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Research on biomass energy and environment from the past to the future: A bibliometric analysis

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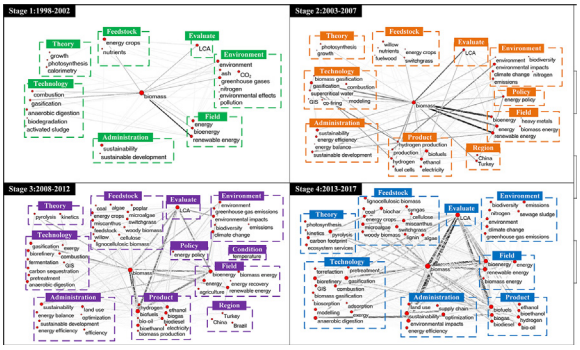
HIGHLIGHTS

- The characteristics of related articles (1998–2017) are analyzed by bibliometrics.
- Co-word analysis was used to make a more comprehensive analysis of the development of the whole field.
- The interaction between biomass energy and the environment begin to become a major concern.

GRAPHICAL ABSTRACT

The development and utilization of biomass energy can help to change the way of energy production and consumption, and establish a sustainable energy system which can effectively promote the development of national economy and strengthen the protection of environment. Here we make bibliometric analysis of 9514 literature reports in Web of Science Core Collection searched with key words of "Biomass energy" and "Environment*" date from 1998 to 2017 and hot topic in the research and development of biomass energy utilization as well as the status and development trend of biomass energy utilization and environment were analyzed based on content analysis and bibliometrics. In order to make a more comprehensive analysis of the development of the whole field, this study adopts the method of Co-word analysis. The interaction between biomass energy and the environment began to become a major concern as the research progressively deepened. This work is of great significance for the development and utilization of biomass energy to put forward specific suggestions and strategies based on the analysis and demonstration of relationship and interaction between biomass energy utilization and environment. It is also useful for researchers to select the future research topics.



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ABSTRACT

The development and utilization of biomass energy can help to change the ways of energy production and consumption and establish a sustainable energy system that can effectively promote the development of the national economy and strengthen the protection of the environment. Here,we perform a bibliometric analysis of 9514 literature reports in the Web of Science Core Collection searched with the key words "Biomass energy" and "Environment*" date from 1998 to 2017; hot topics in the research and development of biomass energy utilization, as well as the status and development trends of biomass energy utilization and the environment, were analyzed based on content analysis and bibliometrics. The interaction between biomass energy and the environment began to become a major concern as the research progressively deepened. This work is of great significance for the development and utilization of biomass energy to put forward specific suggestions and strategies based on

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the analysis and demonstration of relationships and interactions between biomass energy utilization and environment. It is also useful to researchers for selecting the future research topics.

1. Introduction

With the progress of society and development of the economy, the problems with resources and the environment become increasingly more important, representing the two main difficulties confronted by global development (Bridgwater 1999; Chi 2008; Li et al. 2004; Shao-Jie 2008; Xiang-Dong 2008). All countries in the world are looking for new types of energy that are sustainable and clean and that can replace conventional fossil fuels, and the development of new energy and renewable energy has been regarded as the focus of a new trend of industry promotion and development. Biomass energy, which has caught worldwide attention in recent years, is a renewable resource that can be transformed into three phases of fuel: gas, liquid and solid (An and TMA, 2014; Bimbela et al. 2014; Ioelovich 2015; Vamvuka 2011). Biomass energy becomes a new alternative energy source together with other new energy sources, such as wind energy, solar energy, nuclear energy. The efficient development and clean use of biomass resources has been a subject of concern to all countries in the world (Benhelal et al. 2013; Papathanasiou and Anderson 2001; Sadamichi et al. 2012). As one of the important renewable energy sources, biomass energy occupies an important position in the energy system (Arena et al. 2010; Frombo et al. 2009; König 2011; Papadopoulos and Katsigiannis 2002). The development and utilization of biomass energy can help to change the ways of energy production and consumption (Masera 2002; Yazdian et al. 2010; Zhu and Pan 2010) and establish a sustainable energy system that can effectively promote the development of national economy (Kalt 2015; Keoleian and Volk 2005; Krishnan and Mccalley 2016; Zeng 2008) and strengthen the protection of the environment (Demirbas 2010; Sajdak and Piotrowski 2013). It is of great significance for the development and utilization of biomass energy to put forward specific suggestions and strategies based on the analysis and demonstration of relationship and interaction between biomass energy utilization and the environment.

Bibliometrics, a very effective method of summarizing and analyzing, can be used for exploring the structure, characteristics and laws of a subject by studying the distribution, scalar relationship and change regulation of literature and information (Chen et al. 2005; Hood and Wilson 2001; Liang and Gong 2017; Mao et al. 2015). With the help of this method, the hot spots and trends of scientific research on the direction of the environment and biomass energy utilization in the last 20 years could be summarized. There is no doubt that the conclusions obtained by comparative and synthetic research on content analysis and bibliometrics have evident theoretical significance to the development of biomass energy utilization.

In this work, a bibliometric analysis of 9514 articles reports in the Web of Science Core Collection searched with the keywords of "Biomass energy" and "Environment*" dated from 1998 to 2017 was carried out up to February 1, 2018. Hot topics in the research and development of biomass energy utilization, as well as the status and development trend of biomass energy utilization and the environment, were analyzed based on content analysis and bibliometrics.

2. Methodology

2.1. Bibliometric analysis methods

Bibliometrics is a statistical method used to assess and quantify the number and growth trend of a particular subject. The literature system and the measurement characteristics consider the object studied using a metering method, such as a mathematical or statistical method. The research progress of a particular field can be analyzed and evaluated systematically through quantitative analysis on the quantity structure and change regulation of literature information.

2.2. Impact factor and H series index

The impact factor (IF), proposed by Eugene Garfield in 1972, is the most common evaluation index of the influence of a journal. IF is a reflection of the average number of quotes cited in the previous year by the papers published in the first two years of a journal. There is a strong correlation with the quality of the papers published in a journal. Therefore, IF is also regarded as an important index to evaluate the academics and influence of the paper.

The authoritative and accurate IF report in academic fields is issued by the American Institute of Science and Technology Information (ISI), which is published by the Journal of Science and Technology (JCR, Journal Citation Reports). This paper adopts the IF published by JCR in 2014. The H-index, proposed by Hirsch in 2005, is another index for evaluating the influence of a journal. The H-index refers to a certain period of time that h papers from a country/region, a periodical, an organization, etc. have been quoted at least h times. The advantage of the H-index is to combine the number of published papers and its influence into one indicator, which is a

Table 1
Document type information of literature reports during 1998–2017.

DT	NR	Percentage (%)
Article	6634	69.73
Review	1221	12.83
Proceedings paper	1155	12.14
Proceedings paper	419	4.4
Editorial material	38	0.4
Book chapter	31	0.33
Retracted publication	8	0.08
Reprint	3	0.03
News item	2	0.02
Data paper	1	0.01
Correction	1	0.01
Meeting abstract	1	0.01

DT: Document type; and NR: Number.

Table 2
Language information of periodical articles during 1998–2017.

Language	Article count	Percentage (%)
English	6505	98.06%
Polish	24	0.36%
Spanish	23	0.35%
Portuguese	20	0.30%
German	18	0.27%
French	15	0.23%
Chinese	13	0.20%
Croatian	4	0.06%
Czech	3	0.05%
Turkish	3	0.05%
Japanese	2	0.03%
Slovak	2	0.03%
Italian	1	0.02%
Serbo-Croatian	1	0.02%
Total	6634	

Table 3
Characteristics of periodical articles from 1998 to 2017.

PY	TP	AUTP	No. AU	AU/AUTP	NR	NR/TP	PG	PG/TP
1998	80	80	235	2.94	2447	30.59	901	11.26
1999	69	69	201	2.91	2297	33.29	749	10.86
2000	66	66	194	2.94	2325	35.23	856	12.97
2001	84	84	282	3.36	2764	32.90	967	11.51
2002	78	78	252	3.23	3054	39.15	1023	13.12
2003	104	104	330	3.17	3755	36.11	1355	13.03
2004	89	88	310	3.52	3710	41.69	1163	13.07
2005	117	117	413	3.53	4205	35.94	1365	11.67
2006	170	170	596	3.51	6093	35.84	1915	11.26
2007	191	191	689	3.61	7523	39.39	2178	11.40
2008	228	228	843	3.70	8931	39.17	2537	11.13
2009	309	309	1168	3.78	12028	38.93	3121	10.10
2010	377	377	1418	3.76	16986	45.06	4222	11.20
2011	463	462	1931	4.18	21737	46.95	4978	10.75
2012	501	501	2107	4.21	25024	49.95	5400	10.78
2013	570	570	2476	4.34	25334	44.45	6125	10.75
2014	638	638	2941	4.61	31434	49.27	7246	11.36
2015	772	772	3632	4.70	39074	50.61	8938	11.58
2016	828	828	3920	4.73	41312	49.89	9358	11.30
2017	900	900	4330	4.81	49771	55.30	10668	11.85

TP: The number of articles published in the year; AUTP: The number of articles published with authors in the year; No. AU: A total number of authors in the year; NR: Number of references; and PG: The number of pages.

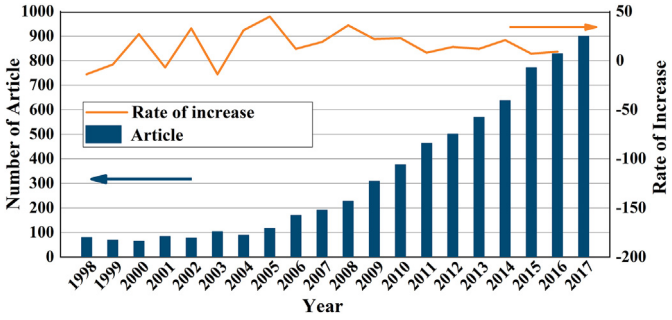

Fig. 1. The annual number of periodical articles during 1998–2017.

brief and concise expression of the extent of its influence. This work uses IF and H-index to evaluate and quantify the influence of periodicals, countries/regions and institutions.

2.3. Content analysis and analysis method

Content analysis can sum up the contents of the literature from a quantitative point of view. Co-words analysis is one of the most important technologies for content analysis. It is an effective tool for analyzing research hotspots and research trends. Compared with other methods of content analysis, co-words analysis can display information in multiple dimensions. In this work, co-words analysis is used to extract related words in titles, keywords and abstracts to study the research hotspots in related fields and the trend of research. In this work, co-words analysis is used to study the research hotspots in related fields and the trend of research by extracting related words in titles, keywords and abstracts. The main method for the analysis of co-words in this work is social network analysis (SNA). In this study, we build social networks including all nodes through social network analysis and use nodes to reflect the number of research articles, keywords and institutions. This work uses bibexcel and pajek software that have been widely used in previous research to visualize the data network in order to analyze the more complex network of cooperation between states and organizations.

3. Results

3.1. Characteristics analysis of the literature reports

First, we simply comb and analyze the statistical data of the literature to obtain the preliminary conclusions. The presentation of literature type for the 9514 reports retrieved in this work is shown in Table 1 below. There are 6634 periodical articles in the reports, accounting for 69.73%. The number of periodical articles is the most and the periodical articles can greatly symbolize the trend of development and change of relevant studies. Therefore, we focus on the analysis and evaluation of the periodical articles in the following analysis.

Language information of periodical articles during 1998–2017 is shown in Table 2. The most used language in the published articles is English, accounting for 98.06%, sequentially followed by Polish (0.36%), Spanish (0.35%), Portuguese (0.30%), German (0.27%) and French (0.23%). Chinese ranked in seventh place with a percentage of 0.20%. The total number of articles published with these seven languages accounts for 99.76%. English is still the most important language in this field.

Table 4
Publication of the first 20 countries/regions (1998–2017).

Country	TP	TPR (%)	SPR (%)	CPR (%)	FPR (%)	RPR (%)	C	C%	H-index
USA	1456	1(21.99)	1(22.9)	2(17.16)	1(21.99)	1(19.04)	180	12.36	80
China	710	2(10.72)	2(9.8)	3(15.63)	2(9.2)	2(9.51)	164	11.26	50
UK	608	3(9.18)	12(2.21)	1(46.23)	4(4.97)	4(5.28)	485	33.31	49
Italy	449	4(6.78)	3(6.23)	5(9.72)	3(5.89)	3(5.96)	102	7.01	51
Germany	362	5(5.47)	4(4.42)	4(11.06)	5(4.47)	5(4.59)	116	7.97	43
Spain	314	6(4.74)	5(4.11)	8(8.1)	6(3.97)	6(4.11)	85	5.84	47
Canada	284	7(4.29)	8(3.46)	7(8.67)	8(3.29)	7(3.64)	91	6.25	41
Brazil	244	8(3.69)	7(3.54)	13(4.48)	9(3.28)	8(3.38)	47	3.23	35
India	243	9(3.67)	6(3.59)	15(4.1)	7(3.32)	9(3.26)	43	2.95	32
France	233	10(3.52)	11(2.42)	6(9.34)	12(2.52)	12(2.58)	98	6.73	28
Sweden	212	11(3.2)	10(2.85)	11(5.05)	10(2.73)	10(2.79)	53	3.64	29
Turkey	180	12(2.72)	9(2.94)	26(1.53)	11(2.57)	11(2.61)	16	1.10	26
Netherlands	173	13(2.61)	16(1.71)	9(7.44)	14(1.86)	14(1.97)	78	5.36	33
Australia	160	14(2.42)	15(1.76)	10(5.91)	16(1.77)	13(1.99)	62	4.26	27
Japan	153	15(2.31)	14(1.81)	12(4.96)	13(1.95)	15(1.94)	52	3.57	28
Denmark	125	16(1.89)	19(1.42)	14(4.39)	17(1.56)	17(1.62)	46	3.16	21
Poland	122	17(1.84)	13(1.94)	29(1.33)	15(1.78)	16(1.74)	14	0.96	28
Finland	121	18(1.83)	18(1.51)	16(3.53)	18(1.51)	18(1.55)	37	2.54	24
Malaysia	107	19(1.62)	17(1.54)	23(2)	19(1.47)	19(1.5)	21	1.44	29
Greece	96	20(1.45)	20(1.35)	23(2)	20(1.25)	20(1.27)	21	1.44	21

TP: Total number of articles; TPR(%): The ranking and percentage of the total number of articles; SPR(%): The ranking and percentage of the country's individual publication; CPR (%): The ranking and percentage of articles for the country collaborated with other countries; FPR (%): The ranking and percentage of articles for the country as the first author country; RPR (%): The ranking and percentage of articles for the country as the corresponding author country; C: The number of articles published by the country in cooperation with other countries; and C%: The percentage of articles published by the country in cooperation with other countries.

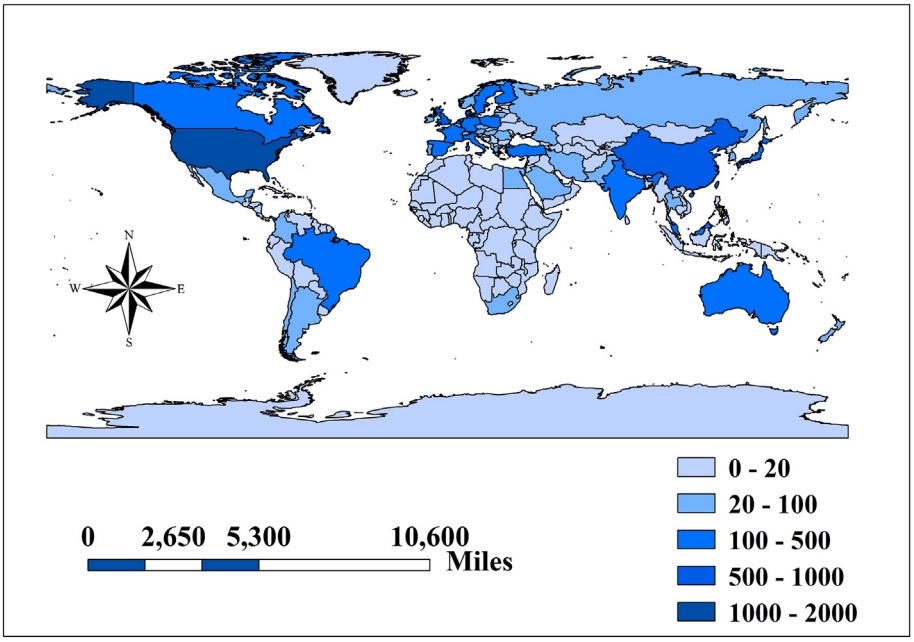

Fig. 2. Global distribution of periodical articles published (1998–2017).

Table 3 shows the analysis data of the characteristics of periodical articles from 1998 to 2017. The total amount of varying trends of periodical articles during 1998–2017 is clearly shown in Fig. 1. The number of periodical articles published shows a slight fluctuation approximately 80 from 1998 to 2004. The total number of authors and references also changes little in this period of time. The total amount of articles, authors or references of biomass energy environment research has been significantly increased since 2004. The number of published articles increased from 89 in 2004 to 900 in 2017. This can be seen much more clearly in Fig. 1. The average number of authors increased from 2.94 in 1998 to 4.81 in 2017, and the average number of references increased from 30.59 to 55.3. It can be seen that the research in this field has been heating up in the past 20 years, and the internal cooperation and exchange are increasingly and more active. The red line can also reflect the changing trend of the number of articles. It can be seen that the growth rate of periodical articles fluctuated clearly before 2004. The growth rate began to become stable after 2006, and the annual number of periodical articles began to grow steadily.

3.2. National/regional contribution analysis

The contribution of different countries/territories and institutes was studied by analyzing the postal addresses of periodical articles. The basic situation of the top 20 countries (or regions) in the publication of articles is as shown in Table 4. and the details are clearly shown in Fig. 2. The United States published the most articles with an amount of 1456 in the field of biomass energy and environment. At the same time, it ranked second in cooperation with other countries. The United States is also the first in the respects of depth and influence, with a H-index up to 80. Taking the total number of articles and the H-index into consideration, China was ranked second. The performance of North America and the Nordic region is also good. Furthermore, Brazil, India and Australia also did well in the field of biomass energy and the environment.

As shown in Fig. 3, the number of periodical articles published by the top five countries basically remained stable before 2004. The annual number of periodical articles began to grow obviously grow approximately 2005. It shows that research in the field of biomass energy and environment has developed rapidly since 2005. The growth advantage of the United States is more obvious.

Fig. 4 shows the cooperation network of the top 20 productive countries/regions. The cooperative relationship between different countries is represented by the connection between them. The bigger the point is, the more important the country is. The thicker and deeper the line is, the closer the cooperation is. Fig. 4 shows that the United States and China play very important roles in this field, while the cooperation between China and the United States is also very close. In addition, the United States has more cooperation with the United Kingdom, Italy and Brazil. China has plenty of cooperation with the UK, Germany and India. A wide range of cooperation and contacts already exist between the productive countries/regions. However, it can also be seen in Fig. 4 that there is still more space for the development of exchanges and cooperation in this field. For example, the United States and China, the two major leading countries have had no exchanges and cooperation with countries such as Finland and Greece in the last 20 years.

3.3. Institutes contribution analysis

The basic situation of the top 20 institutes in the publication of articles is shown in Table 5. The United States led the index, with 9 institutes, followed by China and the UK with 4 institutes and 2 institutes, respectively. There was one institution, respectively, from Sweden,

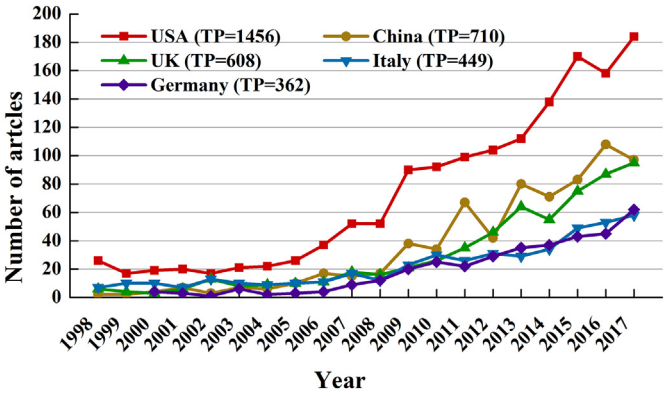

Fig. 3. Annual growth curve of the top five countries in the total number of periodical articles during 1998–2017.

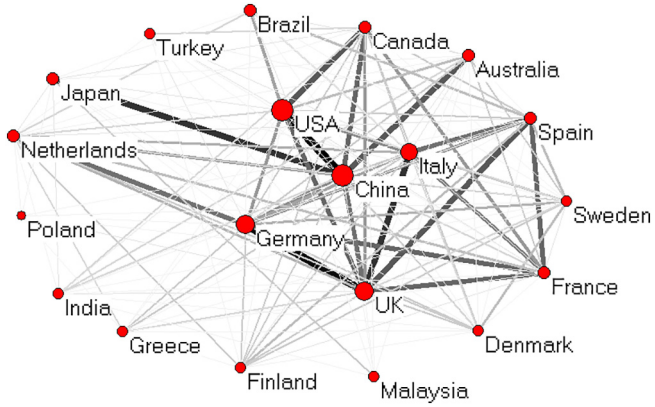

Fig. 4. The cooperation network of the top 20 productive countries/territories.

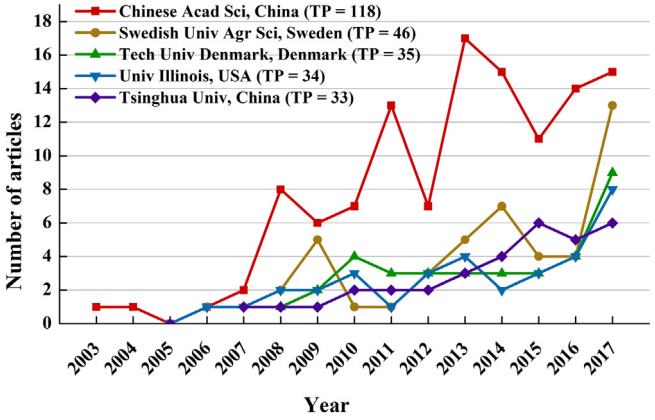

Fig. 5. Annual growth curve of the top five institutions in the total number of periodical articles during 1998–2017.

Germany, France, Brazil and the Netherlands. The Chinese Academy of Sciences published the most articles (128 articles), which is far beyond that of other institutions. There is no significant difference in the number of articles published by other agencies.

As shown in Fig. 5, the number of periodical articles published by the top five institutions basically began to obviously grow approximately 2005. American institutions did not come out at the top of the list, although the United States had published the most articles. Among the institutions, the Chinese Academy of Science had the highest number of periodical articles during 1998–2017. It is also the earliest institution to enter the field of biomass and environment, which started related research as early as 2000, while the other institutions began to start in 2004. The Chinese Academy of Science was also the first in the respects of depth and influence with a H-index of 22.The number of articles published by the top five institutions showed an increasing tendency in fluctuation.

3.4. Subjects and journals analysis

The contributions of the top 17 subjects in biomass and environment research from 1998 to 2017 are shown in Table 6. Energy & Fuels is the most popular topic, which had 2245 records. Environmental Sciences & Ecology, with 2042 articles, occupied the second place. The number of the top two journals accounts for 64.62% of the total number of articles. Moreover, there were 1561 and 1112 articles in the fields of Engineering and Agriculture respectively, which indicated that the applications-based research is rapidly developing rapidly together with theoretical research.

Fig. 6 illustrates the top five most frequent subject categories in terms of the number of annual periodical articles. In line with the trend of the number of articles published, the number of periodical articles published in the subjects of Energy & Fuels, Environmental Sciences & Ecology, Engineering, Agriculture and Biotechnology & Applied Microbiology remained steady from 1998 to 2004. The number of articles published in these 5 subjects has been significantly increased since 2004. However, compared with the subjects of Energy & Fuels, Environmental Sciences & Ecology and Engineering showed a steady increase in the number of articles published after 2011. The number of articles published in the subjects of Agriculture and Biotechnology & Applied Microbiology obviously slowed down. In summary, the main research areas of biomass energy and the environment were Energy & Fuels, Environmental Sciences & Ecology and Engineering from 1998 to 2017. This suggests that the research gradually began to turn to more comprehensive research on the environment and engineering from the early relatively unitary technology application research.

Table 7 shows the 18 most productive journals during 1998–2017. More than 30% of the biomass energy and environment related articles are published in the top 18 journals, which are listed in Table 7. BIOMASS & BIOENERGY is the most productive journal with 358 articles, followed by JOURNAL OF CLEANER PRODUCTION (191) and ENERGY (169). APPLIED ENERGY ranks 5th in the number of articles, but with

Table 5
The performance of the top 20 most productive institutions.

Institute	TP	TPR (%)	SPR (%)	CPR (%)	FPR (%)	C%	H-index
Chinese Acad Sci, China	128	1(1.93)	1(3.04)	1(1.17)	1(1.5)	35.94	22
Swedish Univ Agr Sci, Sweden	43	2(0.65)	2(0.85)	3(0.51)	2(0.62)	46.51	16
Tech Univ Denmark, Denmark	35	3(0.53)	6(0.67)	8(0.43)	3(0.51)	48.57	13
Univ Illinois, USA	34	4(0.51)	3(0.78)	22(0.33)	4(0.47)	38.24	16
Tsinghua Univ, China	33	5(0.5)	27(0.41)	2(0.56)	25(0.29)	66.67	10
Univ Minnesota, USA	31	6(0.47)	8(0.56)	10(0.41)	5(0.45)	51.61	12
Texas A&M Univ, USA	31	6(0.47)	8(0.56)	10(0.41)	5(0.45)	51.61	13
INRA, France	31	6(0.47)	4(0.7)	32(0.31)	7(0.44)	38.71	15
Univ Sao Paulo, Brazil	30	9(0.45)	4(0.7)	46(0.28)	8(0.42)	36.67	18
Iowa State Univ, USA	29	10(0.44)	8(0.56)	18(0.36)	11(0.38)	48.28	13
Univ London Imperial Coll Sci Technol & Med, UK	29	10(0.44)	18(0.48)	10(0.41)	10(0.41)	55.17	12
USDA ARS, USA	29	10(0.44)	7(0.63)	32(0.31)	8(0.42)	41.38	17
Michigan State Univ, USA	29	10(0.44)	27(0.41)	7(0.46)	16(0.35)	62.07	13
Shanghai Jiao Tong Univ, China	28	14(0.42)	48(0.3)	3(0.51)	33(0.26)	71.43	8
Univ Calif Berkeley, USA	27	15(0.41)	14(0.52)	22(0.33)	25(0.29)	48.15	12
Peking Univ, China	27	15(0.41)	70(0.26)	3(0.51)	42(0.24)	74.07	11
Univ Manchester, UK	25	17(0.38)	18(0.48)	32(0.31)	12(0.36)	48.00	10
Oregon State Univ, USA	25	17(0.38)	18(0.48)	32(0.31)	12(0.36)	48.00	8
Univ Utrecht, Netherlands	25	17(0.38)	14(0.52)	46(0.28)	12(0.36)	44.00	13
Univ Wisconsin, USA	25	17(0.38)	18(0.48)	32(0.31)	22(0.3)	48.00	14

Table 6
The 17 most productive subjects during 1998–2017.

Subject	TP	Percentage (%)
Energy & Fuels	2245	33.84
Environmental Sciences & Ecology	2042	30.78
Engineering	1561	23.53
Agriculture	1112	16.76
Biotechnology & Applied Microbiology	963	14.52
Science & Technology - Other Topics	804	12.12
Chemistry	615	9.27
Thermodynamics	361	5.44
Marine & Freshwater Biology	309	4.66
Materials Science	230	3.47
Business & Economics	228	3.44
Forestry	186	2.80
Plant Sciences	173	2.61
Oceanography	151	2.28
Mechanics	136	2.05
Electrochemistry	135	2.03
Microbiology	132	1.99
Water Resources	122	1.84
Meteorology & Atmospheric Sciences	119	1.79
Geology	107	1.61
Biochemistry & Molecular Biology	98	1.48

Table 7
The 20 most productive journals during 1998–2017.

Journal	TP	Percentage (%)	IF
Biomass & Bioenergy	358	5.40	3.219
Journal of Cleaner Production	191	2.88	5.715
Energy	169	2.55	4.520
Energy Policy	154	2.32	4.410
Applied Energy	154	2.32	7.182
Bioresource Technology	141	2.13	5.651
Renewable Energy	141	2.13	4.357
International Journal of Hydrogen Energy	108	1.63	3.582
Global Change Biology Bioenergy	104	1.57	4.655
Energy Conversion and Management	92	1.39	5.589
Environmental Science & Technology	84	1.27	6.198
Energy & Fuels	80	1.21	3.091
Fuel	77	1.16	4.601
Bioenergy Research	71	1.07	2.487
Plos One	61	0.92	2.806
Energy Sources Part A-Recovery Utilization and Environmental Effects	53	0.80	0.527
Biofuels Bioproducts & Biorefining-biofpr	52	0.78	3.694

the highest IF value of 7.182 among these 18 journals. Fig. 7 shows the publication pattern of the top 5 journals. It is notable that JOURNAL OF CLEANER PRODUCTION soars rapidly after 2013. The number of articles published in BIOMASS & BIOENERGY and APPLIED ENERGY declined significantly since 2014.

3.5. Keyword and high cited articles analysis

There were 5647 articles with key words. The data are shown in Table 8. This work divided the 1998–2017 years into four stages for a better understanding of the data. The details of analysis on keywords in each stage are shown in Fig. 8. In general, four stages of field classification were the same, but with advancing time, the research in different fields focused on different directions, and at the same time, the relationship with biomass energy utilization and environment research was also changing. The development of a single keyword with time can be obviously seen in Fig. 8. Biomass, bioenergy and renewable energy are the keywords that most frequently appeared. The frequency of the emergence of broad terms of environment and energy has begun to decline. This suggests that the related research is being gradually deepened. Concerning the research method, life cycle assessment (LCA) kept the momentum of rapid rise. This trend suggests that LCA is becoming one of the most important methods for the study of relationship and interaction between biomass energy utilization and the environment. In addition to this, environment impact is another hotspot. This phenomenon shows that the environment-related problems in biomass energy research have been paid increasingly more attention, and the research emphasis is gradually trending toward this direction. However, the studies with climate change as a keyword decreased slightly in the fourth stage after gradually rising in the first three stages. In more specific technical research, gasification and switchgrass maintained a steady growth trend. Biogas and microalgae had a sudden increase from the second stage to the third stage, which showed that these two directions had become new research hotspots in this period. However, the increase in the fourth stages is not obvious. This means a decline in the concern of these two directions at this time. Biorefinery and biodiesel were a new research points that appeared in the second stage. Biorefinery maintained a steady and sustained growth while biodiesel dipped in the fourth stage after a rapid growth during the third stages.

Co-word analysis can make a good use of the keywords contained in the "time" attribute. Therefore, the dynamic changing process of study discipline study could be presented much more objectively and reasonably. This work divided the period from 1998 to 2017 into four stages, and the analysis of keywords in each stage is shown in Fig. 9. The domain classification of the four stages increased. However, the research focused on different directions and the relations of different fields were also changing over time. To make a more comprehensive analysis of the development of the whole field, this study adopts the method of co-word analysis. Known from the analysis, sustainability, sustainable development and renewable energy had always been a focal point in study of biomass energy and the environment during the whole period.

In the transition from stage 1 (1998–2002) to stage 2 (2003–2007), the interconnections of keywords began to become closer. There was research concerning China and Turkey in this period. In the aspect of

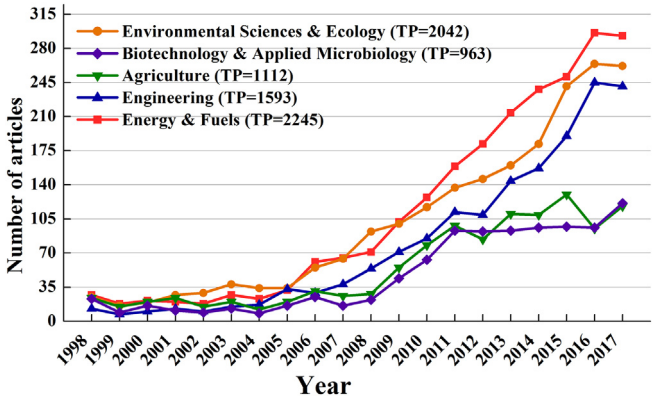

Fig. 6. The number of articles of the top 5 subjects during 1998–2017.

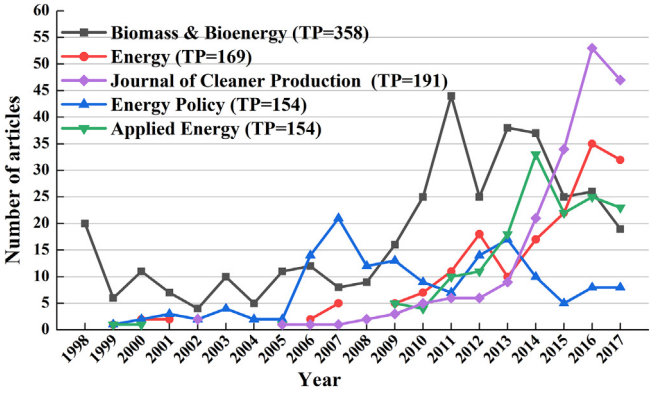

Fig. 7. The number of articles of the top 5 journals during 1998–2017.

Table 8
Changing tendency of top 22 key words over time during 1998–2017.

Keywords	TP	98-17R (%)	98-02R (%)	03-07 R (%)	08-12 R (%)	13-17R (%)
Biomass	623	1(10.72)	1(15.28)	1(16.16)	1(16.41)	1(14.39)
Bioenergy	223	2(3.84)	48(1.11)	3(4)	2(6.88)	3(5.98)
Life cycle assessment	220	3(3.78)	208(0.56)	5(2.4)	6(3.98)	2(6.26)
Renewable energy	194	4(3.34)	3(5)	2(4.64)	4(4.42)	4(4.53)
Sustainability	140	5(2.41)	6(2.5)	10(1.6)	7(3.47)	5(3.73)
Biofuel	114	6(1.96)	48(1.11)	15(1.44)	5(4.17)	6(3.11)
Energy	113	7(1.94)	4(4.17)	4(3.36)	8(3.03)	11(2.37)
Gasification	110	8(1.89)	15(1.94)	8(1.92)	14(2.21)	8(2.8)
Biofuels	106	9(1.82)	208(0.56)	6(2.08)	3(5.18)	8(2.8)
Biogas	100	10(1.72)	508(0.28)	68(0.48)	9(2.71)	7(2.96)
Pyrolysis	92	11(1.58)	15(1.94)	46(0.64)	13(2.27)	10(2.5)
Microalgae	79	12(1.36)	508(0.28)	292 (0.16)	20(1.58)	11(2.37)
Anaerobic digestion	75	13(1.29)	24(1.67)	46(0.64)	19(1.64)	14(2)
LCA	74	14(1.27)	508(0.28)	26(0.96)	15(2.02)	13(2.06)
Biorefinery	68	15(1.17)	–	46(0.64)	20(1.58)	15(1.97)
Hydrogen	67	16(1.15)	508(0.28)	9(1.76)	15(2.02)	17(1.69)
Biodiesel	64	17(1.1)	–	68(0.48)	11(2.59)	16(1.88)
Switchgrass	60	18(1.03)	164(0.83)	38(0.8)	32(1.07)	18(1.6)
Climate change	57	19(0.98)	164(0.83)	10(1.6)	18(1.83)	24(1.36)
Combustion	57	19(0.98)	15(1.94)	26(0.96)	34(1.01)	24(1.36)
Environmental impact	57	19(0.98)	208(0.56)	26(0.96)	25(1.39)	20(1.51)
Environment	55	22(0.95)	2(5.83)	17(1.28)	15(2.02)	41(0.8)

TP: The total number of key words during 1998–2017;and R%: The ranking and percentage of the key words in different years.

management, except for sustainable development, sustainability, energy efficiency and energy balance, other aspects, such as land use, began to receive attention. New techniques, such as geographic information system (GIS), began to be introduced into this field. The specific applied techniques, such as biofuels, ethanol hydrogen production and fuel cells (Hill et al. 2006; Lehmann 2007), became important topics of energy research in the field of biomass and the environment. (Riahi et al. 2007; Werf et al. 2006). Moreover, environmental impacts have received much more attention since then.

With the formation of the Kyoto Protocol, countries from all around the world began to pay attention to the problems of mitigating climate change and reducing greenhouse gas emissions. From stage 2 (2003–2007) to stage 3 (2008–2012), the relationship between the keywords was strengthened. Life cycle assessment played an increasingly important role (Lardon et al. 2009). In the topic of energy, research focusing on the study of biofuel technology, and more abundant types of technologies have been conducted. For example, biogas, biodiesel, bioethanol, bioethanol and hydrogen began to appear enthusiastically. In stage 4 (2013–2017), energy efficiency and optimization continued to be a concern. Related research was much more systematic and comprehensive than before. As time went on, the focus of research on feedstock was increasing. The content of the research was gradually transferred from general concepts, such as energy crops and nutrients to specific crops, such as microalgae, Miscanthus, and switchgrass, and most of the new sources of feedstock were non-grain crops. Since the 1990s, the development of biomass energy has brought a series of problems, for example, the grain-planting structure was heavy on corn, the total grain supply declined, and the price of grain (oil) increased with oscillatory behavior. Therefore, the development of non-grain biofuels is still an important issue. The biogeochemistry of the carbon cycle is a very important topic in the field of energy. But carbon cycle only appeared 2, 2, 5 and 5 times for the stages from 1 to 4. This phenomenon indicated that the related research was still very rare. A comprehensive and in-depth evaluation and analysis of biomass energy and environment should be carried out based on strengthened research of carbon cycle.

Keywords are divided into twelve classes, such as theory, technology, administration and so forth (as shown in Fig. 10), in order to facilitate the analysis. From the analysis of the keywords of the four stages in Fig. 10, we can see that the research in the last 20 years has been mainly focused on the aspects of raw materials, products, technology and management. The number of the top nine countries with the largest number of articles is shown in Table 9.

The total number of keywords from the United States was the largest (7147)

and the species (4390) was also the highest. This result shows that the United States has the most active research in this field

and the related research is also the most comprehensive. China is close behind

and this is in line with the previous analysis. The number and type of keywords in Britain and Brazil are lower

indicating that their research is biased in a few areas

The classifications of keywords in the 9 countries are shown in radar maps in Fig. 11. It can be seen from the radar maps that the difference in the direction of research of the top 9 productive countries was very large. Studies in the United States, China, Britain, Spain, Canada and India mainly focused on technical aspects. Italy, Germany, Spain and Canada had more research on management. The United States and Germany were more concerned about the impact of the environment, and they had more research in theory. Brazil, Canada, and Spain focused on the research of biomass energy products. In terms of raw materials, the studies of the United States, Germany and Canada were more prominent. Brazil was also more devoted to research in this area.

4. Future research directions

The development of bioenergy must follow the principle of "not competing with people, not competing with grain", taking the cost

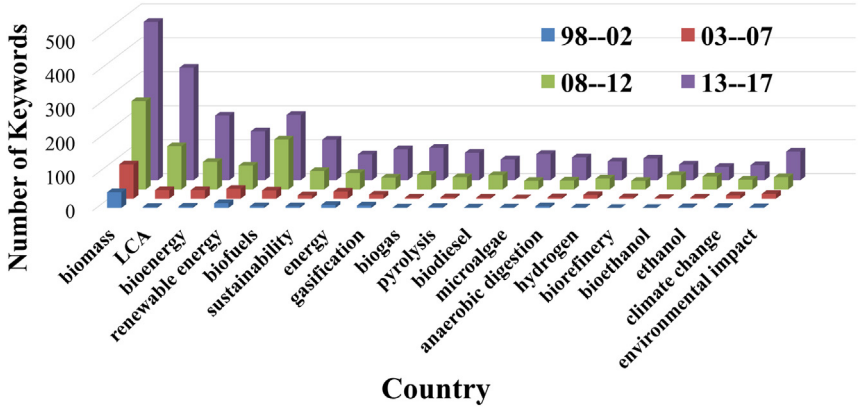

Fig. 8. Chang tendencies of top 22 keywords over time during 1998–2017.

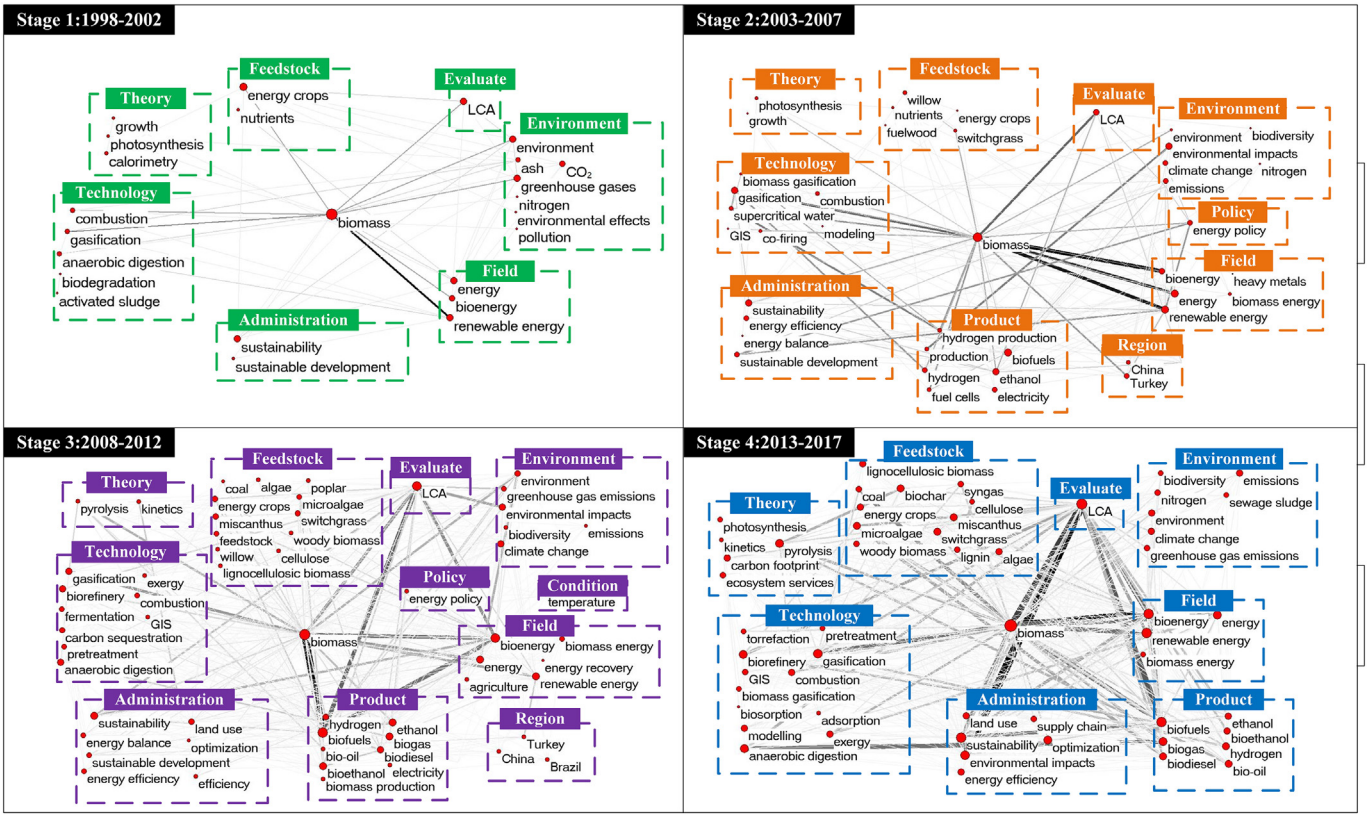

Fig. 9. The interconnection network and evolution of keywords in articles published during 1998–2017. Notes: ① The relative number of keywords is represented by the size of the red dots. The larger the red dot is, the more frequently that keyword appeared in the related articles. ② The number of co-occurrences is represented by the pattern of the gray lines. The thicker and darker the line is, the larger the number of co-occurrences of two keywords that were used by the authors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and ecological protection into account. Only when bioenergy crops have the same economic effects as traditional crops, and they cannot cost too much energy for planting, do farmers have enthusiasm. Biomass sources should be mainly agroforestry waste and non-grain crops.

The technical cost of agricultural and forestry waste as the main raw material is higher, and there are less commercialized projects. Research on microalgae as a raw material for biofuels is basically in the laboratory stage. Therefore, it is also an important direction for the development of biomass energy technology to reduce the technical cost, increase the output and carry out engineering application research.

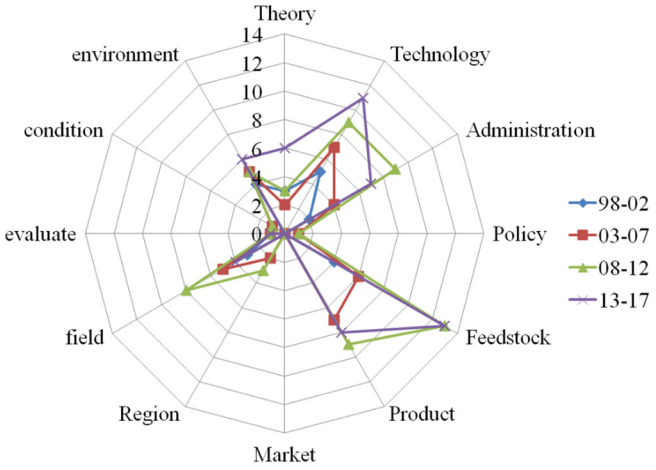

Fig. 10. Radar map of the keywords category changing tendency during 1998–2017.

One purpose of developing biomass energy is to improve the ecological environment. The reutilization of the byproducts of biomass energy engineering not only affects the continuous operation of biomass projects but also causes serious secondary pollution. Another problem is that the recycling and transportation cost of biomass energy engineering is very high. Life cycle assessment played an increasingly important role in studying and solving these problems in a more comprehensive and thorough way.

Exchanges and cooperation between different countries and regions can promote the more rapid and comprehensive development of biomass. There is still much room for communication between countries. A balanced development of the environment and the economy can be better realized by combining feedstock, product market, advantage technology and advanced management experience together. The study of the characteristics of different regions in the field of biomass is conducive to the complementary cooperation of the international community.

The reutilization of the byproducts of biomass energy engineering not only affects the continuous operation of biomass projects but also causes serious secondary pollution. Another problem is that the recycling and transportation cost of biomass energy engineering is very high. Evaluation methods such as life cycle assessment have played

Table 9
Number and category of keywords from the top 9 productive countries/regions during 1998–2017.

Country	USA	China	UK	Italy	Germany	Spain	Canada	Brazil	India
Total	7147	2301	1503	1992	1338	1212	1016	946	1001
Category	4390	1696	1042	1334	1031	924	758	721	745

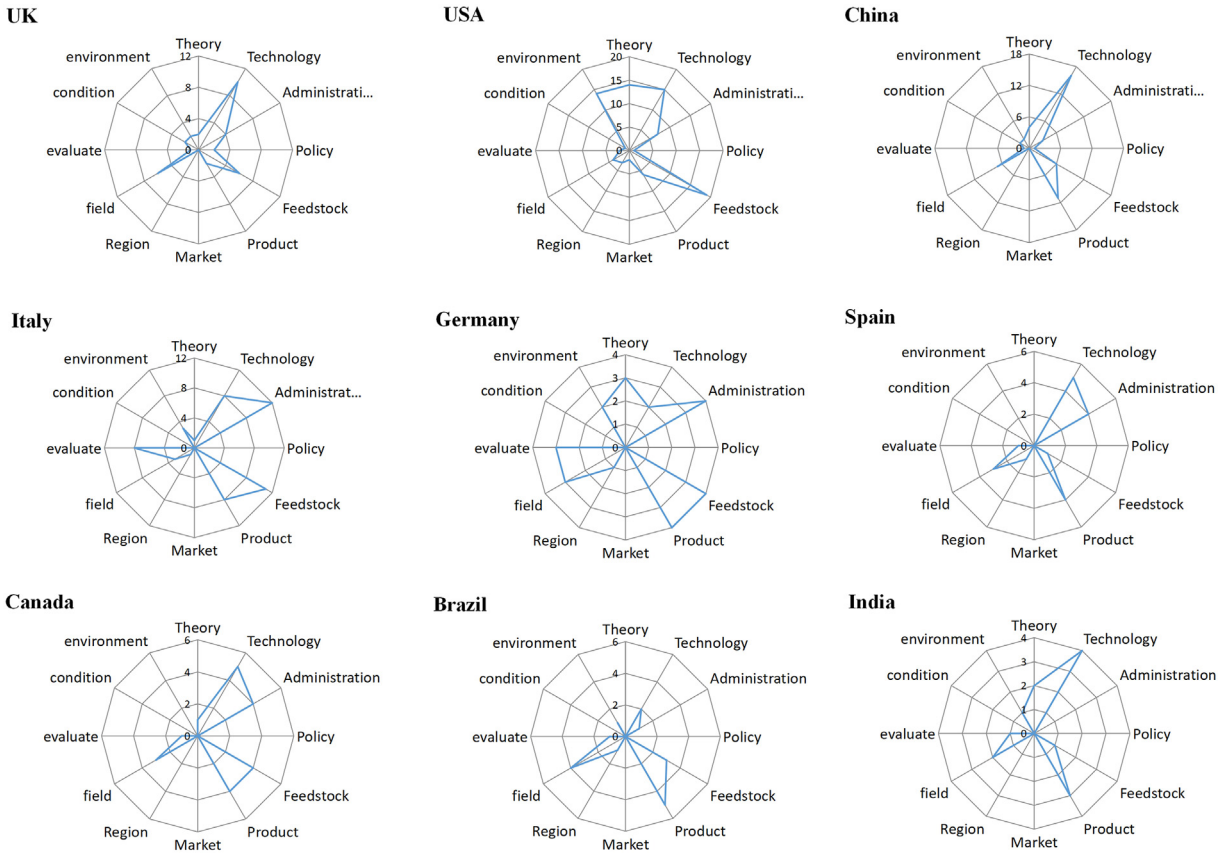

Fig. 11. Radar maps of keywords from the top 9 productive countries during 1998–2017.

an increasingly important role for studying and solving these problems in a more comprehensive and thorough way.

5. Conclusions

The characteristics of biomass energy and environment relevant articles from 1998 to 2017 are analyzed through the method of bibliometrics based on the Web of Science Core Collection database. This work reveals that the research on biomass energy and the environment has been becoming increasingly more extensive and global over the past 20 years. Studies on the related research have been also going deeper and further in these subjects. The most used language in the published article in English, accounting for 98.06% The United States is one of the most important contributors in the field of biomass energy and the environment, with the highest H-index of 80 and the most articles of 1456. However, the Chinese Academy of Science had the largest number of periodical articles (128) and the highest H-index (22) among all the institutions. It is also the earliest institution to have started the related research. The United States and China play the most important roles in this field, while the cooperation between China and the United States is also very close. However, there is still more space for the development of exchanges and cooperation in this field. Subject analysis suggests that the research gradually began to turn toward more comprehensive research on environment and engineering from the early relatively unitary technology application research. Energy efficiency and optimization began to be a concern. With the development of technical research, other associated problems have gradually aroused people's attention. The development of biomass fuel technology and industrialization has been improving. Higher requirements for a diverse supply of biomass material have been proposed. The interaction between biomass energy and the environment has begun to become a major concern as the research has progressively deepened. In addition, we have emphatically analyzed the interconnection network and the evolution of keywords, research differences among productive countries, and research topics of biomass and environment.

The development of non-food biofuels is still an important issue in the field of raw materials. It is an important direction for the development of technology to reduce the cost of technology, improve production and carry out the research of engineering applications. The introduction of LCA and other evaluation methods will contribute to the healthy development of biomass energy and the improvement of the ecological environment. The complementary cooperation of the international community can promote a faster and more comprehensive development of biomass resources.

Acknowledgments

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