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RESEARCH ARTICLE

# Bioenergy research under climate change: a bibliometric analysis from a country perspective

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**Abstract**
Development of bioenergy will be a key component for meeting increasing energy demands while mitigating global warming. With the intent of identifying current topics of major interest and development of research directions in the field of bioenergy under climate change, we conducted a bibliometric analysis and network analysis from a country perspective based on 3050 articles published since 1999 derived from the Scopus database. The results indicated that USA, UK, and Germany led other countries in terms of number of publications (1006, 366, and 280 articles, respectively) and *h*-index (greater than 50) in this research area. The USA has also produced a large number of articles in highly respected journals. Compared with developed countries, some developing countries (e.g., China, India, and Brazil) have a larger proportion of publications which are cited less than 10 times and researchers who have academic age of 1 year. The number of publications dealing with some of these research topics coming from developing countries has lagged behind the number of similar publications coming from developed countries. In spite of this, research on sustainable energy systems is still needed for developing countries to further establish feasible systems that can effectively promote global economic development and strengthen climate change mitigation efforts.

**Keywords** Bioenergy · Climate change · Bibliometric analysis · Network analysis · Country perspective

## Introduction

For decades, climate change (including increasing temperatures, changing precipitation patterns, and increasing number and severity of extreme weather events) is mainly driven by anthropogenic greenhouse gas (GHG) emissions and has had significant effects on energy production, transmission, and consumption (Peters et al. 2017; Jackson et al. 2019). Mitigating detrimental GHG emissions and meeting increasing energy demands are becoming two of the most important worldwide challenges (Xu and Boeing 2013). The development of economically rational, sustainable, and renewable energy sources that can replace conventional fossil fuels and play a role in mitigating climate change has become an urgent goal (Bessou et al. 2011). Among various alternatives, bioenergy has caught worldwide attention and has become a well-established research topic due to its potential to provide liquid fuels for transportation and reduce GHG emissions (Bauen et al. 2009).

Of the many bioenergy definitions, the US Department of Energy defines bioenergy as "useful, renewable energy produced from organic matter," whereas Food and Agriculture Organization of the United Nations defines bioenergy as "energy from biofuels." As fuels produced directly or indirectly from biomass, biofuels can be converted to bioenergy and classified into four generations depending on their biomass feedstock (Dutta et al. 2014; Mat Aron et al. 2020): first-generation biofuel is retained from edible starch- and sugar-based feedstocks and vegetable oil; second-generation biofuel

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is produced from lignocellulose feedstocks including agricultural by-products and wastes, forest residues, and woody biomass that require no specific quality of land area, water supply, and fertilizers for cultivation; third-generation biofuel is extracted from algae (microalgae and macroalgae) because of their high growth rate and low requirement of arable land; and fourth-generation biofuel focuses on the genetic modification of the microalgae which can capture large amounts of carbon dioxide ($CO_2$) for photosynthesis and enhance the production of biofuel.

Although recent published papers cover many different perspectives of bioenergy or biofuels, it is of great importance to identify the current progress and future development of bioenergy research as related to climate change (Yu and Meng 2018). Bibliometric analysis can serve as an innovative and objective way of connecting various aspects of scientific investigations in order to reveal research trends in various disciplines of science, including the research field of bioenergy (e.g., Li et al. 2020; Zhang and Yu 2020a). Such analysis includes a series of quantitative and visual methodologies to analyze the patterns and dynamics of publications, and to interpret the scientific trends within a specific topic (Pritchar 1969; Zhang and Yu 2020a). In the area of bioenergy, some studies used bibliometric analysis to map research activities and tendencies related to global bioenergy research (Xu and Boeing 2013; Mao et al. 2018). These studies identify the most productive countries/regions in this field but do not comprehensively explore the differences of bibliometric characters and research tendencies between countries. Jackson et al. (2019) indicated that coal use in developing countries (e.g., China and India) comprising two-thirds of their fossil $CO_2$ emissions and oil and natural gas consumption in developed countries (e.g., USA and European Union countries) were both expected to play the leading roles in fossil $CO_2$ emissions. Different countries adopted different energy structures to support economic development and cope with climate change. Regarding this, there is still an urgent need to carry out studies focused on the status and characteristics of bioenergy research under climate change conditions from a country perspective.

To fill this research gap, this paper (1) applies the bibliometric method to summarize the status and development trends of bioenergy research under climate change using the general statistics of academic performance and major research areas, as well as productive institutions and journals from a country perspective, (2) analyzes the distributions of citation frequency and researcher characteristics (author type and academic age) of productive countries/regions using bibliometric analysis, and (3) integrates network analysis and cluster analysis methods to identify the features of academic collaboration between different countries/regions and to discover research topics of major interest by surveying the high frequency author keywords from articles published between 1999 and 2018. In addition, potential research directions are provided according to the results of this study. The overall objective of this paper is to describe the status of studies in the field of bioenergy under climate change from a country perspective, offering a fresh perspective and suggestions to researchers and policymakers for future research and policy formulation.

## Data and methods

Data were collected from the Scopus database (https://www.scopus.com/search/form.uri?display=basic). Scopus is one of the most influential databases offering standardized and high-quality academic publication information. The retrieval date was March 14, 2019. The keywords of "climate change" and "bioenergy" were selected, and a total of 3050 English language papers (articles or reviews) published from 1999 to 2018 were obtained with the topic field search (TS) of article title, abstract, and keywords:

TS = (("climat* W/3 chang*") AND ("biomass W/3 energ*" OR "bioenerg*" OR "biofuel*")).

These 3050 articles were analyzed on various aspects of the publication characteristics such as countries, institutions, authors, and keywords. Indicators which represented scientific production and impact (e.g., the number of publications, citations, and *h*-index for each country/institution) were used in this study. The *h*-index is used as a measure of academic achievement (Hirsch 2005) and is defined as the highest number of articles of an author (or institutions, countries/regions) with at least *h* citations each. The migration of the center of gravity for publications and citations was analyzed to assess the overall variation in this scientific field, and was calculated according to the method reported by Zhang et al. (2017). For investigating the distributions of author type and academic age of productive countries/regions, this study defined the academic age as "span in years… between the first and the most recent article" (Milojevic 2012). This study also classified all of the authors into three types in terms of his/her ultimate authorship role (Milojevic et al. 2018): corresponding authors (CA; authors who had ever served as the authors for correspondence), first authors (FA; authors who were listed as lead authors but had never served as corresponding authors), and supporting authors (SA; authors who had never had the role of corresponding author or first author in their careers). This study adopted an author name disambiguation method which assigned a unique number to each author (Scopus Author Identifier) provided by Scopus to obtain accurate information for authors (the Scopus database did not provide the information of author full name) (Zhang and Yu 2020b). Manual disambiguation of Scopus author profiles based on information of researchers (e.g., affiliation, subject area, and co-author information) was also conducted to avoid errors produced in the above process (Zhang and Yu 2020b). The academic cooperation among countries/regions and co-occurrence of author keywords were presented by co-occurrence networks. Besides, the frequency of author keywords was also investigated using heat maps. The definition of "top" or "productive" in this study was based on the total number of related publications.

R (version 3.5.1; Statistics Department of the University of Auckland, https://www.r-project.org/) and VOSviewer (version 1.6.10; http://www.vosviewer.com/; van Eck and Waltman 2010) were used to conduct bibliometric analysis, network analysis, and cluster analysis. The R packages used in this study mainly contained "bibliometrix," "stringr," "rgeos," and "rworldmap" (Aria and Cuccurullo 2017).

## Results and discussion

### General statistics

Table 1 shows the statistical characteristics of articles published from 1999 to 2018. The number of articles published showed a slight fluctuation around 20 before 2005, and then steadily increased, reaching 320 in 2018. The number of citations per publication reached more than 100 from 2004 to 2006 as a result of the publication of some excellent articles during this period (see Table S1 in Supplementary Information for more details). The number of authors, institutions, countries, and references per publication began to increase dramatically during the past decade. The number of journals continuously increased and remained stable from 2014. Only the number of pages per publication showed an overall declining trend during this 20-year period, with the highest value of 21.5 occurring in 2003 and the lowest value of 9.8 occurring in 2018. These data indicate that the research in this field had been expanding during the past 10 years and also that academic cooperation has been increasing and more active. Xu and Boeing (2013) conducted an investigation on research activities and tendencies of global biofuel. They indicated that biofuels research became more developing and collaborative according to increasing annual output of publications and average number of authors per publications.

**Table 1** General statistics of selected bioenergy/biofuel publications related to climate change published from 1999 to 2018

| Year | TP | TC | TC/TP | TA | TA/TP | TJ | TP/TJ | TCO | TCO/TP | TI | TI/TP | TPG | TPG/TP | TR | TR/TP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1999 | 5 | 108 | 21.6 | 7 | 1.4 | 5 | 1 | 3 | 1.2 | 5 | 1.2 | 57 | 11.4 | 129 | 25.8 |
| 2000 | 16 | 957 | 59.8 | 37 | 3.3 | 14 | 1.1 | 7 | 1.6 | 18 | 1.5 | 248 | 15.5 | 810 | 50.6 |
| 2001 | 8 | 199 | 24.9 | 26 | 3.3 | 7 | 1.1 | 5 | 2.3 | 9 | 1.5 | 170 | 21.3 | 373 | 46.6 |
| 2002 | 18 | 1247 | 69.3 | 49 | 2.9 | 14 | 1.3 | 11 | 1.4 | 19 | 1.3 | 277 | 15.4 | 474 | 26.3 |
| 2003 | 17 | 1377 | 81.0 | 41 | 2.6 | 14 | 1.2 | 15 | 1.9 | 19 | 1.4 | 365 | 21.5 | 678 | 39.9 |
| 2004 | 30 | 3796 | 126.5 | 69 | 2.4 | 25 | 1.2 | 14 | 1.7 | 34 | 1.5 | 400 | 13.3 | 1265 | 42.2 |
| 2005 | 21 | 3080 | 146.7 | 76 | 3.9 | 17 | 1.2 | 15 | 2.6 | 44 | 2.5 | 245 | 11.7 | 829 | 39.5 |
| 2006 | 46 | 8607 | 187.1 | 137 | 3.1 | 35 | 1.3 | 21 | 2.1 | 69 | 2.0 | 525 | 11.4 | 1717 | 37.3 |
| 2007 | 99 | 4790 | 48.4 | 248 | 2.8 | 74 | 1.3 | 30 | 2.3 | 140 | 2.1 | 1045 | 10.6 | 3503 | 35.4 |
| 2008 | 117 | 11522 | 98.5 | 325 | 2.9 | 93 | 1.3 | 29 | 2.1 | 160 | 1.9 | 1348 | 11.5 | 5166 | 44.2 |
| 2009 | 177 | 12503 | 70.6 | 598 | 3.5 | 126 | 1.4 | 45 | 2.2 | 255 | 2.1 | 2576 | 14.6 | 9216 | 52.1 |
| 2010 | 208 | 14149 | 68.0 | 686 | 3.4 | 147 | 1.4 | 44 | 2.4 | 332 | 2.3 | 2599 | 12.5 | 12264 | 59.0 |
| 2011 | 243 | 11630 | 47.9 | 814 | 3.5 | 150 | 1.6 | 49 | 2.4 | 394 | 2.3 | 2991 | 12.3 | 14215 | 58.5 |
| 2012 | 248 | 9534 | 38.4 | 1007 | 4.3 | 166 | 1.5 | 57 | 2.9 | 493 | 2.8 | 2953 | 11.9 | 15178 | 61.2 |
| 2013 | 244 | 9097 | 37.3 | 963 | 4.3 | 153 | 1.6 | 49 | 2.8 | 430 | 2.6 | 3046 | 12.5 | 16081 | 65.9 |
| 2014 | 299 | 7021 | 23.5 | 1271 | 4.7 | 181 | 1.7 | 59 | 2.9 | 534 | 2.7 | 3382 | 11.3 | 18834 | 63.0 |
| 2015 | 301 | 6541 | 21.7 | 1209 | 4.2 | 171 | 1.8 | 51 | 2.8 | 560 | 2.7 | 3506 | 11.6 | 21426 | 71.2 |
| 2016 | 303 | 3808 | 12.6 | 1294 | 4.6 | 176 | 1.7 | 67 | 3.0 | 576 | 2.8 | 3298 | 10.9 | 19472 | 64.3 |
| 2017 | 330 | 2922 | 8.9 | 1554 | 5.1 | 173 | 1.9 | 69 | 3.2 | 667 | 3.0 | 3548 | 10.8 | 24992 | 75.7 |
| 2018 | 320 | 906 | 2.8 | 1459 | 5.0 | 170 | 1.9 | 62 | 3.2 | 668 | 3.0 | 3133 | 9.8 | 24632 | 77.0 |

*TP* total number of publications, *TC* total number of citations, *TC/TP* citations per publication, *TA* total number of authors, *TA/TP* authors per publication, *TJ* total number of journals, *TP/TJ* publications per journal, *TCO* total number of countries/regions, *TCO/TP* countries/regions per publication, *TI* total number of institutions, *TI/TP* institutions per publication, *TPG* total number of pages, *TPG/TP* pages per publication, *TR* total number of references, TR/TP references per publication

## National analysis

During these past 20 years, 81 different countries have published articles on the topic of bioenergy under climate change. The publication statistics for the 20 countries/regions most productive in publishing articles in this research area are shown in Table 2. Similar to the results derived from previous publication (e.g., Xu and Boeing 2013; Mao et al. 2018), USA published the most articles (1006) and achieved the most citations (58,793). USA also had by far the highest *h*-index (106), the number of highly cited articles (111 articles with more than 100 citations), and the highest numbers of institutions (700) and authors (2679) conducting research in this field. USA, Germany, and UK cooperated the most with other countries. Xu and Boeing (2013) indicated that USA headed biofuel research by the article ranking of countries with the highest citations and *h*-index, and collaborated mainly with other productive countries (e.g., UK, Germany). Based on 9514 literature reports in the field of biomass energy and environment in Web of Science from 1998 to 2017, Mao et al. (2018) also showed that USA was ranked first in the respects of the total number of articles and the *h*-index. Chen and Ho (2015) identified that the USA produced 49% of all highly cited articles (articles with at least 100 citations) and contributed the most single, internationally collaborative, first-author, and corresponding-author articles in the research field of biomass. Switzerland, Netherlands, and UK were the countries that had the highest citations per article, indicating the outstanding performance of the European region. Regarding the citations per article on the topic of biomass energy shown in Yu and Meng (2018), the Netherlands ranked first and it was followed by the UK. Most of these 20 countries had more papers published with international collaboration than papers published with only input from within their own country (SCP vs MCP). There was little difference between SCP and MCP values for both Sweden (79 vs 77) and Brazil (52 vs 53). Taking Brazil as example, it is the largest sugarcane producer and has significant investment in bioethanol production and biofuel research (Creutzig et al. 2015; IRENA 2020). These led Brazil to have the ability to balance between independent

**Table 2** General statistics for the 20 most productive countries/regions regarding the number of publications from 1999 to 2018 dealing with bioenergy under climate change

| Country | TP | TC | TC/TP | NHCP | SCP | MCP | FCP | CCP | *h*-index | SY | EY | NCC | TA | TI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| USA | 1006 | 58793 | 58.4 | 111 | 619 | 387 | 787 | 774 | 106 | 1999 | 2018 | 73 | 2679 | 700 |
| UK | 366 | 26019 | 71.1 | 53 | 172 | 194 | 241 | 243 | 73 | 2000 | 2018 | 49 | 824 | 190 |
| Germany | 280 | 11913 | 42.5 | 24 | 107 | 173 | 181 | 164 | 51 | 2000 | 2018 | 54 | 632 | 219 |
| Canada | 213 | 6585 | 30.9 | 14 | 91 | 122 | 124 | 148 | 44 | 1999 | 2018 | 37 | 421 | 135 |
| *China* | *172* | *8456* | *49.2* | *8* | *73* | *99* | *110* | *111* | *33* | *2006* | *2018* | *40* | *520* | *150* |
| Australia | 165 | 9313 | 56.4 | 19 | 71 | 94 | 97 | 100 | 44 | 2003 | 2018 | 41 | 338 | 111 |
| Netherlands | 162 | 12374 | 76.4 | 23 | 51 | 111 | 86 | 92 | 50 | 2001 | 2018 | 40 | 299 | 65 |
| Sweden | 156 | 7031 | 45.1 | 15 | 79 | 77 | 110 | 105 | 38 | 2002 | 2018 | 40 | 259 | 71 |
| Italy | 150 | 4968 | 33.1 | 11 | 62 | 88 | 94 | 100 | 36 | 2003 | 2018 | 43 | 362 | 109 |
| France | 132 | 5073 | 38.4 | 9 | 49 | 83 | 69 | 72 | 36 | 2003 | 2018 | 41 | 289 | 93 |
| *India* | *132* | *4859* | *36.8* | *6* | *83* | *49* | *106* | *97* | *28* | *2002* | *2018* | *31* | *331* | *123* |
| Finland | 123 | 3685 | 30.0 | 7 | 69 | 54 | 93 | 89 | 28 | 2001 | 2018 | 36 | 252 | 52 |
| Spain | 112 | 4006 | 35.8 | 8 | 33 | 79 | 56 | 66 | 26 | 2005 | 2018 | 47 | 239 | 67 |
| *Brazil* | *105* | *5102* | *48.6* | *7* | *52* | *53* | *76* | *74* | *25* | *2004* | *2018* | *32* | *307* | *86* |
| Austria | 93 | 5862 | 63.0 | 12 | 18 | 75 | 45 | 43 | 37 | 2006 | 2018 | 34 | 134 | 38 |
| Norway | 87 | 5987 | 68.8 | 11 | 40 | 47 | 55 | 51 | 32 | 2002 | 2018 | 31 | 116 | 37 |
| Japan | 78 | 4695 | 60.2 | 9 | 26 | 52 | 40 | 48 | 32 | 2000 | 2018 | 40 | 160 | 59 |
| Denmark | 77 | 3177 | 41.3 | 10 | 26 | 51 | 40 | 40 | 25 | 2004 | 2018 | 39 | 146 | 30 |
| Switzerland | 71 | 6501 | 91.6 | 13 | 17 | 54 | 34 | 30 | 29 | 2004 | 2018 | 37 | 107 | 30 |
| Belgium | 66 | 4154 | 62.9 | 9 | 20 | 46 | 33 | 31 | 25 | 2004 | 2018 | 34 | 118 | 46 |
| World | 3050 | 113794 | 37.3 | 219 | 2163 | 887 | - | - | 144 | 1999 | 2018 | - | 9753 | 3238 |

Developing countries are italicized

*TP* total number of publications, *TC* total number of citations, *TC/TP* citations per publication, *NHCP* number of highly cited publications (≥ 100 citations), *SCP* number of single-country publications, *MCP* number of multi-country publications, *FCP* number of first country publications, *CCP* number of corresponding country publications, *SY* starting publication years, *EY* ending publication year, *NCC* number of collaborative countries/regions, *TA* total number of authors, *TI* total number of institutions research and international cooperative research. Only USA and India showed a clear preference for publishing without international collaboration as shown in the much greater values of SCP than MCP for those two countries shown in Table 2. Xu and Boeing (2013) also identified USA and India contributed a great quantity of single-country articles (2298 and 186, respectively) than internationally collaborative articles (711 and 90, respectively) in the field of biofuel.

Figure 1 shows the bubble map of the geographical distribution of publications and the centroid migration over time. Bubble colors represent the total citations of a country; bubble size represents the number of publications published by a country. The center of gravity for both numbers of publications and citations migrated slightly eastward over the four periods. The center of gravity for numbers of publications migrated from 36.1° N, 68.0° W in the first period (1999–2003) to 40.6° N, 61.7° W in the fourth period (2014–2018), with a total migration distance of 737.7 km. The center of gravity for citations migrated from 43.2° N, 91.1° W in the first period to 39.9° N, 64.7° W in the fourth period, with a total migration distance of 2220.5 km. The center of gravity for number of publications was far apart from the center of gravity for citations during the first period. This was because USA produced nearly half of the citations of the world (47.8%) from only a handful of publications (29.7% of the publications in the world) during the first period. In summary, although publications from Asian countries and Australia have increased quickly in recent years, publications from USA, Canada, and developed European countries have dominated the research in this field because of their longer expertise than developing countries.

The proportion of papers that were cited more than 100 times (Fig. 2) was higher for some European countries (e.g., Switzerland, Belgium, Denmark, Norway, Netherlands, and UK). Some developing countries, such as India, China, and Brazil, produced a larger proportion of publications which were cited less than 10 times, with values of 54.5%, 54.1%, and 55.2%, respectively. However, any exploration and research attempts regarding bioenergy research from developing countries are worthy endeavors, and the development of scientific research for developing countries will promote scientific research progress for countries in this classification.

Figure 3 shows the cooperation network for the top 58 publication-producing countries/regions for countries that have published more than five articles. A wide range of cooperation was represented between the productive countries/regions. Countries on the same continent were more closely connected. USA played a very important world role in this field, and cooperated with other countries frequently. Through network analysis, Mao et al. (2015) suggested that USA took the central position in the international collaboration network in the research field of biomass energy, while Mao et al. (2018) indicated the cooperation between USA and China was very close. While the cooperation between USA and Canada was very close, UK and Germany had enormous influence on research done in the European countries. China and India led the research in Asian countries.

## Institution analysis

The publication statistics for the top 15 publication-producing institutions are shown in Table 3. The University of California

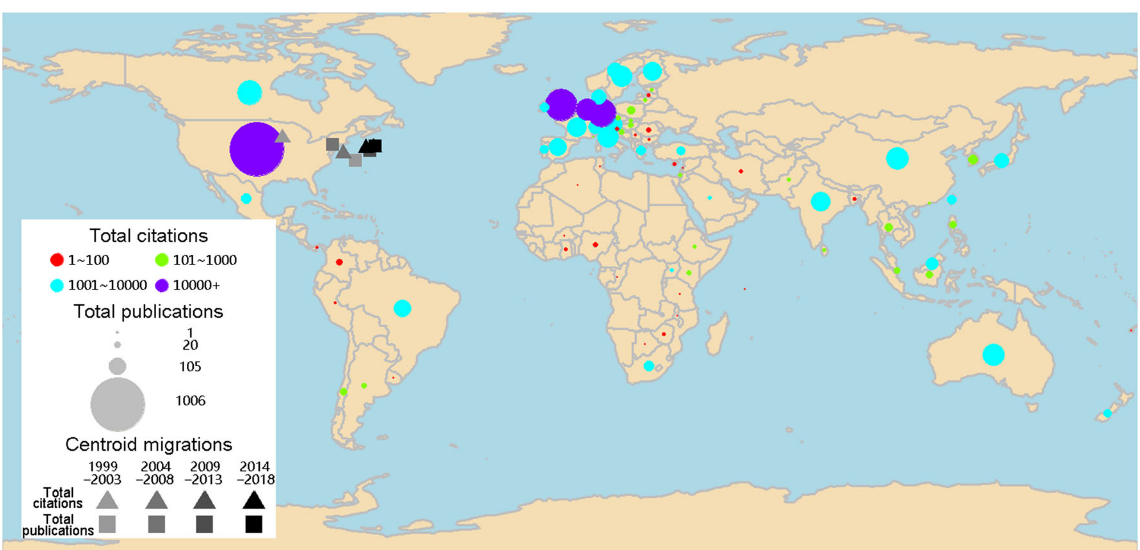


**Fig. 1** Global geographic distribution and centroid migration of publications and citations of bioenergy research related to climate change from 1999 to 2018. Bubble colors represent the total citations of a country. Bubble size represents the number of publications published by a country. The centers of gravity for both numbers of publications and citations for four periods are shown by square and triangle, respectively. Darker gray symbol colors indicate time periods closer to recent years

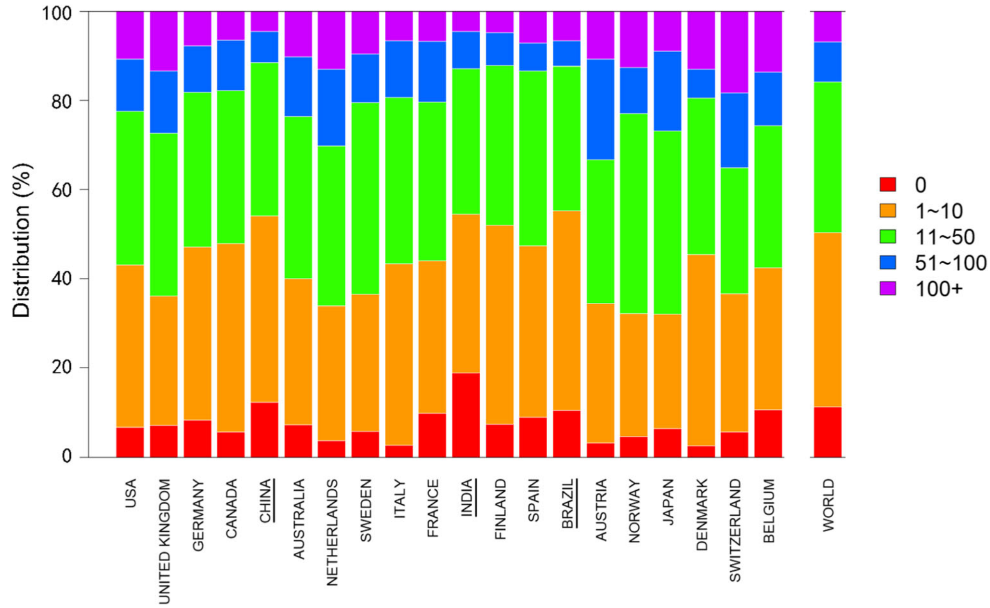


**Fig. 2** Citation frequency distribution of top 20 countries/regions (and the world) publishing bioenergy research related to climate change from 1999 to 2018. Developing countries are underlined

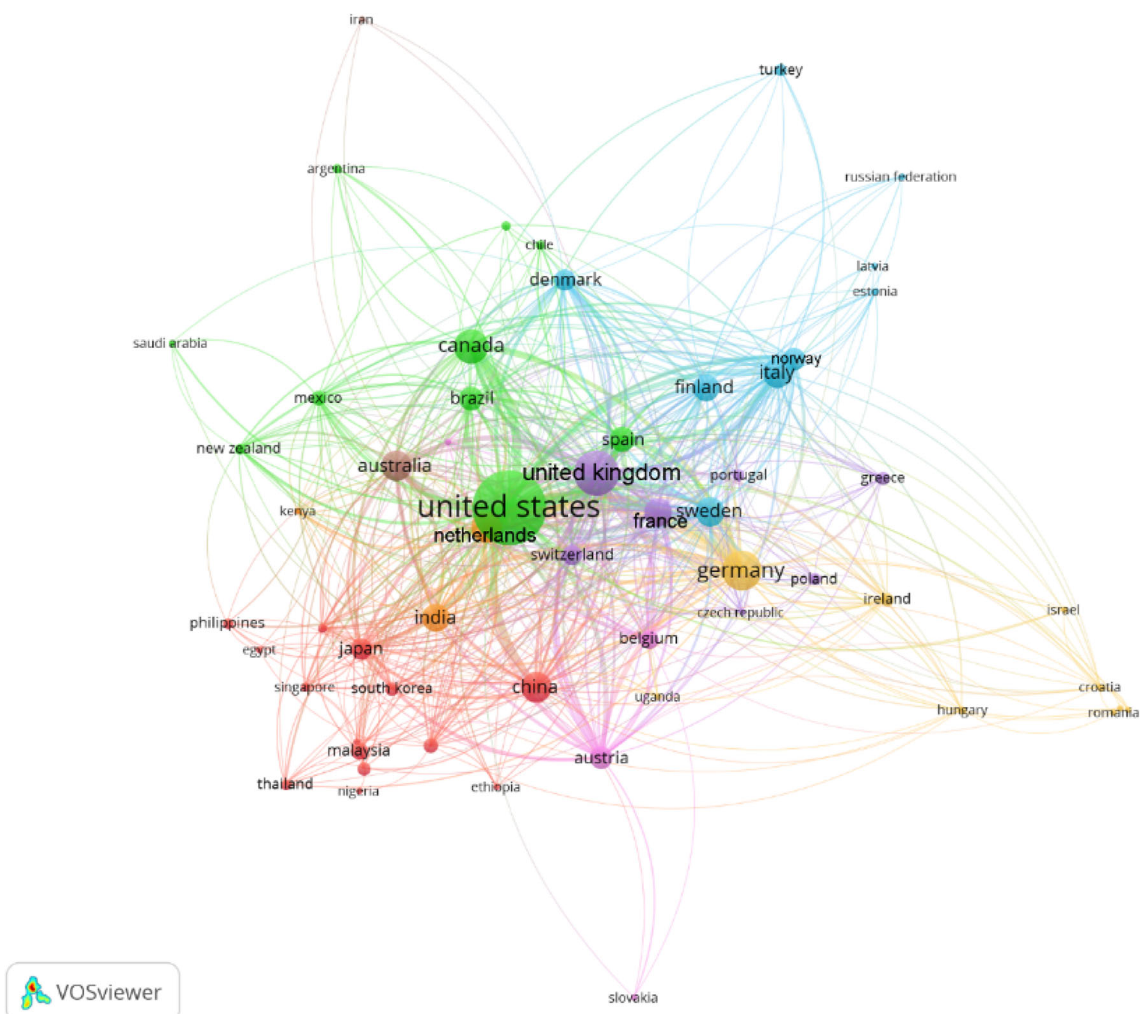


**Fig. 3** Academic cooperation among major countries/regions which published more than five articles dealing with bioenergy research related to climate change from 1999 to 2018. Clusters are shown by different colors. Importance of countries/regions is represented by their centrality in the network. Bigger circles represent more publications by a country. Thicker lines indicate more and closer cooperation between countries

**Table 3** General statistics for the 15 most productive institutions regarding the number of publications from 1999 to 2018 dealing with bioenergy under climate change

| Institute | Country | TP | TC | TC/TP | NHCP | SIP | MIP | FIP | CIP | *h*-index | SY | EY | NCI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| University of California System | USA | 95 | 9459 | 99.6 | 18 | 25 | 70 | 47 | 60 | 37 | 2005 | 2018 | 178 |
| University of Aberdeen | UK | 37 | 3605 | 97.4 | 9 | 4 | 33 | 16 | 18 | 22 | 2000 | 2018 | 105 |
| Stanford University | USA | 34 | 4831 | 142.1 | 11 | 3 | 31 | 12 | 12 | 22 | 2004 | 2018 | 64 |
| University of Washington | USA | 33 | 2634 | 79.8 | 2 | 7 | 26 | 16 | 17 | 17 | 2004 | 2018 | 126 |
| Swedish University of Agricultural Sciences | Sweden | 32 | 827 | 25.8 | 2 | 9 | 23 | 23 | 34 | 14 | 2008 | 2018 | 61 |
| Utrecht University | Netherlands | 28 | 2032 | 72.6 | 4 | 2 | 26 | 12 | 12 | 12 | 2003 | 2018 | 55 |
| Chalmers University of Technology | Sweden | 27 | 1895 | 70.2 | 4 | 8 | 19 | 17 | 18 | 15 | 2002 | 2018 | 36 |
| Imperial College London | UK | 26 | 4341 | 167.0 | 4 | 5 | 21 | 10 | 14 | 14 | 2004 | 2018 | 53 |
| Wageningen University & Research | Netherland | 26 | 1923 | 74.0 | 3 | 8 | 18 | 14 | 20 | 15 | 2005 | 2017 | 54 |
| Oregon State University | USA | 26 | 1140 | 43.8 | 3 | 3 | 23 | 10 | 11 | 13 | 2008 | 2018 | 49 |
| Potsdam Institute for Climate Impact Research | Germany | 26 | 1766 | 67.9 | 3 | 1 | 25 | 17 | 24 | 15 | 2005 | 2018 | 73 |
| Technical University of Denmark | Denmark | 25 | 1078 | 43.1 | 4 | 5 | 20 | 13 | 15 | 14 | 2010 | 2018 | 51 |
| University of Eastern Finland | Finland | 24 | 482 | 20.1 | 1 | 5 | 19 | 17 | 21 | 11 | 2011 | 2018 | 29 |
| Michigan State University | USA | 23 | 1477 | 64.2 | 6 | 6 | 17 | 15 | 17 | 12 | 2008 | 2018 | 39 |
| Michigan Technological University | USA | 23 | 606 | 26.3 | 2 | 6 | 17 | 13 | 14 | 9 | 2009 | 2018 | 35 |

*TP* total number of publications, *TC* total number of citations, *TC/TP* citations per publication, *NHCP* number of highly cited publications (≥ 100 citations), *SIP* number of single-institution publications, *MIP* number of multi-institution publications, *FIP* number of first institution publications, *CIP* number of corresponding institution publications, *SY* starting publication year, *EY* ending publication year, *NCI* number of collaborative institutions

System from USA published the most articles and had the most highly cited articles (95 and 18, respectively), received the most citations (9459), and obtained the highest *h*-index (37), all of which were far greater than the values found for the other institutions in this list. Wageningen University & Research from Netherland and Chalmers University of Technology from Sweden had the highest proportion of studies published by a single institution, indicating the strong scientific research ability in this field. Imperial College London from UK and Stanford University from USA achieved good results for the number of citations per publication (167.0 and 142.1, respectively). University of Aberdeen from UK published studies focused on bioenergy under climate change earlier, and worked together with other institutions. Chen and Ho (2015) identified that the most productive institutions in the USA contributed most of the highly cited articles. Although the Chinese Academy of Sciences was identified as the most publication-producing organization in Mao et al. (2015), a bias in institute analysis in this study should be noted that the Chinese Academy of Sciences (China) had over 100 branches in different cities. The articles published by this institute were divided into branches, which may drop the rank of this institute.

## Distribution of author type and academic age from a country perspective

For the top 20 publication-producing countries, author type and academic age showed great differences from country to country (Fig. 4 a and b). Brazil had the smallest proportion of CAs (5.5%) and a larger proportion of FAs (21%), indicating that Brazil likely hosted related research programs, while some European countries had larger proportions of CAs (Austria, Sweden, and Belgium). India had the largest proportion of FAs (21.8%), indicating that India likely continued efforts to advance learning and achievements in the field of bioenergy related to climate change. Regarding the academic age of researchers publishing bioenergy research related to climate change, most of the researchers conducted related research for 1 year (87% in the world) or more than 11 years (11.6% in the world). Only Austria and Sweden had a mean academic age of more than 4 years. These European countries had a larger proportion of researchers who had an academic age of more than 11 years. China had the lowest mean academic age of 1.6 years, caused by the largest proportion of researchers who had academic age of one year (95.7%). It is still unclear why Chinese researchers have not continued to advance their research in this field.

## Journal analysis from a country perspective

Table 4 shows the number of articles published by the top 20 publication-producing countries in the top 10 productive journals and three famous multidisciplinary journals (and their series). About 30% of the articles related to bioenergy under climate change were published in these journals. *GCB Bioenergy* published the most articles in this field (116 publications), followed

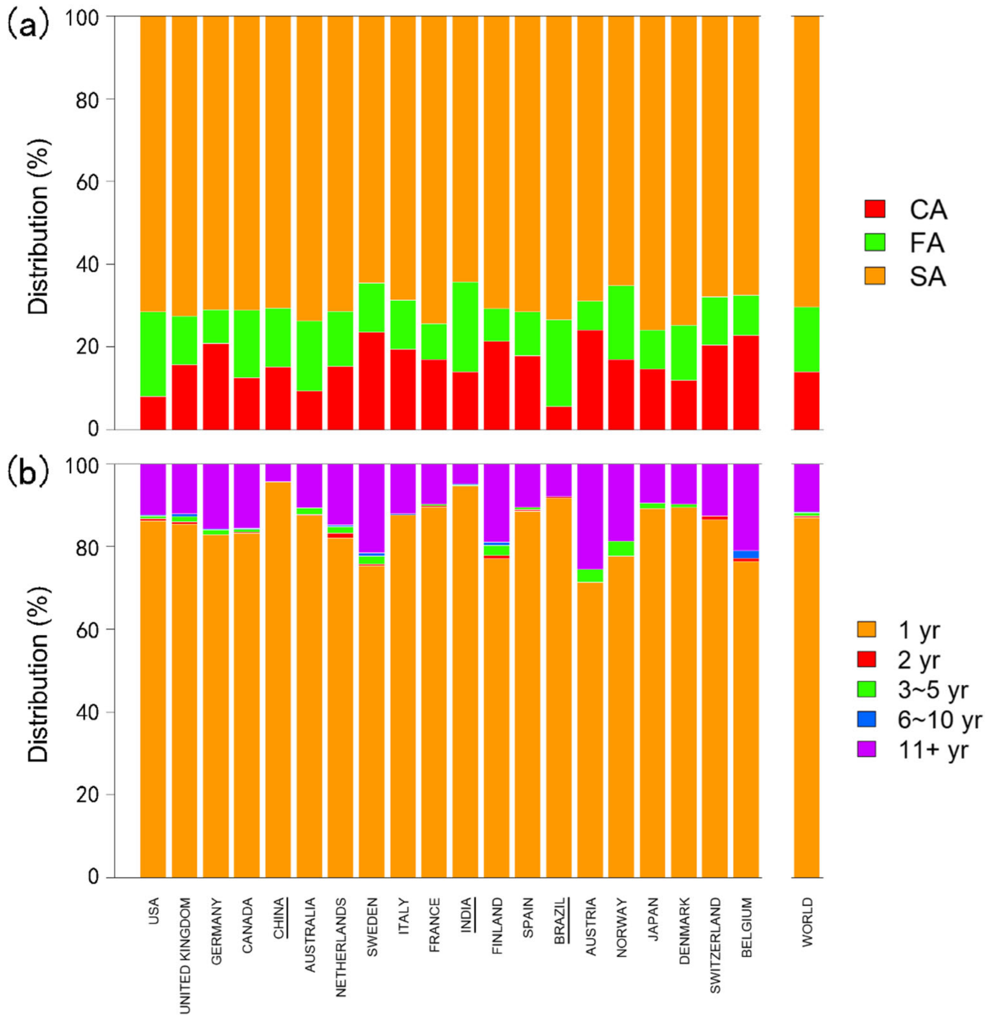


**Fig. 4** Distributions of **a** author type and **b** academic age for the top 20 publication-producing countries/regions publishing bioenergy research related to climate change from 1999 to 2018. CA means corresponding authors, FA means first authors, and SA means supporting authors. Developing countries are underlined

by *Renewable & Sustainable Energy Reviews* (111), *Biomass & Bioenergy* (98), *Energy Policy* (78), and *Journal of Cleaner Production* (58). USA and UK had the most articles published relating to bioenergy under climate change in most of these journals. China published more papers in *Renewable & Sustainable Energy Reviews* than other countries. USA published more articles than any other country in the three multidisciplinary journals (and their series). In the field of bioenergy under climate change, 81.5%, 82.6%, and 61.4% of the articles published in *Proceedings of the National Academy of Sciences of the United States of America*, Science Series (*Science* and *Science Advances*), and Nature Series (Journals with Nature and Nature Reviews titles published by the Nature Publishing Group) came from USA, respectively.

## Keyword analysis from a global perspective

We analyzed keywords from a global perspective (Fig. 5) and found that dynamic development and change of the top 80 author keywords occurred more than 15 times from 2008 to 2018 (this time span was selected as the annual number of publications ≥ 100). The keywords "climate change" and "bioenergy" are in core positions relative to most other keywords, with the strongest connections between them. In earlier time periods, agriculture, carbon, GHG emissions, and global warming were the research keywords. During this period, the related research was still stuck in these broad categories. Following this, the biogeochemistry of the carbon cycle attracted widespread attention in the field. After the formation of the Kyoto Protocol, countries from all around the world initiated energy research to mitigate climate change (Mao et al. 2018). Some kinds of biofuels were proposed, such as biodiesel and bioethanol (Hoekman et al. 2012; Aditiya et al. 2016). In recent years, some methods and techniques were adopted in related research, such as life cycle assessment (LCA; an approach of decision support to evaluate the potential environmental impact and resources consumed in each step of a product or service supply chain), carbon footprint analysis, and biorefinery, which helped to reduce the recycling and transportation costs of biomass energy engineering (Rugani et al. 2013; Parajuli et al. 2015). These frequencies of occurrence suggest that these are becoming some of the

**Table 4** Number of publications dealing with bioenergy under climate change published in the main productive journals by the top 20 publication-producing countries/regions from 1999 to 2018

| | *GCB Bioenergy* | *Renewable & Sustainable Energy Reviews* | *Biomass & Bioenergy* | *Energy Policy* | *Journal of Cleaner Production* | *Environmental Science & Technology* | *Applied Energy* | *Environmental Research Letters* | *Climatic Change* | *Bioresource Technology* | *PNAS* | Science Series | Nature Series | Others |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| USA | 37 | 10 | 18 | 15 | 8 | 37 | 10 | 24 | 29 | 7 | 22 | 19 | 27 | 743 |
| UK | 27 | 10 | 11 | 16 | 7 | 0 | 6 | 7 | 6 | 1 | 5 | 6 | 9 | 255 |
| Germany | 20 | 3 | 10 | 12 | 2 | 4 | 3 | 8 | 6 | 1 | 3 | 2 | 12 | 194 |
| Canada | 10 | 3 | 4 | 5 | 0 | 4 | 4 | 2 | 3 | 2 | 1 | 2 | 3 | 170 |
| *China* | *8* | *12* | *2* | *3* | *5* | *4* | *5* | *2* | *0* | *2* | *1* | *2* | *1* | *125* |
| Australia | 9 | 5 | 2 | 3 | 0 | 2 | 0 | 1 | 0 | 0 | 1 | 1 | 4 | 137 |
| Netherlands | 6 | 4 | 8 | 7 | 7 | 1 | 5 | 2 | 9 | 1 | 2 | 2 | 4 | 104 |
| Sweden | 11 | 2 | 12 | 6 | 3 | 1 | 6 | 0 | 3 | 1 | 1 | 1 | 1 | 108 |
| Italy | 5 | 6 | 6 | 4 | 8 | 0 | 3 | 0 | 1 | 1 | 1 | 0 | 2 | 113 |
| France | 5 | 2 | 2 | 2 | 3 | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 3 | 103 |
| *India* | *2* | *9* | *4* | *2* | *2* | *2* | *2* | *1* | *1* | *5* | *0* | *1* | *0* | *101* |
| Finland | 12 | 5 | 12 | 1 | 3 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 85 |
| Spain | 4 | 8 | 4 | 2 | 8 | 0 | 1 | 1 | 3 | 0 | 0 | 1 | 1 | 79 |
| *Brazil* | *8* | *7* | *5* | *2* | *3* | *2* | *2* | *1* | *1* | *0* | *0* | *2* | *1* | *71* |
| Austria | 5 | 1 | 3 | 5 | 1 | 1 | 6 | 3 | 5 | 0 | 1 | 0 | 1 | 61 |
| Norway | 5 | 1 | 2 | 1 | 3 | 2 | 0 | 3 | 0 | 0 | 1 | 0 | 1 | 68 |
| Japan | 0 | 2 | 1 | 1 | 0 | 3 | 6 | 1 | 1 | 1 | 0 | 0 | 1 | 61 |
| Denmark | 8 | 2 | 3 | 3 | 0 | 0 | 3 | 2 | 0 | 3 | 1 | 1 | 0 | 51 |
| Switzerland | 4 | 1 | 1 | 2 | 1 | 4 | 1 | 2 | 1 | 5 | 2 | 1 | 0 | 46 |
| Belgium | 6 | 1 | 4 | 2 | 1 | 0 | 1 | 0 | 2 | 1 | 1 | 1 | 2 | 44 |
| World | 116 | 111 | 98 | 78 | 58 | 51 | 49 | 42 | 40 | 34 | 27 | 23 | 44 | 2279 |

Science Series: *Science* and *Science Advances*; Nature Series: Journals with Nature and Nature Reviews titles published by the Nature Publishing Group. PNAS Proceedings of the National Academy of Sciences of the United States of America. Developing countries are italicized

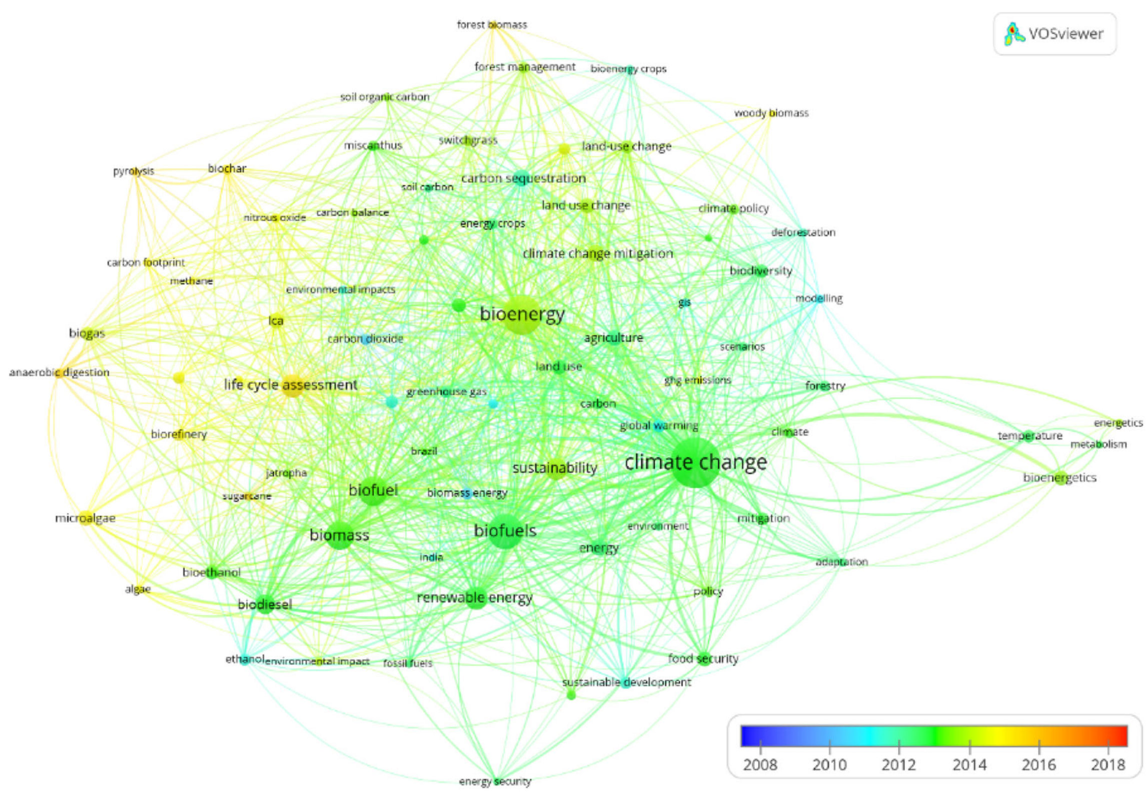


**Fig. 5** Co-occurrence of author keywords that occurred more than 15 times from 2008 to 2018 (this time span was selected as the number of annual publications ≥ 100). The years in which specific keywords frequently occur are shown by different colors. Importance of keywords is represented by their centrality in the network. More occurrences of keywords are shown with bigger circles. More co-occurrences of keywords are shown with thicker lines

most important methods for the study of the relationships and interactions between biomass energy and climate change (Mao et al. 2018). Meanwhile, the development of a new generation of biofuels was put on the research agenda. Microalgae began to be used as a biomass source due to its extensive application potential in renewable energy production (Bahadar and Khan 2013; Khan et al. 2018). In previous bibliometric-based studies, the production of biodiesel from microalgae was confirmed as the main area of recent biofuels research (Xu and Boeing 2013). For high-frequency keyword analysis from a country perspective, please see Supplementary Information Figs. S1 and S2.

## Up-to-date research advances from a country perspective

Under this background, the research topics were observed to be different between the primary developed countries (USA, UK, and Germany) and developing countries (China, India, and Brazil) (Fig. 6). The number of publications dealing with some of these research topics for developing countries has lagged behind the number of similar publications coming from developed countries by one to two years (Fig. 6). Knowledge regarding bioenergy production was concentrated in some topics (environmental and economic impacts, and agricultural biomass plantations) in a few well-studied countries (Robledo-Abad et al. 2017). Ethanol from maize and other cereals in the USA, and biodiesel from oilseed rape in Europe and soybean crops in the USA are already being commercially produced (Creutzig et al. 2015). With the help of supportive government policy, new technologies such as anaerobic digestion of biomass have become a common technology used in many developed nations to generate renewable energy (Edwards et al. 2015). Coal use is already being replaced by renewables for electricity generation (Jackson et al. 2019). New energy types such as cellulosic ethanol have confirmed the potential to offer substantial environmental advantages compared with petroleum-based liquid transportation fuels, particularly in reducing GHG emissions especially in developed countries (Murphy and Kendall 2015). However, cellulosic ethanol is still not economically competitive, making cost reduction a top priority (Liu et al. 2019).

For developing countries, especially for populous nations such as China, Brazil, and India, biomass has significant potential to boost energy supplies to meet rising demand (IRENA 2020). Trends in China's coal use are declining because of the push for cleaner air (Jackson et al. 2019). On the basis of updated liquid and gaseous biofuels, China should also develop densified solid biofuel to achieve the goal of China's 12th Five-year Plan (2011–2015) for the development

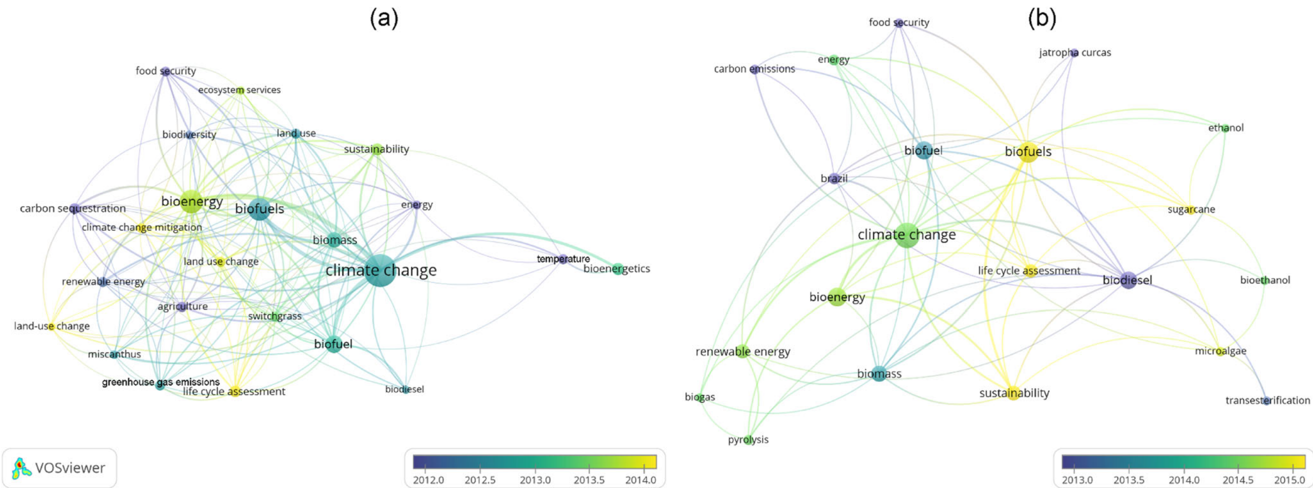


**Fig. 6** Co-occurrence of author keywords which occurred more than 15 times for the top three publication-producing developed countries (**a**; USA, UK, and Germany) and five times for developing countries (**b**; China, India, and Brazil) from 1999 to 2018. These keywords were derived from publications completed by the corresponding authors who came from these six developed countries and developing countries. The years that specific keywords frequently occur are shown by different colors. Importance of keywords is represented by their centrality in the network. More occurrences of keywords are shown with bigger circles. More co-occurrences of keywords are shown with thicker lines

of biomass energy (Zhou et al. 2016). Brazil is the first country in Latin America to adopt a national voluntary mitigation goal by law. In Brazil and the rest of the Latin American region, bioenergy is identified as one of the most promising energy-saving and low-carbon options (Martínez et al. 2015; Portugal-Pereira et al. 2015). For example, Brazil is the leader in liquid biofuels and has already commercially produced bioethanol from sugarcane (Creutzig et al. 2015; IRENA 2020). Most of the global supply of biofuels is comprised of bioethanol from Brazil and the USA (Bauen et al. 2009). Compared with other biofuels from terrestrial crops in Europe and Brazil, algae biofuels are the most efficient alternative in terms of avoiding competition with food crops (Carneiro et al. 2017). But the energy efficiency of algae biofuels could be improved if its production pathways are carefully chosen and optimized (Carneiro et al. 2017). In addition, co-benefits of palm oil production have been widely reported in some developing countries in Southeast Asia (e.g., Malaysia, Indonesia) (Creutzig et al. 2015).

## Identifying the relationship between bioenergy and climate change

The GHG emissions from biofuel are dependent not only on the gas emitted from burning fuel but also from the supply stages of biofuel such as production, harvest, transport, and processing of feedstock biomass, and from the carbon debt from converting any ecosystem into biofuel production (Dutta et al. 2014; Reid et al. 2020). Bioenergy deployment may offer significant potential for limiting climate change to 1.5 or 2.0 °C (Creutzig et al. 2015; Peters et al. 2017). Creutzig et al. (2015) summarized some literature focused on the first and second-generation biofuels and indicated that biofuels from sugarcane, perennial grasses, crop residues, and many forest products have lower life cycle GHG emissions than other fuels. Mat Aron et al. (2020) indicated that all types of biofuel generation cause GHG emissions, but in relatively lower amounts compared with fossil fuels. Among these, third-generation biofuel shows the lowest net GHG emissions. Considering the effect of direct and indirect land use change and LCA of biofuel sources, some studies have investigated the GHG emission mitigation potential of biofuel using systematic review and meta-analysis (e.g., Whitaker et al. 2010; Harris et al. 2015; El Akkari et al. 2018). Whitaker et al. (2010) analyzed GHG balance of first- and second-generation biofuels from 44 LCA studies. Excluding co-product credits of GHG data, first-generation ethanol from wheat-grain and sugar beet produced greater GHG emissions (62 and 56 g $CO_2$ equivalent $MJ^{-1}$ for wheat-grain and sugar beet, respectively) than second-generation ethanol that ranged from 24 to 30 g $CO_2$ equivalent $MJ^{-1}$. Similarly, El Akkari et al. (2018) analyzed 50 articles relying on LCA principles and showed that second-generation biofuels may achieve ~ 50% reduction of GHG emissions compared with fossil fuels, and have a larger GHG abatement potential than first-generation biofuels. Converting grassland to produce biofuels appears to cut half of the GHG emissions compared with fossil energy sources. However, converting forest ecosystems may lead to negative GHG savings. In accordance with the results of El Akkari et al. (2018), Harris et al. (2015) quantified the effects of land use change to second-generation bioenergy crops on GHG emissions in temperate zone agriculture systems. General trends in GHG emissions were identified from 188 original studies and revealed that transitions from arable to perennial grasses (e.g., Miscanthus, switchgrass), short rotation coppice (poplar or willow), and first-generation crops and from grass to perennial grasses resulted in reduced GHG emissions. However, land use change from forests to perennial grasses and to first-generation biofuel cropping may be associated with enhanced GHG emissions.

Searle and Malins (2015) reassessed the upper-end estimates of potential biomass availability from dedicated energy crops by identifying up-to-date assumptions for parameters including crop yields, land availability, and costs. After accounting for forestry, crop residues, wastes, and current trends in bioenergy allocation and conversion losses, these authors concluded that the maximum plausible limits to total biomass availability and biofuel potentials would be 60–120 and 10–20 EJ year$^{-1}$ in 2050, respectively. However, there are still many known controversies regarding bioenergy, illustrating that the potential for bioenergy under climate change may be a double-edged sword (Schubert and Blasch 2010). Bioenergy production requires land and water resource, and is thus inextricably linked with food security and environmental quality (Lynd et al. 2015; Walsh et al. 2015; Kline et al. 2017). For example, in Malaysia and Indonesia, vast oil palm plantations are being established in cleared large native rainforests (Tenenbaum 2008). Seaweed and microalgae aquaculture may offer opportunities to improve biofuel production from forests and energy crop plantations (Walsh et al. 2015; Duarte et al. 2017).

## Study limitations

Some limitations should be noted regarding this study: (1) although including other terms such as "global warm*" or "greenhouse effect" in the search term would expand results, this study chose to limit the search string to avoid over-representing particular subdisciplines; (2) some related articles may have been published in journals that are not indexed by Scopus, and some authors may have additional publications focusing on other topics. This incompleteness will reduce the metrics and affect the determination of author type and academic age (Milojevic et al. 2018). Furthermore, many articles may have been written in languages other than English, thereby causing an underestimation of research activities from non-English-speaking countries (Liu et al. 2014); (3) some articles published in journals that do not contain author keywords (e.g., *PLoS ONE*) were excluded from the analysis of author keywords network (Zhang et al. 2019); and (4) some countries have historical complexities (e.g., Serbia, Montenegro) that may have slightly affected the results of this study.

# Conclusions and perspective

Under climate change, there are growing opportunities and demands for bioenergy to provide renewable energy for heat and power. From the analysis of this study, USA, Canada, and some European countries have done well regarding publishing research results in the field of bioenergy under climate change. Some developing countries have started to play a greater role in such research. Currently, academic cooperation is still insufficient in some Asian and African nations due to language and cultural barriers. More international cooperation may improve the comprehensive development of energy research so that advanced expertise and experiences derived from developed countries can be shared with developing countries. Additionally, the work done by developing countries is also conducive to the complementary research conducted by developed countries. To conclude, developed countries should concentrate on the further development of new bioenergy sources (e.g., algal-derived bioenergy), harmonized assessment methodologies, advanced energy technology, and execution of reliable political decisions (Bentsen and Felby 2012). Developing countries, such as China, India, and Brazil, should go deeper into the debate of food and feed security versus growing biofuel demand, change inappropriate energy consumption structure, accelerate the commercialization and industrialization of biofuel achievements, and develop bioenergy in a sustainable way (Kumar et al. 2015; Qin et al. 2018). More investigations are desirable to explore the technical and economic potential of bioenergy and to evaluate the impacts of its production on the environment and climate change across the world.

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**Authors' contributions** Yajie Zhang: conceptualization; data curation; formal analysis; investigation; methodology; resources; software; validation; visualization; writing—original draft.

Qiang Yu: funding acquisition; project administration; supervision; writing—review and editing.

Juan Li: conceptualization; methodology; software; validation; supervision; writing—review and editing.

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**Data availability** This work uses Scopus data provided by Elsevier B.V. (https://www.scopus.com/search/form.uri?display=basic). The codes that support the findings of this study are available from the first author upon reasonable request.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflicts of interest.

**Ethical approval** Not applicable.

**Consent to participate** Not applicable.

**Consent to publish** Not applicable.

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