*Biomechanism and Bioenergy Research (*)*****

Global Trends and Status in Bioenergy Research during the Years 2000-2020: A Systematic Bibliometric Analysis

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ABSTRACT

The increase in worldwide energy consumption and the issues arising from the use of fossil fuels have drawn attention towards sustainable energy sources. Bioenergy is a sustainable energy source that can help accomplish the goals of sustainable development. Aimed at the bibliometric analysis of articles on bioenergy, this study explored a total of 16,773 articles published in the Scopus database from 2000 to 2020. The cooperation of the authors and countries was established and studied by using social network analysis based on co-authorship. Also, to check the hot topics, the keywords and their interrelations were assessed based on co-occurrences. Additionally, the interrelationship of the keyword clusters was studied. The relevant research institutions, sponsors, and journals were addressed as other dimensions. The research showed that although the United States is the pioneer, China has made extensive investments and has put a special focus on bioenergy. This research shows the increasing importance and attention to bioenergy and, analyzes various aspects of bioenergy and illustrates the trend and progress of this subject over the last two decades. It would also help researchers develop bioenergy by identifying the most recent hot topics and their interrelations.

INTRODUCTION

The economic growth and the expansion of urbanization have increased the demand for energy (Singh *et al.*, 2020). This energy is mainly supplied by fossil fuels, which are less expensive than other fuels whereas the consumption of these fuels entails extensive environmental issues, including global warming, the increased emission of greenhouse gases, air pollution, climate change, and the acidification of oceans (Guo *et al.*, 2018; Spagnolo *et al.*, 2020). The annual population growth is 1.5% and the annual growth of energy demand is 1.1%, which clearly shows that we need to find a sustainable alternative for fossil fuels (Nanda and Berruti, 2021). There is no clear relationship between countries' economic growth and pollution, but it can be said that in countries where the rule of law is stronger, the spread of pollution is lower (Castiglione *et al.*, 2015). There is no way but to seek sustainable sources given the environmental issues, energy security, and the price of energy carriers. In other words, the world cannot rely on fossil fuels and has to move toward neutral carbon and renewable energies, such as bioenergy, solar energy, wind energy, and nuclear energy (Song *et al.*, 2020b; Sun *et al.*, 2021). For instance, Fig. 1 depicts the graph of the Persian Gulf crude oil free on board (FOB) price for the United States (US Energy Information Administration, 2020). The FOB, indeed, is the price without considering the shipping expenditure at the customs frontier of the economy from which they are exported. Accordingly, the crude oil price has been in the range of 38-106 USD/barrel in the last decade, which is too volatile for a reliable source of energy, making fossil fuels unreliable.

The movement towards renewable energy sources at a large scale can influence the countries with economies dependent on non-renewable energies, so these countries should be adapted to the upcoming conditions (Kahia *et al.*, 2017).

Biomass can play a profound role in the future of global energy. Compared to non-renewable energies, the energy derived from biomass can be developed with environmental, economic, and social approaches (Mohammadi *et al.*, 2020; Narwane *et al.*, 2021). The use of biomass for energy generation can solve the issues arising from landfills with all their tremendous environmental and economic implications. Another advantage of this energy source is that it is carbon-neutral; which means it produces as much carbon during burning as it has absorbed in the production chain (Ibraeva *et al.*, 2021; Tripathi *et al.*, 2019).

Effective policies are developed to support bioenergy. Presently, bioenergy is the fourth source of energy production after coal, oil, and natural gas. We need to pursue sustainable sources of biomass and the

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maturity of relevant technologies considering environmental and economic sustainability (Song *et al.*, 2020a).

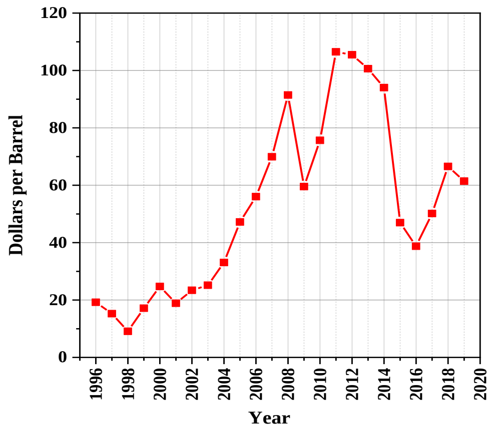

Fig. 1. U.S FOB Costs of Persian Gulf Countries Crude Oil during 1996-2019 (US Energy Information Administration, 2020).

For an in-depth investigation of an issue, it is of crucial significance to know the trend of its research and development over time. Bibliometric is an efficient method to display the different dimensions and trends of the development of an issue by mathematical, statistical, and graphical methods (Du *et al.*, 2014; Liang and Gong, 2017; Merigó *et al.*, 2016). With the aid of a bulk of data (keywords, authors, countries, journals, institutions, and sponsors), it is possible to identify the important points, boundaries, and commons of a topic, which can then be referred to as an appropriate guideline (Du and Teixeira, 2012; Persson *et al.*, 2004).

Mao *et al.* (2018) provide a bibliography on biomass energy and the environment. They analyzed articles from 1998 to 2017 that used "Biomass energy" and "Environment" in the title, keywords, and abstract. Bibliometric of 9514 articles showed that research into biomass energy and its interaction with the environment became increasingly important. Ferrari et al. Ferrari *et al.* (2020) reviewed a bibliographic analysis of progress by limiting the subject area to "Agricultural and Biological Sciences" in the Scopus database. Their analysis covered 9504 articles between 2000 and 2019 in which the keywords "Bioenergy" or its derived terms (e.g., bioenerg, bioenergies, bioenergetic, and so on) appeared in the title, keywords or abstract. They examined the bibliography of bioenergy with an agricultural approach.

The present study aims to evaluate research on energy derived from biomass. This study focuses on the growth trend of articles, countries and their international cooperation, research institutions and journals, authors, and keywords over 2000-2020. This study provides a comprehensive view of bioenergy by examining more than 16700 articles on six subject areas and quantifying all findings, including the relevance of keyword clusters; so that the link between different subjects and the scientific gaps can be identified to set the scene for its future growth.

MATERIALS AND METHODS

Bibliometric Analysis Methods

When researching a specific field of study, it is important to have knowledge about research trends past, present, and future. Bibliometric as multi-disciplinary study aims to evaluate and quantify the number and growth of literature on a particular topic. Measurement methods are including mathematics, statistics, and visualization. Through systematic analysis of the results, one can infer whether greater or lesser attention has been paid to a particular field.

Impact Factor and H-index

H-index and IF (impact factor) are two important indicators of data quality. IF was first defined by Eugene Garfield, the founder of the Institute for Scientific Information (ISI), in 1972. It reflects the authenticity of a journal in a certain research field versus the other journals. IF is calculated by the following equation:

$$IF = \frac{\alpha}{\beta} \quad (1)$$

In which α represents the number of citations to the journal articles in other journals in the last two years β and represents the number of papers published in the journal in the last two years. This makes IF an important metric for assessing the importance and influence of the paper. (Mao *et al.*, 2018).

H-index was proposed by Jorge E. Hirsch in 2005 for scientific assessment of researchers' effectiveness (Hirsch, 2005). This index means that H articles published by a researcher have been cited at least H times. The advantage of this parameter is that it shows the number and impact of articles simultaneously. This index is presently regarded as the best criterion for people's scientific assessment (Ioannidis *et al.*, 2016).

The present research employed both IF and H-index to evaluate the quality of the studied parameters. They were derived from the Journal Citation Reports (JCR), SCImago Journal Rank (SJR), Scopus and Elsevier.

Social Network Analysis (SNA)

SNA is a method to study the critical points and their interrelations (Lee *et al.*, 2014). Visualization of Similarities (VOS) is an appropriate software to study these relations and provide a graphical representation of data (Gaviria-Marin *et al.*, 2019). The present study employed VOSviewer, which developed by "Nees Jan van Eck" and "Ludo Waltman" at "Leiden University", to portray and analyze the data (the cooperation network of authors, countries, and keywords). An important point that will be discussed is the clustering analysis of the keywords.

Keywords and Constraints on Data Collection

This article used the Scopus database. First, the impact indicators (IF, h-index, citescore and citations) implemented are better than those provided by Web of Science(WoS) and have fewer chances of being manipulated (Pranckutė, 2021). Also, the number of records recorded was higher in similar search circumstances, which helped the statistical universe. For the bibliometric analysis, all relevant papers were used from the Scopus database published in the time period of 2000-2020. Because Scopus is constantly updating its data, the data was extracted on December 14, 2020, and the results were stored.

To comprehensively study the topic of 'bioenergy', all likely keywords in the titles, abstracts, and keywords were explored and the results were filtered to provide a good sample. The keywords employed included 'bio mass power generation', 'bio-mass power generation', 'biomass power generation', 'bio mass energies', 'bio-mass energies', 'biomass energies', 'bio energies', 'bio-energies', 'bioenergies', 'bio-mass energy', 'bio mass energy', 'biomass energy', 'bio energy', 'bio-energy', and 'bioenergy'. The initial search gave 35,821 papers. They were confined to the years 2000-2020. To ensure precision and purposefulness, the subject area was limited to have articles at least in one of the categories of 'environmental science', 'agricultural and biological science', 'energy', 'chemical engineering', 'engineering', and or 'chemistry'. Finally, 24,524 papers were yielded. A significant portion of these publication (95.8%) was in English, which were classified into articles (71.39%), conference papers (10.15%), review papers (9.71%), book chapters (4.63%), and other documents (4.12%). The papers were confined to English articles, resulting in a total of 16,773 documents. Fig. 2 presents how the documents were filtered.

Based on Scopus, each paper may be placed in more than one subject category. Fig. 3 presents the number of papers published in each subject category according to the final data.

RESULTS AND DISCUSSION

First, the data analysis is presented in table 1 in a broad sense. The number of articles, authors, and citations had an ascending trend. The number of articles and authors have grown by 19 and 28 times in the last 20 years while their rates of growth started to grow in 2006. This ascending trend of the publication of articles, policies, and plans in these years shows the significance of and attention to renewable energies and bioenergy. Fig. 4 displays the trend of the publication of articles in the field of bioenergy the policies and regulations related to renewable energy over 2000-2020. These regulations, some of the important ones are illustrated in Fig. 4, had a significant effect on the growth of articles (IRENA, Global Renewable Energy Policies & Measures Database). Most of these policies have been enacted with a long-term vision. For example, the Paris Agreement commits the countries to keep the mean global temperature at less than 2°C above the pre-industrial temperature and attempts to limit temperature growth to 1.5°C above the pre-industrial level. This agreement and similar agreements have laid the ground for the growth of publications. The red chart also reflects the growth of the articles. Before 2005, the growth rate of articles fluctuated, while since 2006, with increasing attention to bioenergy, the growth rate has begun to stabilize, and articles have grown steadily.

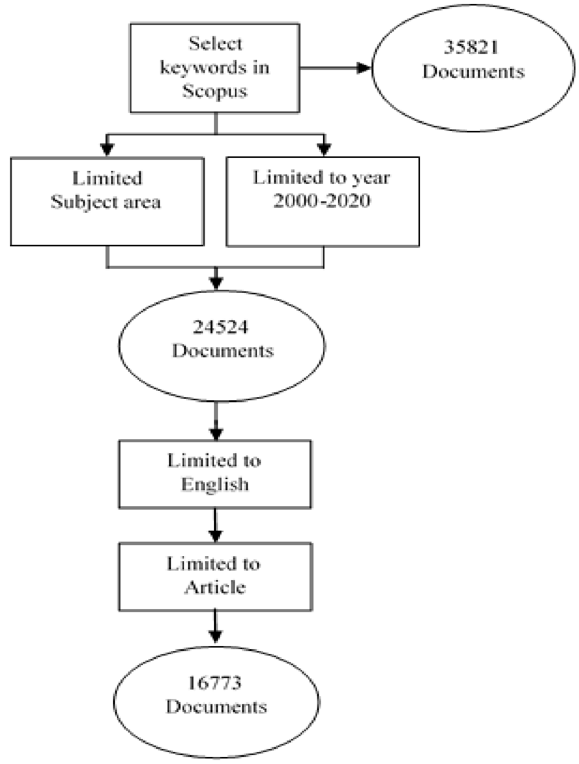

Fig. 2. The methodology process of the study

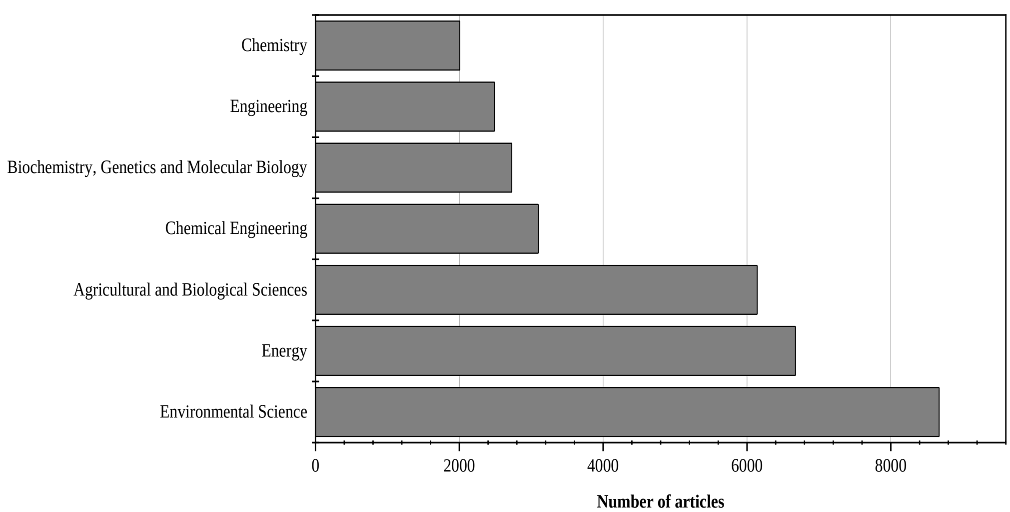

Fig. 3. Distribution of all publications among seven major research categories.

Table 1. Characteristics of periodical articles from 2000 to 2020.

Year	TP	AU	AU/TP	CI	CI/TP	NR	NR/TP
2000	96	268	2.79	5456	56.83	2720	28.33
2001	93	263	2.83	5683	61.11	2478	26.65
2002	121	329	2.72	10762	88.94	2868	23.70
2003	124	352	2.84	10678	86.11	3533	28.49
2004	94	286	3.04	7426	79.00	2783	29.61
2005	128	376	2.94	8134	63.55	3272	25.56
2006	190	554	2.92	9109	47.94	4619	24.31
2007	255	692	2.71	14422	56.56	7279	28.55
2008	375	1174	3.13	24277	64.74	10272	27.39
2009	511	1753	3.43	30192	59.08	15358	30.05
2010	671	2487	3.71	34437	51.32	21738	32.40
2011	942	3469	3.68	43692	46.38	32293	34.28
2012	1020	3813	3.74	38717	37.96	35430	34.73
2013	1149	4396	3.83	36906	32.12	40516	35.26
2014	1347	5141	3.82	36339	26.98	45759	33.97
2015	1482	5713	3.85	35214	23.76	52051	35.12
2016	1449	5750	3.97	28711	19.81	54068	37.31
2017	1593	6267	3.93	24948	15.66	61045	38.32
2018	1530	6222	4.07	16682	10.90	61783	4038
2019	1733	6826	3.94	11285	6.51	73054	42.15
2020	1870	7559	4.04	3493	1.87	85589	45.76

TP: The number of articles published in this year, AU: A total number of authors in the year, CI: A total number of`citations in the year, NR: Number of References.

Analysis of Countries/Territories and International Cooperation

Fig. 5 displays the distribution of countries/territories in article publication on bioenergy. The color by which the countries/territories are shown indicates the number of articles on bioenergy published by them from 2000 to 2020. The United States and China have published over 2000 articles over these 20 years and they are colored red. Also, the performance of some European countries, Brazil and India, has been favorable. The countries have regulated their policies and plans for the movement towards renewable energies. Most countries/territories are moving towards a carbon-neutral state. For example, Norway has set the scene to accomplish this goal by 2030 and Sweden by 2045, while the UK, France, Spain, and New Zealand are planning to accomplish it by 2050 (Welfle *et al.*, 2020).

In the Scopus database, 227 countries/territories have participated in article publication. The 20 leading countries/territories are listed in table 2. A look at the statistics shows that the United States accounts for a significant portion of articles published on biomass energy (27.94%) followed by China (16.06%), the UK (7.01%), Germany (6.67%), and India (5.36%) in the next ranks. In the next column, the number of articles per country is calculated using the country's population, with Finland having the most articles per capita on bioenergy.

Indeed, these Figs. represent the number of articles published by each country/territory independently or in cooperation with other countries/territories. For clarity, two extra columns are included in the table to distinguish the articles written by single country (SC) and the articles whose first author is from a certain country (FA). It was revealed that the United States has made great progress in this field, but China is growing to take the first place. The last column shows the H-index of the countries/territories in environmental engineering derived from the SJR website.

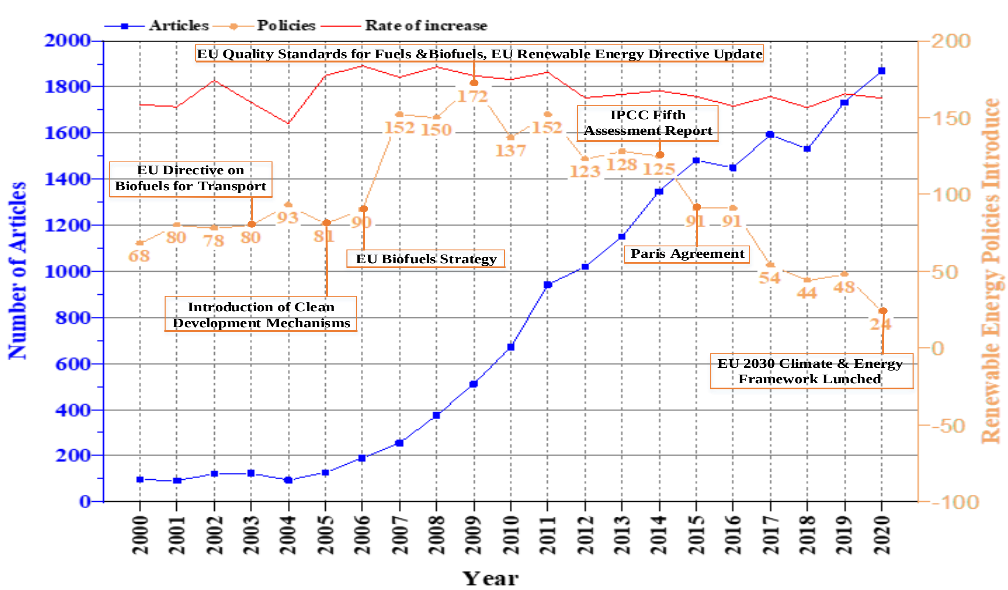

Fig. 4. The annual number of periodical articles and policies during 2000-2020.

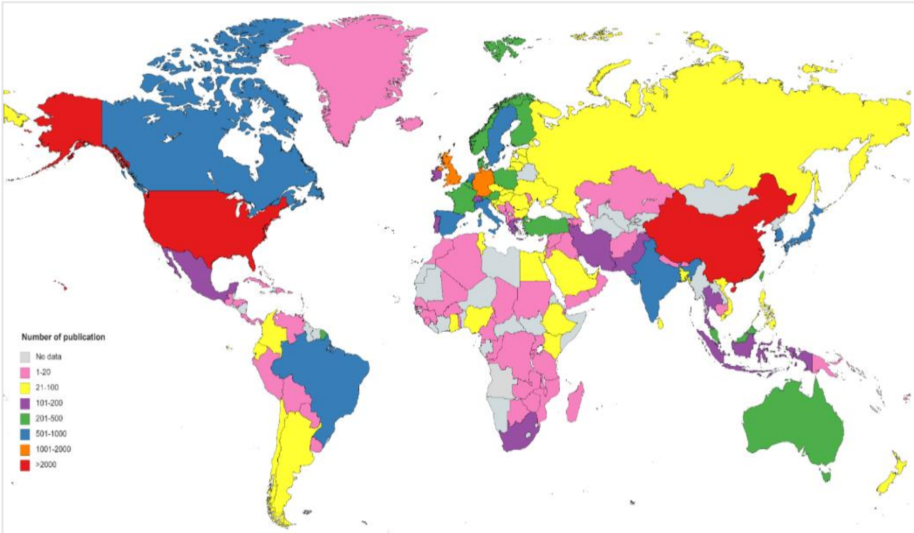

Fig. 5. Global distribution of periodical articles published (2000-2020).

Table 2. Top 20 most productive countries/territories in bioenergy research.

No	country/territory	Rec	(%)	(Rec/Pop)*E6	(Rank) SC		(Rank) FA		H-index (Environmental Engineering)
1	United States	4686	(27.94)	14.1	(1)	3056	(1)	3723	307
2	China	2694	(16.06)	1.8	(2)	1577	(2)	2290	236
3	United Kingdom	1175	(7.01)	17.3	(4)	540	(3)	798	215
4	Germany	1119	(6.67)	13.3	(5)	525	(5)	768	183
5	India	899	(5.36)	0.6	(3)	645	(4)	775	196
6	Italy	835	(4.98)	13.8	(7)	449	(7)	604	154
7	Brazil	761	(4.54)	3.5	(6)	490	(6)	643	218
8	Canada	750	(4.47)	19.8	(8)	378	(8)	517	136
9	Sweden	646	(3.85)	63.9	(9)	316	(9)	447	178
10	Spain	563	(3.36)	12.0	(13)	267	(10)	388	166
11	Netherland	560	(3.34)	32.6	(17)	164	(14)	328	142
12	Japan	526	(3.14)	4.1	(10)	285	(11)	367	171
13	South Korea	514	(3.06)	10.0	(11)	279	(13)	361	190
14	Australia	496	(2.96)	19.4	(15)	200	(15)	293	153
15	France	477	(2.84)	7.3	(14)	203	(16)	283	162
16	Finland	464	(2.77)	83.7	(12)	270	(12)	363	113
17	Denmark	344	(2.05)	59.3	(19)	132	(17)	216	143
18	Malaysia	289	(1.72)	8.9	(20)	125	(19)	208	108
19	Taiwan	277	(1.65)	11.6	(18)	149	(20)	192	125
20	Turkey	264	(1.57)	3.1	(16)	178	(18)	210	159

Rec: Records, Pop: Population, SC: Single-Country Articles, FA: First-Author Articles

The number of articles published by countries in different years is displayed in Fig. 6. The United States published 50 articles in 2000 whereas other countries concerned themselves with bioenergy to a much lesser extent in the same year. Countries have paid significant attention to this topic in 2006 and 2007 when the growth rate of articles was higher in the United States and China than the other countries. China had often seen upward growth, especially in 2017 and 2019, when it grew significantly.

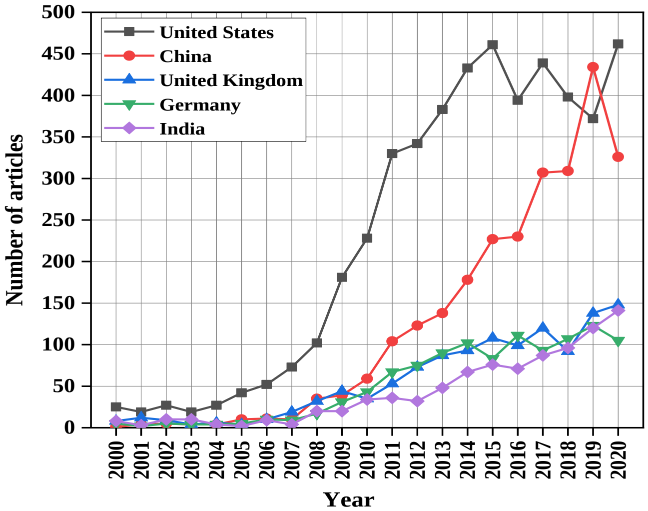

Fig. 6. Annual growth curve of the top five countries in the total number of periodical articles during 2000-2020.

Table 3 presents the collaborations between the 20 countries/territories that have contributed the most in publishing articles. The Link column shows the number of countries/territories that have collaborated with the target country. The United States had the greatest collaboration with other countries. Total Link Strength represents the number of articles published in cooperation with other countries/territories. The number of citations to the articles of each country/territory is given in another column. Since some articles were older and more cited, the data were normalized in the last column to solve this problem.

Fig. 7, which was derived from VOSviewer, displays the cooperation of countries/territories. The center countries of the graph (e.g., the United States and the UK) had greater cooperation than the others. On the other hand, the countries/territories to the margin have played less important roles in collaborations. Countries are classified into four colors: blue, green, red and yellow. The countries that have cooperated the most are in the same cluster. Additionally, the thickness of the connecting lines represents the number of articles published by the connected countries/territories in collaboration

Analysis of Research Institutions and Journals

Table 4 presents 10 research institutions with the most articles on bioenergy from 2000 to 2020. Over 16% of the articles were published by these institutions.

Table 5 lists 10 sponsorship programs that have published the most articles. Among them, China was the leading sponsor of articles with a share of 8.38%. The United States had the greatest number of sponsorship programs (four programs). This shows the investment of China in bioenergy

Table 3. Co-authorship links and strength in the top 20 countries/territories.

No	country/territory	Link	Total Link Strength	Citations	Norm. Citation Score
1	United states	86	1610	154896	5045.6023
2	Germany	77	587	30666	1207.95
3	United Kingdom	73	626	41498	1483.42
4	China	68	1115	60929	3363.165
5	Italy	67	383	23151	997.7749
6	France	63	270	15137	591.9103
7	Sweden	63	327	21016	662.7122
8	Canada	59	367	18798	719.6084
9	India	58	248	18468	982.2496
10	Australia	56	286	15487	642.7121
11	Spain	56	296	14311	633.306
12	Netherlands	55	391	24248	808.2463
13	Denmark	51	211	11768	546.4278
14	Japan	51	237	12083	484.5196
15	Finland	50	193	9965	360.1955
16	Norway	50	125	6482	242.7185
17	Austria	48	179	11369	366.0018
18	Belgium	48	161	9633	335.0129
19	Malaysia	46	163	6150	365.8708
20	South Korea	45	233	14888	625.4924

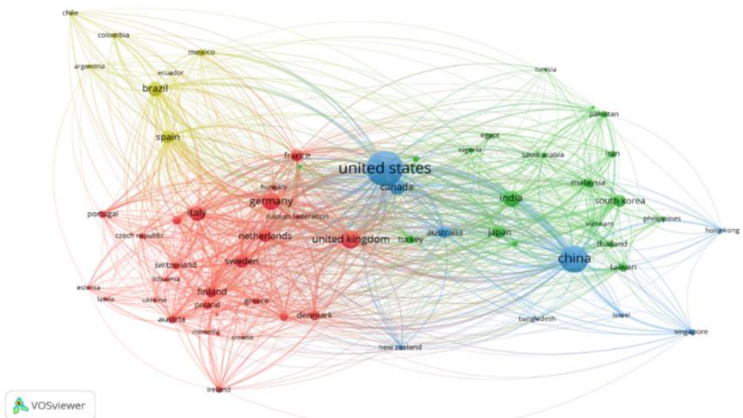

Fig. 7. Collaboration network between pioneer countries/territories in bioenergy research.

Table 4. Top 10 most productive institutions/government agency in bioenergy.

Rank	Institute	Country	Total Publication
1	Chinese Academy of Sciences	China	441
2	USDA Agricultural Research Service, Washington DC	United States	356
3	Ministry of Education China	China	298
4	University of Illinois at Urbana-Champaign	United States	376
5	Sveriges lantbruksuniversitet	Sweden	266
6	Universidade de Sao Paulo - USP	Brazil	223
7	United States Department of Agriculture	United States	219
8	Oak Ridge National Laboratory	United States	212
9	Wageningen University & Research	Netherlands	186
10	Michigan State University	United States	186

Table 5. Top 10 funding sponsors of bioenergy projects.

Rank	Sponsor Name	Country	Funded Articles
1	National Natural Science Foundation of China	China	1181
2	National Science Foundation	United States	423
3	U.S. Department of Energy	United States	367
4	Conselho Nacional de Desenvolvimento Científico e Tecnológico	Brazil	270
5	National Institute of Food and Agriculture	United States	268
6	European Commission	-	242
7	Fundamental Research Funds for the Central Universities	China	225
8	U.S. Department of Agriculture	United States	222
9	Seventh Framework Programme	-	218
10	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior	Brazil	214

Table 6 presents 15 journals with the most articles. "Biomass and Bioenergy" had the greatest number of articles followed by "Bioresource Technology" and "Gcb Bioenergy" in the second and third ranks, respectively. "Biosensors and Bioelectronics", which had the highest IF of 10.25, was ranked 12th.

Analysis of Authors

According to the Scopus data, a total of 55,507 authors have published articles in this field among whom 41,408 authors (74.59%) have published only one article. Fig. 8 shows the trend of authors' contributions in different years. The authors' contribution in writing articles has increased since 2005, and the growing trend in the number of authors is in line with the growing trend of articles in 2005.

Table 7 presents the top 20 bioenergy authors. "Bruce E. Logan" has published the highest number of articles. "Zhen (Jason) He" and "Peter Smith" were ranked second and third, respectively. The United States had seven researchers in this list, which was the highest number of authors from a country.

Table 6. Top 15 most productive journals in bioenergy.

Rank	Journal Title	IF	Country	TP (%)	Citescore
1	Biomass and Bioenergy	3.55	United Kingdom	1177(6.98)	6.6
2	Bioresource Technology	7.53	Netherland	1079(6.43)	12.8
3	Gcb Bioenergy	5.31	Germany	622(3.71)	10.7
4	Plos One	2.74	United State	351(2.09)	5.2
5	Bioenergy Research	2.19	United State	344(2.05)	17.32
6	Renewable Energy	6.27	United Kingdom	296(1.76)	11.2
7	Journal of Cleaner Production	7.24	Netherland	281(1.68)	10.9
8	Energy	6.08	United Kingdom	268(1.6)	9.9
9	Energy Policy	5.04	United Kingdom	264(1.57)	8.7
10	Applied Energy	8.84	United Kingdom	263(1.56)	16.4
11	Science of The Total Environment	6.55	Netherland	231(1.38)	8.6
12	Biosensors and Bioelectronics	10.25	United Kingdom	204(1.22)	17.6
13	Environmental Science and Technology	7.86	United State	184(1.09)	12.6
14	Industrial Crops and Products	4.24	Netherland	184(1.09)	6.9
15	Energies	2.7	Switzerland	176(1.05)	3.8

TP: Total Publication

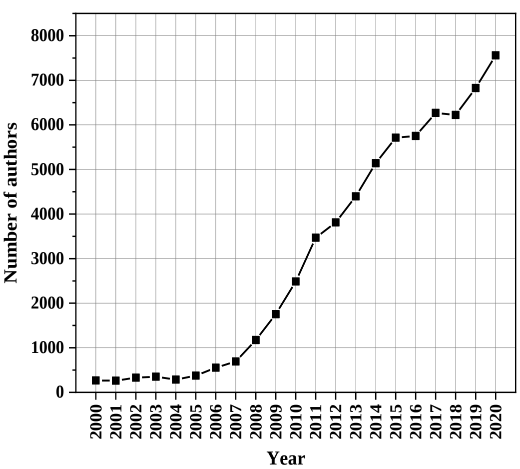

Fig. 8. Annual growth of authors during 2000-2020.

Analysis of Keywords

Keywords in a research study indicate the subject matters of the article. In addition to providing significant insight into the research process and attention in different years, they can be used to predict the future trends of research studies. Data and visualizations in this section have been derived from VOSviewer.

A total of 30,090 keywords were recorded, of which 388 keywords were repeated at least twenty times. These words are sometimes similar to each other. For example, 'LCA' and 'Life Cycle Assessment' represent the same concept, and also, some words have generic and are not worth studying. For instance, since 'bioenergy' was the central keyword of the search, it was repeated too many times. These keywords could ruin our analysis. After refinement, the number of keywords was decreased to 339.

Fig. 9 shows the links between the words. Each node represents a keyword, the size of which indicates the number of repetitions and the line between the keywords indicates the frequency of their links. Higher link strength thickens the linking line of the keywords. Based on this Fig., the keywords can be divided into five categories: red, green, blue, yellow, and purple.

Table 9 presents the five most repeated keywords of the clusters. The columns specify the frequency of repetition, beginning year, mean based on the weighted mean of each keyword in different years, and termination. In the following, each cluster is examined

Cluster 1 includes the keywords of 'biomass', 'renewable energy', 'sustainability', 'life cycle assessment', and 'climate change' among which 'biomass' has been most frequently repeated and has played a key role among the other keywords. The main focus of this category is on the assessment of biomass energies and the issues related to sustainability. In addition to these subjects, this category points to the policies of energy, land, and renewable energies, such as solar and wind energy. This cluster has the most keywords among all clusters.

Cluster 2 contains the keywords of 'switchgrass', 'miscanthus', 'biochar', 'energy crops', 'carbon sequestration', and so on. These keywords deal with the effect of the use of biomass energy on the absorption of pollutants like carbon and its impact on land and water. The keyword 'biochar' is the most recent keyword. Presently, biochar is used in energy storage and conversion, including oxygen, hydrogen, lithium/sodium-ion batteries, and so on (Liu *et al.*, 2019).

Cluster 3 is composed of the keywords of 'biofuel', 'pyrolysis', 'gasification', 'bioethanol', 'ethanol', and so on. These keywords focus on thermochemical processes for energy generation from biomass. This category has more distribution among the keywords, and 'biofuel' plays a pivotal role in it.

Cluster 4 is composed of 'microbial fuel cell', 'microalgae', 'wastewater treatment', 'bioelectricity', 'hydrogen', and so on. These keywords address bioelectrochemical methods of the electrical current generation. Indeed, they point to electricity generation by fuel cells using different methods.

Cluster 5 includes such keywords as 'anaerobic digestion', 'biogas', 'biodiesel', 'methane', and 'optimization'. They are related to anaerobic digesters, which are related to products and optimization of this process.

Based on clusters 3, 4 and 5, three general methods are considered for bioenergy production – i.e., thermal decomposition, microbial fuel cell, and anaerobic digestion. Among these methods, microbial fuel cells have been taken more seriously while the thermochemical method is most frequently shared with the other subjects.

Table 10 was developed to explore the link of the keywords in each cluster with one another and with other clusters. In this table, each keyword represents a Fig.. The Fig.s presented in table 10 represent the number of articles in which two keywords specified in the horizontal and vertical rows are registered simultaneously. In other words, greater Fig.s imply a stronger relationship between the two keywords. Furthermore, the boundary between each group is specified with smaller squares. The higher the sum of the Fig.s inside a square, the stronger the relationship between the two cluster is. For example, the sum of the Fig.s inside the square that shows clusters 1 and 3 is greater than that of the square that represents clusters 1 and 2, which means a stronger link of the keywords of clusters 1 and 3 versus those of clusters 1 and 2. Among the clusters, cluster 1 has 884 keywords shared with the other clusters, so it is the most linked to other clusters. This means that the main focus of bioenergy is on this group of keywords. A look at the relationship among the clusters, it is understood that 340 keywords are common among clusters 1 and 3, so these two clusters are most closely related to one another. This reflects a strong relationship of bioenergy with the thermochemical process and the sustainability of this process in the generation of biofuels. Among the 25 most repeated keywords, 'biomass' is the most commonly shared one followed by 'biogas' and 'biofuel'.

Table 7. Top 20 most productive authors of top cited articles in bioenergy research.

Rank	Author	Current Affiliation	Country	TP(%)	H-index
1	Bruce E Logan	Pennsylvania State University	United State	71(0.42)	125
2	Zhen (Jason) He	Washington University in St. Louis	United State	53(0.31)	56
3	Peter Smith	University of Aberdeen	United Kingdom	52(0.31)	125
4	S Venkata Mohan	Indian Institute of Chemical Technology	India	50(0.29)	77
5	André P.C. Faaij	University of Groningen	Netherland	47(0.28)	76
6	Martin Junginger	Utrecht University	Netherland	46(0.27)	40
7	Reinhart Ceulemans	University of Antwerp	Belgium	41(0.24)	66
8	Timothy A. Volk	SUNY College of Environmental Science and Forestry	United State	41(0.24)	31
9	Gail Taylor	University of California, Davis	United State	39(0.23)	44
10	Michael D. Casler	University of Wisconsin-Madison	United State	38(0.22)	36
11	Göran Berndes	Chalmers University of Technology	Sweden	37(0.22)	32
12	Iris Lewandowski	University of Hohenheim	Germany	37(0.22)	35
13	Irini Angelidaki	Technical University of Denmark	Denmark	35(0.20)	79
14	Daniela Thrän	Helmholtz Center for Environmental Research - UFZ	Germany	35(0.20)	20
15	Makarand Ghangrekar	Indian Institute of Technology Kharagpur	India	33(0.19)	34
16	Rob Mitchell	United States Department of Agriculture	United State	33(0.19)	27
17	John Clifton-Brown	Aberystwyth University	United Kingdom	32(0.19)	34
18	Astley Hastings	University of Aberdeen	United Kingdom	32(0.15)	25
19	Mauricio Roberto Cherubin	University of São Paulo	Brazil	31(0.145)	19
20	Gautam Sarath	USDA-ARS Research Molecular Biologist	United State	31(0.145)	48

Table 8. Top 20 most cited papers in bioenergy.

No.	Title	Journal*	Cited	Reference
1	Energy production from biomass (part 1): Overview of biomass	BT	2780	(McKendry, 2002a)
2	Renewable fuels and chemicals by thermal processing of biomass	CEJ	1272	(Bridgwater, 2003)
3	Global potential bioethanol production from wasted crops and crop residues	BB	1263	(Kim and Dale, 2004)
4	Energy production from biomass (part 2): Conversion technologies	BT	1248	(McKendry, 2002b)
5	Enzymatic biofuel cells for implantable and microscale devices	CR	1173	(Calabrese Barton *et al.*, 2004)
6	Simple chemical transformation of lignocellulosic biomass into furans for fuels and chemicals	JACS	1145	(Binder and Raines, 2009)
7	Sustainable biochar to mitigate global climate change	NC	1081	(Woolf *et al.*, 2010)
8	Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent - A critical review	BT	1047	(Mohan *et al.*, 2014)
9	The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe	BB	956	(Lewandowski *et al.*, 2003)
10	Biodiesel production from oils and fats with high free fatty acids	TASAE	926	Canakci and Van Gerpen,) (2001
11	Integration of layered redox proteins and conductive supports for bioelectronic applications	AC	915	(Willner and Katz, 2000)
12	Iron-based cathode catalyst with enhanced power density in polymer electrolyte membrane fuel cells	NC	891	(Proietti *et al.*, 2011)
13	The future of anaerobic digestion and biogas utilization	BT	879	(Holm-Nielsen *et al.*, 2009)
14	Energy production from biomass (part 3): Gasification technologies	BT	828	(McKendry, 2002c)
15	Operational parameters affecting the performance of a mediator-less microbial fuel cell	BB	783	(Gil *et al.*, 2003)
16	Total-factor energy efficiency of regions in China	EP	766	(Hu and Wang, 2006)
17	Comparison of dilute acid and ionic liquid pretreatment of switchgrass: Biomass recalcitrance, delignification and enzymatic saccharification	BT	760	(Li *et al.*, 2010)
18	Environmental life cycle comparison of algae to other bioenergy feedstocks	EST	758	(Clarens *et al.*, 2010)
19	Development of switchgrass (Panicum virgatum) as a bioenergy feedstock in the United States	BB	751	(McLaughlin and Kszos, 2005)
20	Biofuels sources, biofuel policy, biofuel economy and global biofuel projections	ECM	682	(Demirbas, 2008)

*BT: Bioresource Technology, CEJ: Chemical Engineering Journal, BB: Biomass and Bioenergy, CR: Chemical Reviews, JACS: Journal of the American Chemical Society, NC: Nature Communications, TASAE: Transactions of the American Society of Agricultural Engineers, AC: Angewandte Chemie, NC: Nature Communications, EP: Energy Policy, EST: Environmental Science and Technology, ECM: Energy Conversion and Management

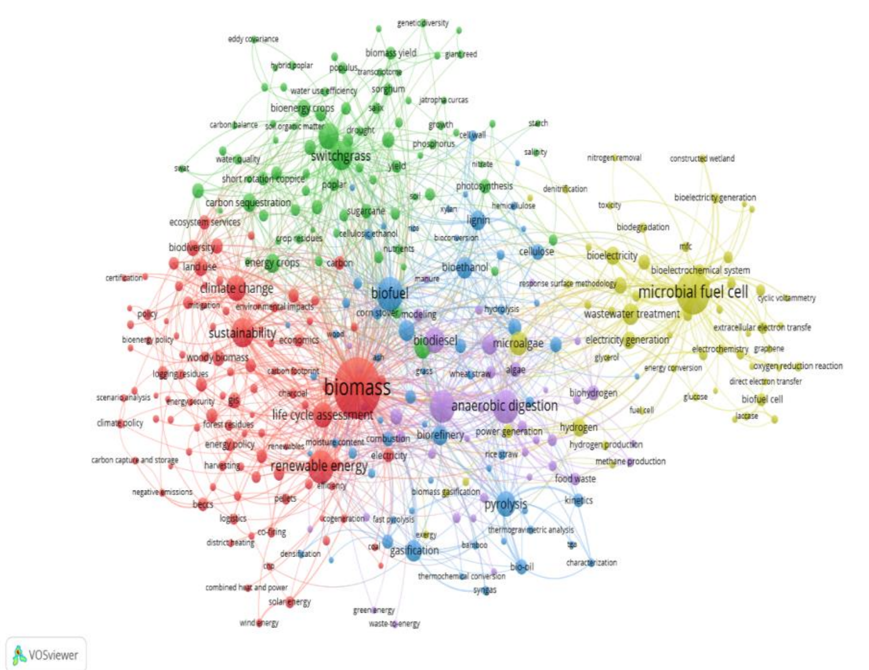

Fig. 9. Co-occurrence network of author keywords with at least twenty times of occurrence**.**

Table 9. Top 5 most-occurred author keywords of clusters 1-5.

	No.	Author Keyword	OC	BY	APY	EY
Cluster 1	1	Biomass	1475	1981	2014.00	2020
	2	Renewable energy	451	1985	2014.50	2020
	3	Sustainability	348	1989	2015.20	2020
	4	Life cycle assessment	260	2000	2015.29	2020
	5	Climate change	258	1992	2014.84	2020
Cluster 2	6	Switchgrass	348	1990	2014.65	2020
	7	Miscanthus	278	1997	2015.44	2020
	8	Biochar	178	2008	2016.44	2020
	9	Energy crops	151	1985	2012.91	2020
	10	Carbon sequestration	140	1993	2013.66	2020
Cluster 3	11	Biofuel	458	1991	2014.44	2020
	12	Pyrolysis	260	1979	2015.48	2020
	13	Gasification	188	1979	2012.99	2020
	14	Bioethanol	184	1998	2014.71	2020
	15	Ethanol	168	1981	2012.68	2020
Cluster 4	16	Microbial fuel cell	749	2000	2016.05	2020
	17	Microalgae	225	2001	2016.12	2020
	18	Wastewater treatment	188	1995	2015.97	2020
	19	Bioelectricity	133	1995	2015.91	2020
	20	Hydrogen	120	1983	2014.42	2020
Cluster 5	21	Anaerobic digestion	440	1982	2015.73	2020
	22	Biogas	425	1982	2015.44	2020
	23	Biodiesel	269	2000	2014.09	2020
	24	Methane	164	1983	2015.35	2020
	25	Optimization	103	1992	2015.74	2020

OC: Occurrence; BY: Beginning Year; APY: Average Publication Year; EY: Ending Year

Fig. 10 displays the details of the keywords and the period in which they have happened. In general, data have been divided into four timeframes. The first timeframe covers a five-year period while the others cover four-year periods. Over time, the discussion on bioenergy has been concentrated on certain subjects. This Fig. shows the trend of the development of each keyword over certain timeframes. The keywords of 'biomass' and 'renewable energy' have been considered from the very beginning so that they have been among the most repeated keywords in different timeframes. As keywords referring to sustainability and the assessment of environment and bioenergy, 'sustainability' and 'life cycle assessment' have always been growing in all timeframes. Some keywords have sharply grown in a certain timeframe, e.g., 'microbial fuel cell' in the fourth timeframe, reflect a significant amount of attention to this topic, which persisted in the fifth timeframe, too. The same happened to 'anaerobic digestion', 'biogas', and 'pyrolysis'. However, attention to some topics like 'biofuel,' 'switchgrass,' and 'ethanol' has not grown or even been decreased in different timeframes.

Table 10. Quantitative relations between 5 top index keywords of 5 major clusters.

		Cluster 1					Cluster 2					Cluster 3					Cluster 4					Cluster 5				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Cluster 1	1	-	77	49	28	21	45	38	11	29	8	69	50	72	22	25	-	33	-	8	14	19	36	18	7	22
	2	77	-	17	12	12	-	4	-	10	-	15	10	14	-	-	9	5	6	7	-	18	29	6	6	6
	3	49	17	-	11	12	12	-	-	5	4	19	-	-	-	5	-	6	-	-	-	7	9	9	-	4
	4	28	12	11	-	11	-	7	6	5	-	15	-	6	4	6	-	-	-	-	-	18	14	9	-	-
	5	21	12	12	11	-	11	6	5	-	9	8	-	-	-	-	-	-	-	-	-	-	4	-	-	-
Cluster 2	6	45	-	12	-	11	-	65	6	7	9	33	6	-	4	4	-	-	-	-	-	-	-	-	-	-
	7	38	4	-	7	6	65	-	-	17	5	19	-	-	4	-	-	-	-	-	-	5	4	-	-	-
	8	11	-	-	6	5	6	-	-	-	10	-	44	11	-	-	6	-	-	-	-	4	-	-	6	-
	9	29	10	5	5	-	7	17	-	-	-	5	-	-	-	-	-	-	-	-	-	6	11	-	-	-
	10	8	-	4	-	9	9	5	10	-	-	8	4	-	-	-	-	-	-	-	-	-	-	-	-	-
Cluster 3	11	69	15	19	15	8	33	19	-	5	8	-	12	-	18	18	-	28	5	4	6	4	10	25	8	4
	12	50	10	-	-	-	6	-	44	-	4	12	-	17	-	-	-	7	-	-	4	9	-	-	-	4
	13	72	14	-	6	-	-	-	11	-	-	-	17	-	-	-	-	-	-	-	10	9	4	4	-	-
	14	22	-	-	4	-	4	4	-	-	-	18	-	-	-	-	-	4	-	4	5	5	12	25	-	-
	15	25	-	5	6	-	4	-	-	-	-	18	-	-	-	-	-	-	-	-	7	-	4	9	9	-
Cluster 4	16	-	9	-	-	-	-	-	6	-	-	-	-	-	-	-	-	5	71	46	4	7	4	-	-	-
	17	33	5	6	-	-	-	-	-	-	-	28	7	-	4	-	5	-	10	-	-	23	14	27	6	-
	18	-	6	-	-	-	-	-	-	-	-	5	-	-	-	-	71	10	-	13	-	5	5	-	-	-
	19	8	7	-	-	-	-	-	-	-	-	4	-	-	4	-	46	-	13	-	-	-	-	-	-	-
	20	14	-	-	-	-	-	-	-	-	-	6	4	10	5	7	4	-	-	-	-	8	-	7	21	-
Cluster 5	21	19	18	7	18	-	-	5	4	6	-	4	9	9	5	-	7	23	5	-	8	-	139	-	43	-
	22	36	29	9	14	4	-	4	-	11	-	10	-	4	12	4	4	14	5	-	-	139	-	15	33	-
	23	18	6	9	9	-	-	-	-	-	-	25	-	4	25	9	-	27	-	-	7	-	15	-	6	-
	24	7	6	-	-	-	-	-	6	-	-	8	-	-	-	9	-	6	-	-	21	43	33	6	-	-
	25	22	6	4	-	-	-	-	-	-	-	4	4	-	-	-	-	-	-	-	-	-	-	-	-	-

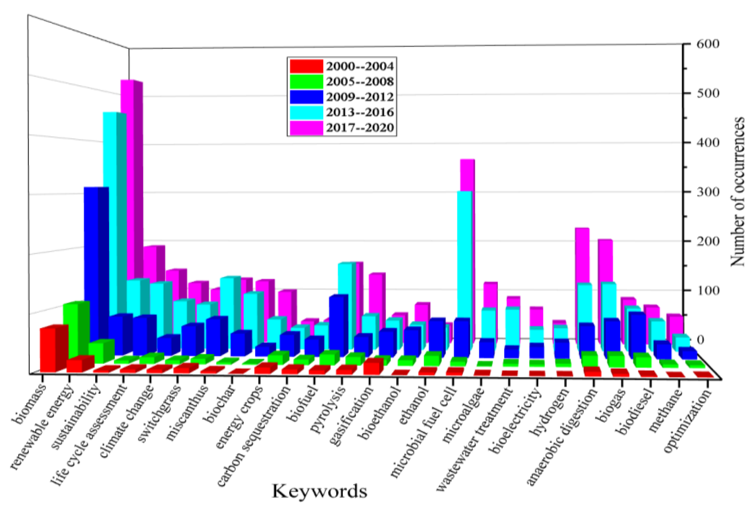

Fig. 10. Change tendencies of top 25 keywords over time during 2000-2020

To study the authors' data, the data about three top authors of each cluster are presented in table 11. "Bruce E. Logan", who is the top author among all authors, is just mentioned in cluster 4 in this table, reflecting his focus on microbial fuel cells. Also, "Martin Junginger" and "André P.C. Faaij" are among the three top authors in clusters 1 and 3. Their focus is on thermochemical processes. An interesting point in table 11 is that some universities have put their efforts only on a certain topic. For example, "Utrecht University" is working on 'sustainability' and 'life cycle assessment' in addition to thermochemical processes. Similarly, the "Technical University of Denmark" and "Pennsylvania State University" have placed their focus on 'anaerobic digestion' and 'microbial fuel cells', respectively.

Table 11. Top 3 productive authors of clusters 1-5.

Cluster	Rank	Name	Affiliation
Cluster 1. Biomass / Renewable energy			
	1	Timothy A. Volk	SUNY College of Environmental Science and Forestry
	2	Martin Junginger	Utrecht University
	3	André P.C. Faaij	University of Groningen
Cluster 2. Switchgrass / Miscanthus			
	1	Peter Smith	University of Aberdeen
	2	John Clifton-Brown	Aberystwyth University
	3	Astley Hastings	University of Aberdeen
Cluster 3. Biofuel / Pyrolysis			
	1	Martin Junginger	Utrecht University
	2	André P.C. Faaij	University of Groningen
	3	Akwasi A. Boateng	United States Department of Agriculture
Cluster 4. Microbial fuel cell / Microalgae			
	1	Bruce E Logan	Pennsylvania State University
	2	Zhen (Jason) He	Washington University in St. Louis
	3	S Venkata Mohan	Indian Institute of Chemical Technology
Cluster 5. Anaerobic digestion / Biogas			
	1	Irini Angelidaki	Technical University of Denmark
	2	Ivet Ferrer	Polytechnic University of Catalonia
	3	Michael Wachendorf	University of Kassel

Research Trend

The human need for energy consumption and environmental degradation are among important issues to consider. In developing countries, e.g., the Asian and African countries, population growth is a major factor involved in energy consumption. The growing economies, e.g., China and India, also contribute to energy consumption greatly. It is projected that global energy consumption will grow by 1.5-3 times by 2050 (Black *et al.*, 2015; Dudley, 2019; Shahsavari and Akbari, 2018). Renewable energies, including bioenergy resources, are more reliable sources than fossil fuels.

A proper way to identify hot topics is to consider the time period from the emergence of a keyword until its termination. Fig. 11 is an example of the link of keywords in which the yellow color represents more novel topics and as one approaches the blue side, the topics become older. Newer topics are among clusters 4 and 5. For example, one can refer to the keywords of 'microbial fuel cell' and 'anaerobic digestion', which are the most frequently mentioned keywords in their own cluster and point to recent interesting topics. On the other hand, some topics are today interested to a lesser extent (e.g., 'gasification'). The measurement of the average publication year in each cluster reveals that clusters 1-5 were interested in 2014,37, 2014,85, 2014,86, 2015,53, and 2015,88, respectively. A glance at the table that presents the termination of each keyword reveals that none of the topics has ever been stopped completely.

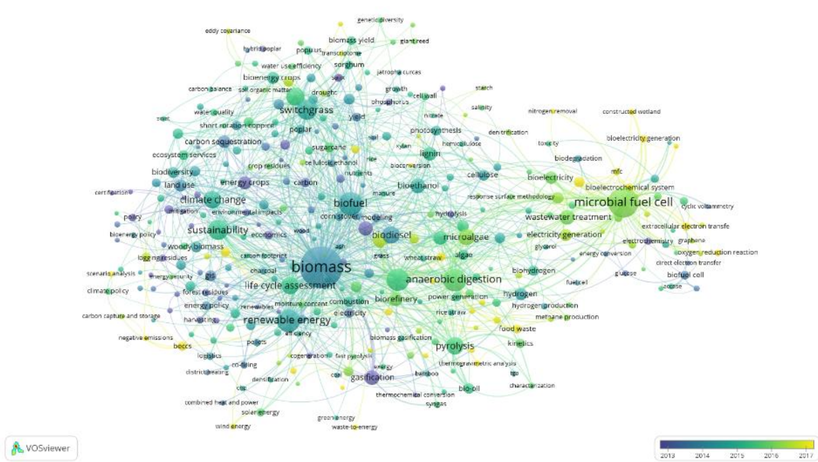

Fig. 11. Overlay network of author keywords with at least 20 times of occurrence.

Fuel cells are a proper replacement for fossil fuels for electricity production. The main constraints of this method are the limited capability of electricity production and the high cost of electrodes, so they are not currently a good method in a large scale. However, the progress in electrodes and the research in this field will make it possible to accomplish this technology at an industrial scale (Slate *et al.*, 2019). 'Anaerobic digestion' is a method in which organic matters are degraded by microorganisms in the absence of oxygen and methane-rich biogas is produced. This method has a promising perspective for the production of rich biogas (Zhang *et al.*, 2019). It is crucial to optimize various parameters of biomass production and exploitation to reduce costs and greenhouse gas emissions (Perea-Moreno *et al.*, 2019). This is a good reason for attention to such keywords as 'microalgae' and 'switchgrass'. Bioenergy production influences the environment differently depending on the region. Bioenergy production can be detrimental to the water, soil, and ecology of the regions (Wu *et al.*, 2018). It is important to identify strategies that affect the environment and costs. These strategies can be assessed by LCA (Rebello *et al.*, 2020). Therefore, this topic can be regarded as a topic that will be welcomed in future research and can supplement other topics.

CONCLUSIONS

The characteristics of the articles on bioenergy published from 2000 to 2020 were explored by a bibliometric method using Scopus database. A total of 16773 articles were reviewed and the main conclusions were obtained as follows:

- The number of articles has grown by 19 times from 97 articles in 2000 to 1870 articles in 2020.
- Articles have engaged 55,507 authors, 227 countries, and 25 subject areas, reflecting the significance of the subject.
- Although the United States has produced the most articles, China has seen the greatest growth, with its articles increasing by 18 times in 2020 versus the first five years (2000-2004).
- The cooperation of the countries is effective in the progress of this renewable energy. The greatest cooperation has been between the United States and China, whereas Germany and the UK cooperate with other countries.
- Among the institutions, the "Chinese Academy of Sciences" has published the most articles and the "National Natural Science Foundation of China" has been the leading funding sponsor.

Research is moving towards comprehensiveness and the integration of subject areas, e.g., the environment and engineering, with other topics. The environmental and economic problems will lead countries towards bioenergy production, which will create the challenge of the production of suitable biomass although extensive regulations and policies have been approved about renewable energies with a long-term vision. Carbon uptake and climate change are important environmental issues that have drawn interest. 'Biochar', which can store and convert energy, is a new topic among bioenergy. Extensive research has dealt with 'biochar', making it a hot topic. Also, bioenergy production methods are moving towards the alleviation of environmental impacts, the improvement of social benefits (the development and welfare of rural communities, the enhancement of energy security), and the conversion of bioenergy into an economic choice. Three methods of 'thermal decomposition', 'microbial fuel cell', and 'anaerobic digestion' have been considered for bioenergy production. Research is moving towards energy optimization by these methods. The integration of environmental, social, and economic impacts with bioenergy production has become a concern of researchers, and LCA has become a tool for this assessment and sustainability. Each method may have pros and cons depending on the regional and market conditions of the countries. By assessments, it will be rendered possible to develop this technology at a faster pace.

DECLARATIONS

Declaration of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Availability Data and Materials

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