). Biotechnology and applied microbiology cover a broad range of topics on the manipulation of living organisms to make products or solve problems to meet human needs, and also include genetic engineering, molecular diagnostic and therapeutic techniques, genome data mining, bioprocess of food and drugs, biological control of pests, environmental bioremediation, and bio-energy production (Web of Science, 2011). As one of categories with technologies and measures to solve biofuels problems, biotechnology and applied microbiology has gained more attentions than chemical engineering, environmental sciences and agricultural engineering.

3.4. Research tendencies and hotspots

Among the 8158 peer-reviewed research articles, 6084 articles (71.4%) had recorded information of author keywords. The 6084 articles had 13,364 unique keywords, which appeared 31,893 times. The frequency of keywords and their ranks follows the power-law distribution (Fig. 7). Most of keywords are not employed frequently, whereas there is a small group of keywords that are widely-used. There were 10,132 keywords which appeared only one time each and 13,033 keywords which each appeared in less than 10 articles, accounting for 77.1% and 97.5% of these 13,364 keywords, respectively. However, the 200 (1.5%) most frequent keywords appeared 11,175 times and were responsible for 35.0% of total keyword occurrences. Based on the compositions of these 200 most frequent keywords, hierarchical cluster analysis (HCA) classified the development period of biofuel research (1991–2012) into three distinct phases (Fig. 8): "First stage (1991–1995)", "Second stage (1996–2006)" and "Third stage 2007–2012". The 50 most frequent keywords appeared 7621

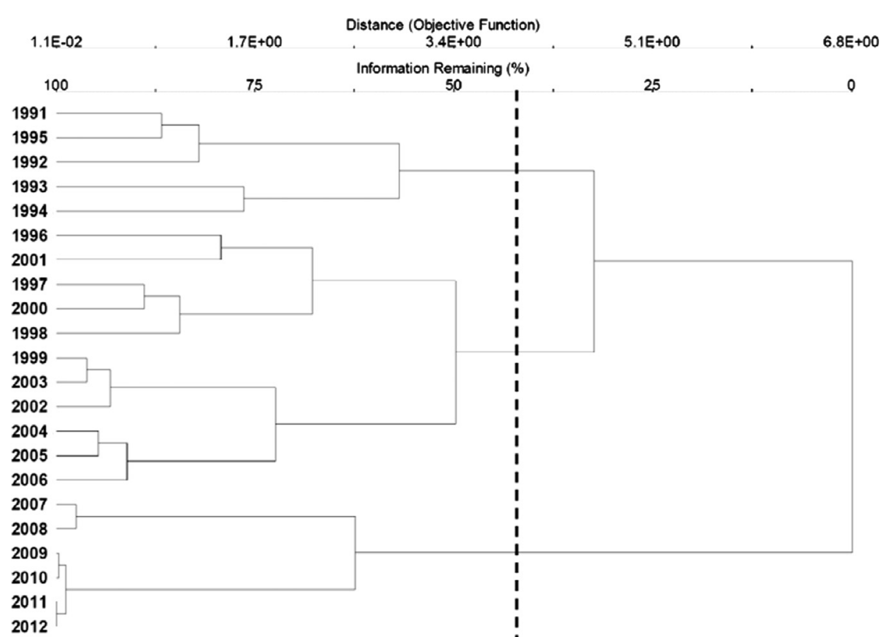

Fig. 8. Dendrogram of several periods of biofuel research based on hierarchical cluster analysis (HCA) of the 200 most frequent keywords.

times and thus less than 0.4% of 13,364 keywords were responsible for 23.9% of total keyword occurrences. The temporal evolution for the 50 most frequently used keywords were presented by the summaries of frequency and rank (Table 5) and the intellectual connections of scientific knowledge are shown by the co-words network (Fig. 9).

Ranking first, the keyword "biofuel" was the search terms in the data retrieval process and occupied the core position in the co-words network which included other three similar terminologies (bioenergy, renewable energy, and energy). The most common products that comprise biofuel are biodiesel and ethanol (bioethanol), and the evolutions of keywords revealed the preference of biofuel products: the rank of "biodiesel" increased from 17 to 2nd and that of "ethanol" from 18 to 4th between the first (1991–1995) and third (2007–2012) of biofuel research (Table 5). This preference over time could be attributed to the properties of biodiesels which are closer to gasoline and petrodiesel [5]. Currently, biodiesel-powered flexible-fuel vehicles are widely available in many countries, since biodiesel can be blended at high levels up to 30% (v/v) and even completely displace petrodiesels in certain vehicles [3]. Also, the availability of biodiesel has been attracted much attention, as indicated by the co-words relationships among "Biodiesel", "Diesel engine" and "Emission" (Fig. 9).

It is not surprising that "biomass" was the keyword with the third highest rank and clearly linked to the core position of co-words network (Table 5, Fig. 9), because biofuel products have to be made from biological feedstock. Although the rank of "biomass" emphasized that the production of biological feedstock is of fundamental importance to biofuel life cycle, the five terminologies related to feedstock and production were not solidified until the second phases, including "Algae", "*Chlorella*", "*Jatropha*", "*Switchgrass*", "Agriculture", "Energy crop". Among these five terminologies, "algae" ranked the highest and its rank increased from 158 during the second phase to 5 in the third phase (Table 5), and showed a close relationship with the keyword "biodiesel" (Fig. 9). Microalgae are fast growing organisms and have the ability to accumulate lipid, and biodiesel from microalgae is even being considered to be the only renewable biofuel that has the potential to completely displace petroleum-derived transport fuels without adversely affecting supply of food and other crop products [27,28]. According to the rank evolutions and co-word relationships of "algae" and "biodiesel", the present study confirmed that the production of biodiesel from algae (microalgae in particular) has been becoming the focus of biofuel.

Compared to conventional petroleum, the recalcitrant nature of biological feedstock leads to more technological obstacles for their processing and transformations [3]. Fortunately, related conversion technologies have recently been developed to realize the applicative potential of biomass-derived feedstock, and biorefinery and biotransformations have attracted considerable attentions from scientist and engineers (Fig. 9). Among the 50 most frequently used keywords, there were 15 keywords related to biomass conversion routes. These were: "Cellulose", "Pretreatment", "Biorefinery", "Lignin", "Pyrolysis", "Cellulase", "Fermentation", "Ionic liquid", "Transesterification", "Lignocellulose", "Combustion", "Enzymatic hydrolysis", "Fatty acid", "Metabolic engineering", and "Gasification" (Table 5, Fig. 9). Ranking 18, the keyword "Biorefinery" is a general terminology of conversion technology which is similar to petroleum-based refinery. Biorefineries are facilities that integrate conversion processes based on the use of biomass feedstock to produce transportation fuels, electricity, high-value chemicals and other useful commodities with minimal wastes and emissions [29]. Several conversion processes in biorefineries can be jointly applied to depolymerize and deoxygenate biomass components, and they can be divided into four major types: mechanical process, thermo-chemical process, biochemical process and physicochemical process [30]. The mechanical process involves pretreatment methods that split lignocellulose into cellulose and lignin [31], and the co-words analysis puts the four frequent keywords of mechanical processes which included "Pretreatment", "Lignocellulose", "Cellulose" and "Lignin" into the same cluster. Three main routes of thermo-chemical processes are gasification, pyrolysis and combustion [32], and these three frequent keywords are correspondingly displayed by the network of co-words (Fig. 9). Biochemical processes are referring to the operations of metabolic engineering and two of the most common conversion types are enzymatic hydrolysis and microbial fermentation [33]. This conversion is presented by four frequent keywords of the co-words network "Metabolic engineering", "Enzymatic hydrolysis", "Cellulase" and "Fermentation" (Fig. 9). Transesterification is the typical method to produce biodiesel and is a physicochemical process by which vegetable oils can be converted to fatty acids [34]. The frequent studies of physicochemical processes were demonstrated by three

Table 5
The temporal evolution of the 50 most frequently used keywords.

Keywords	Whole period 1991–2012		First phase 1991–1995		Second phase 1996–2006		Third phase 2007–2012	
	Cnt	R	Cnt	R	Cnt	R	Cnt	R
Biofuel	2051	1	11	1	169	1	1871	1
Biodiesel	487	2	1	17	30	4	456	2
Biomass	433	3	6	2	49	2	378	3
Ethanol	339	4	1	18	21	6	317	4
Bioenergy	289	5	5	3	24	5	260	6
Algae	265	6	0	152	2	158	263	5
Biofuel cell	255	7	1	19	39	3	215	7
Bioethanol	211	8	0	153	5	40	206	8
Life cycle	182	9	0	154	11	12	171	9
Land use	119	10	0	155	2	159	117	10
Jatropha	114	11	0	156	1	359	113	11
Greenhouse gas	110	12	0	157	3	80	107	12
Sustainability	107	13	0	158	6	36	101	13
Laccase	102	14	0	159	12	9	90	18
Cellulose	101	15	0	160	4	55	97	15
Pretreatment	99	16	0	161	0	1859	99	14
Renewable Energy	99	17	0	162	8	23	91	17
Biorefinery	93	18	0	163	0	1860	93	16
Glucose oxidase	91	19	0	164	9	17	82	21
Lignin	89	20	0	165	4	56	85	19
Pyrolysis	88	21	0	167	9	18	79	23
Emission	88	22	0	166	20	7	68	30
Cellulase	87	23	0	168	3	81	84	20
Switchgrass	87	24	0	169	9	19	78	24
Energy	85	25	1	20	4	53	80	22
Climate change	84	26	1	21	6	35	77	25
Carbon nanotube	81	27	0	170	9	20	72	26
Microbial fuel cell	81	28	0	171	10	14	71	28
Fermentation	76	29	0	172	4	57	72	27
Glucose	75	30	0	173	10	15	65	31
Biosensor	73	31	0	174	14	8	59	34
Ionic liquid	71	32	0	175	0	1861	71	29
Transesterification	68	33	0	176	8	24	60	33
Direct electron transfer	65	34	177	7	58	35		
Lignocellulose	64	35	0	178	2	160	62	32
Biogas	64	36	2	4	4	52	58	36
Vegetable oil	63	37	1	22	11	11	51	39
Hydrogen	60	38	0	179	5	41	55	37
Enzyme	59	39	0	180	8	25	51	40
Combustion	59	40	2	5	11	10	46	45
Enzymatic Hydrolysis	56	41	0	181	1	360	55	38
Diesel engine	53	42	0	182	9	21	44	47
Fatty acid	51	43	0	185	1	361	50	41
Agriculture	51	44	0	183	3	82	48	43
Energy crop	51	45	0	184	7	30	44	48
Metabolic engineering	50	46	0	187	1	362	49	42
Chlorella	50	47	0	186	3	83	47	44
Gasification	49	48	0	188	5	42	44	49
Bio-oil	48	49	0	189	4	58	44	50
Fuel cell	48	50	1	23	10	13	37	59

Cnt=count of occurrences, R=rank.

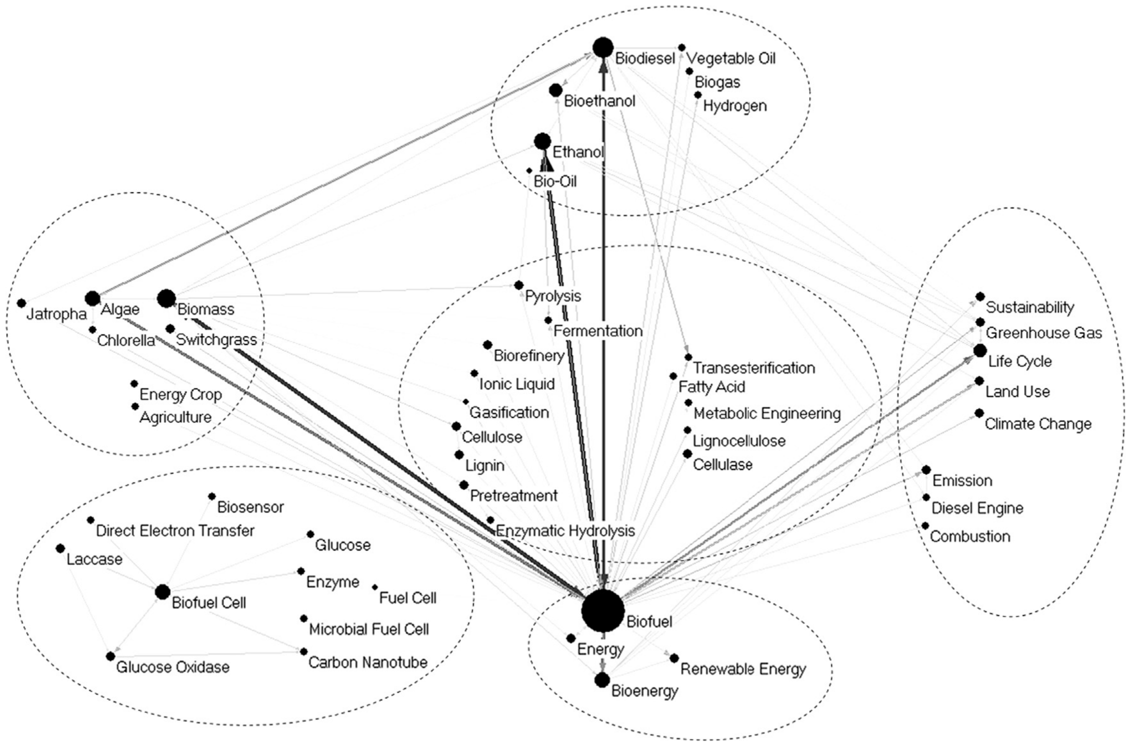

Fig. 9. The co-words network of the 50 most frequent keywords.

keywords which were “Transesterification”, “Vegetable oil” and “Fatty acid”. Additionally, fuel cells are another recent development of biological energy transformations [35]. As found by the present study, the frequent keyword “Biofuel cells” ranked 7 and occupied the central position in the sub-network of co-words analysis which included other 8 frequent keywords: “Laccase”, “Glucose oxidase”, “Carbon nanotube”, “Microbial fuel cell”, “Glucose”, “Biosensor”, “Direct electron transfer” and “Enzyme” (Table 5, Fig. 9).

The use of fossil fuels is not considered sustainable, and thus alternative modern fuels are being researched to ensure sustainable development [36]. At this point, “Sustainability” is one of the most frequent keywords in the co-word network of biofuel, because research on sustainability aims to reduce the often heated debates and provide a rational decision for the use of biofuels [37]. As one of sustainability-based methods, life cycle assessment (LCA) can be used as a holistic decision support technique to quantify the economic, environmental and societal implications of various biorefinery process, feedstock, and integration options [38]. The present rank and position of the keyword “life cycle” confirmed that LCA is an increasingly popular method for biofuel research. The production of biofuel can offset carbon dioxide emissions from the transport industry, and it can be regarded as a potential to mitigate climate change [39]. The co-word analysis showed that the importance and prospective of biofuel research has frequently been emphasized as the reduction of greenhouse gas and the mitigation of changing climate. However, an active debate has recently emerged around greenhouse gas emissions due to indirect land use change of expanding agricultural areas dedicated to biofuel production [40]. The present analysis of keywords confirmed that the influence of biofuel production on land use has attracted much attention (Fig. 9).

4. Conclusions

In this article, we present an overview of global research trends in biofuel field following bibliometric evaluations on publications, journals, categories, institutions, countries and keywords. This temporal analysis confirmed that scientific outputs of biofuel field experienced a substantial growth with increasing publications, collaboration index and references during the period of 1991–2012. At a global scale, USA has been taking a dominant position in biofuel research with the largest number of single country and internationally collaborative articles and followed by its principal collaborators including China, UK, Germany, Canada and South Korea. At an institutional scale, USDA ARS headed the article ranking, followed by Chinese Academy of Sciences and University of California, Berkley. Research collaborations in biofuel fields at institutional scales became more important than that at global scales. The collaboration network also found that the 15 most productive institutions in USA tended to collaborate more with each other than other international institutions. Nevertheless, international collaborative publications always drew more citations than single country publications.

The most commonly used 20 journals were responsible for more than 30% of the total biofuel articles, with *Biomass and Bioenergy* publishing most articles of biofuel research, followed by *Bioresource Technology*. The titles of commonly used journals confirmed that “Technology” (“Biotechnology”) was the focus of biofuels research. The subject category of “Energy& fuels” showed the most interest in biofuel research which was followed by other four common categories including “Biotechnology and applied microbiology”, “Chemical engineering”, “Environmental sciences” and “Agricultural engineering”. The analysis of interdisciplinary network found that biofuel studies have been based on the combination of multi-subject categories. The temporal and co-word analysis of keywords provides clues for research tendencies and hotspots. Biodiesel is the most favorite product and microalgae is the most promising biological feedstock. Thus, the production of biodiesel from microalgae has been becoming the hot aspect of biofuel research. Due to the recalcitrant nature of biological feedstock, the conversion technologies have gained considerable attention from many biofuel studies and biorefineries including mechanical, thermo-chemical, biochemical and physico-chemical processes are still most common research tendencies.

As a holistic method of decision support, LCA is being frequently developed and applied to evaluate the sustainability of biofuel development by considering greenhouse gas emission (climate change) and land use change.

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