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Review

A Scientometric Review: Biomass Gasification Study from 2006 to 2020

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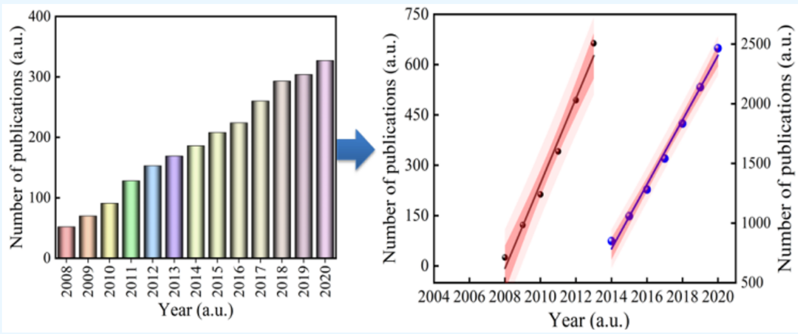

ABSTRACT: Biomass gasification represents a significant way to produce energy from biomass. It features renewable properties and offers great potential for utilization. The application of biomass gasification products, design of the gasifier, type of biomass feedstock, gasification agents, and gasification parameters are key for the biomass gasification process. This work applies bibliometric approaches to provide a comprehensive and objective analysis of worldwide biomass gasification study trends over the period from 2006 to 2020 according to the Web Of Science core collection data. A total of 3222 articles associated with biomass gasification was retrieved, and its number grew annually. The subjects of study are diversified, primarily classified into "Energy & Fuels", "Engineering Chemical", and "Green Sustainable Science Technology". Moreover, *Energy* was a top published journal in the field of biomass gasification. Austrian contributors had the majority of publications, next to China and the USA. Liejin Luo from Xi'an Jiaotong University possessed the greatest H-index. Keyword evaluation showed that biomass gasification is a current hotspot, among which life-cycle assessment, sustainability, and deep processing of gasification products are future research directions. This work is predicted to offer further research interest in biomass gasification.

1. INTRODUCTION

Significant amounts of agricultural waste biomass have been produced over recent years.[1] According to reports, the annual worldwide production of crop straw was assessed to be approximately 2476 million tons.[2] In particular, the production of straw in China amounted to 824 million tons, although with underutilization.[3] With increasing environmental and energy concerns, the application of biomass in a cleaner and sustainable manner is gaining popularity. In terms of biomass feedstock, it is a promising source of clean renewable energy due to its abundance, wide distribution, and CO_2 neutrality.[4] The gasification of biomass into biochar, bio-oil, and noncondensable gas is a representative method of resource utilization.[5,6] More importantly, biomass gasification is considered as a neutrality CO_2 emission in the life-cycle assessment.[7] As is known, biomass gasification can be defined in five stages: moisture evaporation, initial devolatilization, oxidation ($C + O_2 = CO_2$; $2C + O_2 = 2CO$), gasification, and reduction ($C + H_2O = CO + H_2$; $CO + H_2O = CO_2 + H_2$; $C + CO_2 = 2CO$; $C + 2H_2 = CH_4$; $CO_2 + H_2 = CO + H_2O$).[7] The moisture evaporation is generally carried out at 100−200 °C to increase the quality of the produced gas.[8] The initial devolatilization occurs essentially at 300−900 °C in the absence of an oxidizer and ultimately results in the decomposition of the biomass into fuel gas, condensable liquids, and biochar. Oxidation represents a critical procedure that happens above 700 °C and results in the oxidation of pyrolysis products to CO, CO_2, and H_2O in the presence of oxidants (e.g., air, oxygen, and steam).

In addition, the application of biomass gasification products, design of the gasifier, type of biomass feedstock, gasification agents, and gasification parameters are crucial for biomass

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gasification and therefore have received considerable attention from researchers. For instance, apricot shells, spruce trees, and dried sludge by gasification can be transformed into three-phase products (i.e., biochar, bio-oil, and noncondensable gas).[7,9,10] Sharma[11] gasified five various types of feedstock, namely, pine pellets, hardwood pellets, cypress mulch, pine bark nuggets, and corn stover pellets, in the downdraft gasifier. The results indicated that pine and hardwood pellets showed the least ash and the most volatile solids, which were therefore more suitable for gasification. In terms of the biomass feedstock equivalence ratio, Awais et al.[12] investigated the effect of the equivalence ratio of sugar cane bagasse and coconut shell feedstock on syngas composition, calorific value, gasification efficiency, and tar content in the 24 kW downdraft gasifier. It was found that coconut shells were better for gasification compared to sugar cane bagasse. Additionally, Baranowski et al.[13] conducted experiments using steam and CO_2 as the two gasification agents. It was observed that the composition of the syngas changed significantly depending on the gasification agent. A comparison of the gasification of lignite in atmospheres of CO_2 and steam as gasification agents showed that the volume fractions of H_2 and CH_4 were larger in the case of steam gasification at all tested temperatures. In conclusion, parameters such as the composition of raw materials, equivalence ratio, feed rate, and particle size all affect the calorific value, gas composition, biomass carbon, and tar content.[14−17]

Based on these, we believe that the research on biomass gasification belongs to a systematic investigation, which encompasses scientific issues in different directions. It is worth noting that previous works have made significant progress in each scientific question (e.g., design of gasifier, pretreatment of feedstock). However, due to the diversity of biomass gasification process parameters, it is difficult for investigators to ascertain their focus and scientifically determine future trends. As a result, there is a great demand for a systematic evaluation of its investigation areas and directions to explore contemporary investigation hotspots and deeper development trends.

Bibliometrics is the use of literature as a database for quantitative studies.[18] It applies mathematical and econometric approaches for analyzing trends and hotspots.[18] This work analyzed the current status of biomass gasification research from 2006 to 2020 using bibliometric methods, including development trends, research fields, major institutions, key researchers, level, and impact. It is essential to be aware of the current research status, study hotspots, and develop in-depth trends for biomass gasification processes for providing directional orientation toward biomass gasification investigations.

2. RESEARCH APPROACHES

2.1. Information Gathering and Treatment.

The work data were obtained from the Web of Science (WoS) Core Collection of the American Institute for Scientific Information (ISI). The WoS was deemed to be the most comprehensive, containing the most relevant and influential journals in its record and is scientifically robust.[19] All of the literature related to biomass gasification from 2006 to 2020 was searched on October 1, 2021. The resulting data are considered valid when the terms of the search are combined with the title, abstract, and keywords. The geographical distribution obtained in this work was defined through the location of the institution for the author. For instance, literature with addresses from Mainland China, Taiwan, Hong Kong, and Macao is categorized as China. Papers are classified into two categories depending on whether the authors are from the same country or not: single national publication (SP) and international cooperative publications (CP). Through further analysis, seven categories of information were retrieved, as outlined below:

(1) Types of files and their publishing languages
(2) The number of publications during 2006−2020
(3) Subject categories and journals
(4) Author statistics
(5) Geographical distribution
(6) Study hotspots and future trends

2.2. Data Analysis.

Origin software was used to evaluate the annual number distribution of literature, the distribution of main source journals, the distribution of countries/regions, the distribution of disciplines, and the keywords. Meanwhile, research hotspots and frontiers with the visualization capabilities of the VOS viewer were combined. Visualization software enables the study procedure of a research area to be combined on a network map, providing a clearer picture of study trends.[18] Additionally, impact factor (IF) values were derived from Journal Citation Reports in 2020.

3. RESULTS AND DISCUSSION

3.1. File Categories and Their Delivery Languages.

The literature on biomass gasification technology retrieved from the WoS database was divided into five main categories. The bulk of the literature in the form of articles accounted for 71.0%; conference proceedings papers accounted for 22.28% of the literature, followed by review papers accounting for 12.38%, online publications accounting for 0.56%, and editorial materials accounting for 0.186%. These results suggest that biomass gasification technologies can be delivered primarily using scientific papers, including articles and reviews. In addition, these findings indicate that biomass gasification is a comprehensive research domain, primarily conducted via scientific publications.

With respect to the language of publication, nine languages were employed. Over 98% of articles are in English, demonstrating that English is the primary language of scholarly communication. The other languages were Polish, Chinese, German, Spanish, Portuguese, Czech, Italian, and Japanese.

3.2. Quantity of Works from 2006 to 2020.

By searching in the WoS database, a total of 3222 papers related to biomass gasification technology were published between 2006 and 2020. The number of publications per year is shown in Figure 1.

The steady increase in the number of publications since 2006 indicates that biomass gasification is gradually gaining the attention of researchers as one of the most effective and leading application technologies for biomass energy. Because of the critical role of biochar, bio-oil, and noncondensable gas in bioenergy production, fertilizer production, and waste biomass utilization, the regulation of biomass gasification technology is receiving more and more attention.[20]

As shown in Figure 2, the number of papers about this topic has increased since 2006, and the correlation (R^2) between the number and the time of publication is expressed by two linear models: R^2 = 0.98 for the period 2006−2013 and R^2 = 0.99 for the period 2014−2020. The number of papers in the first phase (2006−2013) gradually increased, with an average of

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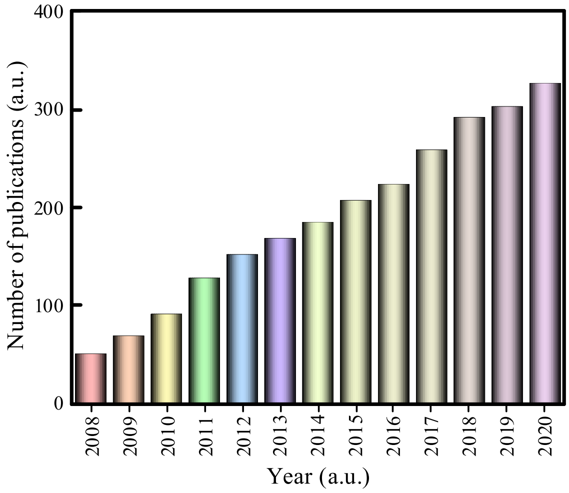

Figure 1. Published output during 2006−2000.

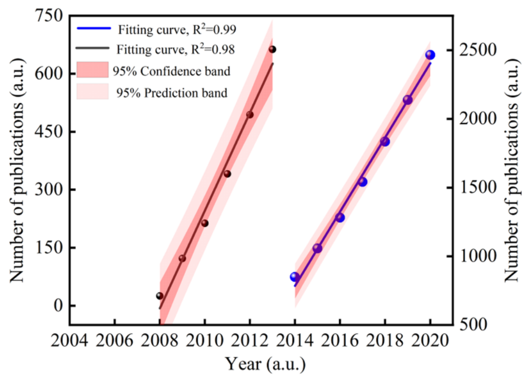

Figure 2. Cumulative number of papers published by year.

110 papers on biomass gasification published per year. However, the number of papers published per year was 225 for the second stage (2014−2020), which is much higher than the previous phase. The largest number of papers regarding biomass gasification was published in the last year of the period, with a total of 2465 papers. Overall, the time trend of publications associated with biomass gasification reveals a constant growth. Moreover, such a trend can explain the increasing recognition of biomass gasification by the scientific community.[21] Given this trend, the number of publications related to biomass gasification is likely to keep growing in the future and is expected to reach ~3216 by 2023.

Except for the number of published papers, there was a significant increase in the number of cited literature, pages, and authors, which is summarized in Table 1.

The average number of citations per article has increased over the years, from 24.71 in 2006 to 46.56 in 2020. Moreover, the average number of authors per paper is equally gradually increasing, for example, from 3.38 in 2006 to 4.95 in 2020. It follows that researchers are studying the field in greater depth and interest. The frequency of citations reveals the significance for an article in a particular area. It is clear that the total number of citations about biomass gasification gradually increases with the year, up to 27560 in 2020.

3.3. Subject Types and Journals. Based on available statistics, the associated publications can be classified into 48 subject types. Most published papers belong to "Energy & Fuels", occupying 63.22% of the total publications, as shown in Table 2.

Table 1. Features for Publication Outputs[a]

PY	P	CF	NR	NR/P	AU	AU/P
2006	52	14	1285	24.71	176	3.38
2007	70	157	2453	35.04	283	4.04
2008	91	394	3769	41.42	319	3.51
2009	128	990	4797	37.48	459	3.59
2010	153	1531	6576	42.98	528	3.45
2011	169	2741	6850	40.53	628	3.72
2012	186	3605	7224	38.84	704	3.78
2013	208	5050	9191	44.19	881	4..24
2014	224	6319	9476	42.30	912	4.07
2015	260	7587	12106	46.56	1059	4.07
2016	293	8950	13980	47.71	1231	4.20
2017	304	10599	16540	54.41	1360	4.47
2018	327	13086	22589	69.08	1587	4.85
2019	355	15704	22672	63.86	1630	4.59
2020	402	19594	27560	68.56	1991	4.95

[a]PY, P, and CF represent the year of publication, the number of publications, and the total number of citations, respectively. NR and AU represent the cited reference count and the number of authors, respectively.

Table 2. Top 10 Subject Categories

subject categories	publications	percentage (%)
Energy & Fuels	2037	63.22
Engineering Chemical	1048	32.52
Green Sustainable Science Technology	492	15.27
Environmental Science	441	13.69
Engineering Environmental	383	11.89
Thermodynamics	362	11.23
Materials Science	279	8.66
Chemistry Physical	238	7.39
Agricultural Engineering	187	5.80
Electrochemistry	169	5.24

On the other hand, the proportion of "Engineering Chemical" was 32.52%, followed by "Green Sustainable Science Technology (15.27%)", "Environmental Science (13.69%)", "Engineering Environmental (11.89%)", "Thermodynamics (11.23%)", "Materials Science (8.66%)", "Chemistry Physical (7.39%)", "Agricultural Engineering (5.80%)", and "Electrochemistry (5.24%)". It shows that the majority of the papers were associated with energy fuels and chemical engineering, which is a crucial field for the application of biomass gasification products.

Analyzing the journal distribution of the literature is a useful way to access high-quality core journals in the domain. The 3222 chosen papers were published in 200 various journals.

In Table 3, the top 10 leading journals in terms of productivity are listed, including details of the number of articles published in each journal, and the percentage and impact factor. The journal *Energy* had the highest number of articles, accounting for 4.84% of the total number of articles published. The second-highest yielding journal is the *International Journal of Hydrogen Energy* (4.69%), followed by *Energy & Fuels* (4.16%), *Renewable Sustainable Energy Reviews* (3.94%), and *Applied Energy* (3.88%). The highest yielding journals can be seen to be strongly associated with energy and

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Table 3. Top 10 Productivity Journals during 2006−2020[a]

journal	TP	%	IF
Energy	156	4.84	6.082
International Journal of Hydrogen Energy	151	4.69	4.229
Energy & Fuels	134	4.16	3.421
Renewable Sustainable Energy Reviews	127	3.94	12.11
Applied Energy	125	3.88	8.848
Fuel	123	3.82	5.578
Energy Conversion and Management	100	3.10	8.208
Biomass & Bioenergy	96	2.98	3.551
BioEnergy Research	80	2.48	2.814
Fuel Processing Technology	75	2.33	4.982

[a]TP, %, and IF are the total publications, the share in publication, and the impact factor, respectively.

fuel, as well. The majority of the top 10 journals showed an IF of over 5.00, creating a remarkable influence on the study field. The large IF and productivity of *Renewable Sustainable Energy Reviews* demonstrated that the journal acted as a crucial contributor to the development of biomass gasification.

3.4. Author Statistics. The results of the analysis show that a total of 13748 authors have been involved in biomass gasification technology over the last 15 years.

Table 4 lists the 10 authors with the most publications in this field. The scholars listed have at least 18 publications related to biomass gasification technology, according to their ranking in terms of the number of publications. Based on statistics, Hofbauer Hermann from the Technical University of Vienna, Austria, has published the most articles, with 44 articles so far and an H-index of 47, indicating that he has been one of the leading researchers in the related field. Following closely, Liejin Guo, who had 31 published papers, was ranked first with an H-index (72), followed by Kumar Ajay (27, H-index 11), Marechal Francois (26, H-index 46), Hui Jin (24, H-index 32), and Yoshikawa Kunio (24, H-index 41). Notably, half of the top 10 most productive authors are from China, implying that more Chinese scholars are focusing on the field of biomass energy.

Table 4. Top 10 Most Productive Writers in 2006−2020

authors	publications	H-index	institute	country
Hofbauer Hermann	44	47	Technische Universitat Wien	Austria
Liejin Guo	31	72	Xi'an Jiaotong University	China
Kumar Ajay	27	11	Oklahoma State University System	USA
Marechal Francois	26	46	Swiss federal Institute of Technology in Lausanne	Switzerland
Hui Jin	24	32	Xi'an Jiaotong University	China
Yoshikawa Kunio	24	41	Tokyo Institute of University	Japan
Guangwen Xu	21	38	Chinese Academy of Sciences	China
Chenhua Wang	19	8	Chinese Academy of Science	China
Aziz Muhammad	18	28	University of Tokyo	Japan
Guanyi Chen	18	37	Tianjin University	China

3.5. Geographic Distribution. To determine the principal countries/regions engaged in biomass gasification technology research and the cooperation between them, the distribution of countries/regions involved in this research was analyzed. As is known, the VOS viewer is one of the critical analysis methods in research. For instance, Jiao et al.[2] used the VOS viewer to provide the keywords network and their community detection related to biochar preparation worldwide research. In other words, the VOS viewer possesses applicability and scientific nature. Figure 3 and Figure 4 show the distribution and knowledge mapping of the co-authoring countries/regions.

Overall, publications on biomass gasification have been published by authors from 95 countries/regions. Comparatively few studies were conducted in Kazakhstan, Algeria, Sudan, Yemen, and Oman. Thereinto, China had the most literature, with 650 publications, accounting for 20.20% of the total publications, followed by the USA and Italy. These results suggest that China may play a critical role in biomass gasification.[22−24] This may be since China is a largely agricultural country (e.g., the gasification of agricultural and forestry waste can contribute to the early achievement of carbon peaking and carbon neutrality).[25] China and the USA published over 300 articles. These independently published articles numbered 1050, accounting for 32.58% of the total literature. Alternatively, 67.48% of the papers were international joint publications featuring 2171 articles. As such, collaborative research has been significantly improved.

Figure 4 depicts the map of knowledge areas in the cocreation countries/regions. The knots stand for various countries and the sizes for the knots denote activities and paper numbers.[26]

The connection between two knots suggests that they cooperatively relate to each other. The tighter the contact, the closer the cooperation among them.[26] Moreover, the total intensity of links between China and the USA remained comparable, but international cooperation with China is primarily focused on the USA, England, and India. The results indicated that China and the USA showed the strongest international partnerships and were the strongest contributors to global cooperation in biomass gasification.

3.6. Study Hotspots and Future Trends. Keyword assessment in the scientific contribution is meaningful to ascertain trends in a particular area.[27] These keywords help to construct the scientific contribution of the field or subject most tightly associated with the topics covered in this investigation.[28] Based on the keyword statistics for the period of 2006−2020, a total of 3251 keywords were retrieved, of which 2450 showed up only once, 340 showed up twice, and 49 showed up more than 10 times. Again, after screening statistics, 460 keywords associated with biomass gasification were retrieved, and those unrelated to biomass gasification were excluded. Gasification was considered the most common, reaching 451, followed by biomass (332), pyrolysis (123), energy (96), and combustion (80). The data suggested that researchers often use biomass for gasification studies.

Co-occurrence analysis of keywords investigates the co-occurrences of keywords in numerous papers and is employed to depict the core components and structures of particular academic fields and to unveil the research frontiers of the discipline. Cluster analysis was performed using VOSviewer software to generate a knowledge domain map of keyword co-occurrence.

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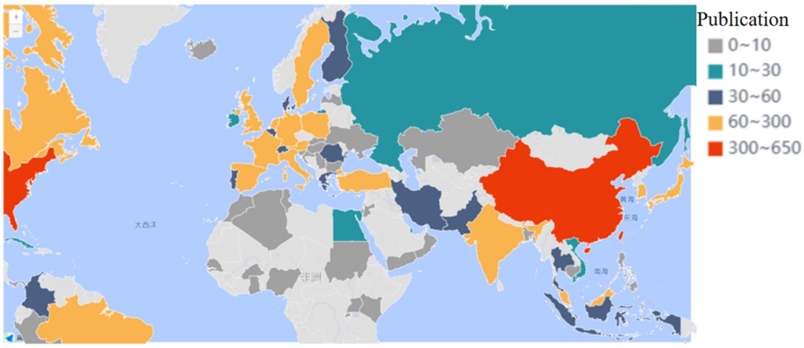

Figure 3. Countries/regions contributing to biomass gasification research from 2006 to 2020.

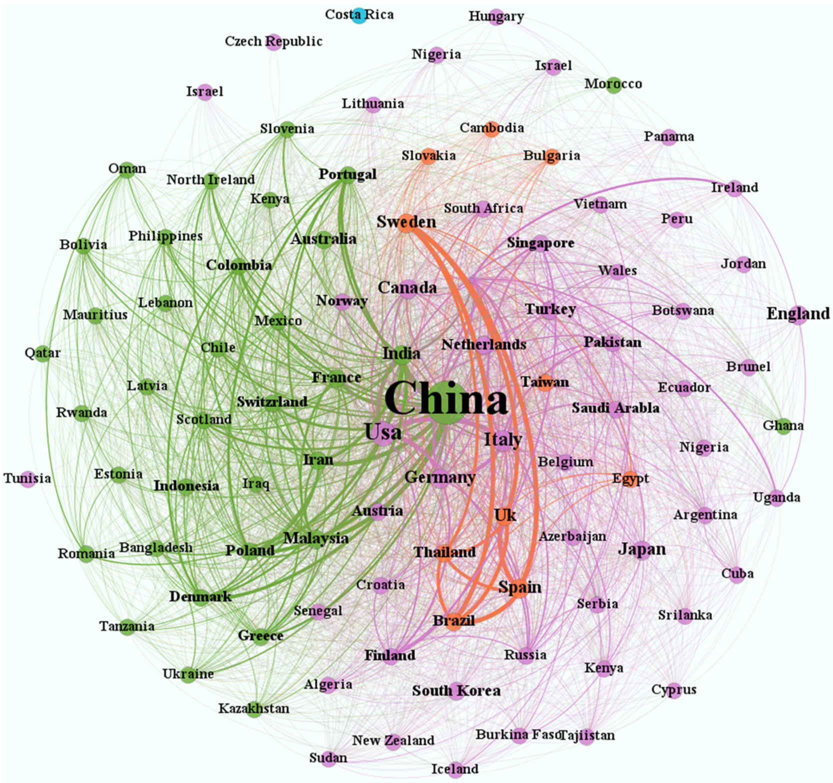

Figure 4. Cooperating countries/regions for biomass gasification in 2006−2020.

As shown in Figure 5, a total of three clusters were obtained. These clusters are focused on the keywords "gasification" and "biomass". In other words, these clusters mainly belong to the systems, products, and economic and environmental benefits of biomass gasification. For instance, "electricity", "power", "bioenergy", "biofuel", "fuel", "CO_2", "gas", "tar", "syngas", "hydrogen", and "biochar" are all products of biomass gasification. "Gasifier", "system", and "design" primarily belong to biomass gasification systems. Of note is that the life-cycle assessment can be considered as an evaluation of the environmental benefits of biomass gasification. Over recent years, the technology of biomass gasification polygeneration to produce three-phase products received growing attention due to the high efficiency of biomass utilization.[29−31] Bio-oil, biochar, and noncondensable gas are significant products for further value-added utilization in this technology.[32,33] The noncondensable gases (e.g., CO, CO_2, and H_2) can be used as boiler fuel and partially replace natural gas. Biochar has a wide range of applications as solid fuel, activated carbon intermediate, and carbon-based compound fertilizer. Bio-oil stands out as a promising clean fuel that can be used for direct combustion or refined to extract fine chemicals.[34] Notably, pyrolysis is equally a thermochemical decomposition procedure wherein the biomass is subjected to heating at higher temperatures in the absence of oxygen.[35] The pyrolysis process is remarkably similar to gasification. The difference is that pyrolysis is performed without oxygen.

The whole period is divided into three phases according to the displayed node colors, as represented in Figure 6.

The first phase was biomass gasification from 2014 to 2015, which focused on biomass, gasification, bioenergy, biofuels, etc. The second phase was from 2016 to 2017, concentrating on syngas, torrefaction, downdraft gasifier, tar, and waste, which are closely related to biomass gasification. For the third phase (2019−2021), biochar, sustainability, adsorption, and oxygen carriers are discussed, which also foreshadows new trends in biomass gasification research. In conclusion, biomass gasification continues to be of interest to researchers. To improve

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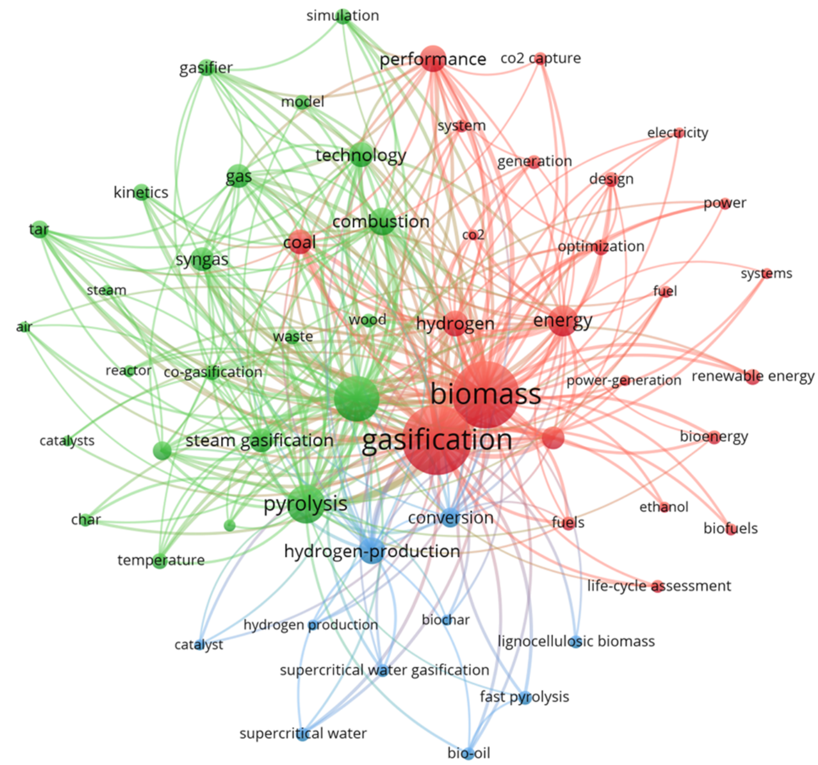

Figure 5. Keyword networks and their community detection were associated with global biomass gasification research.

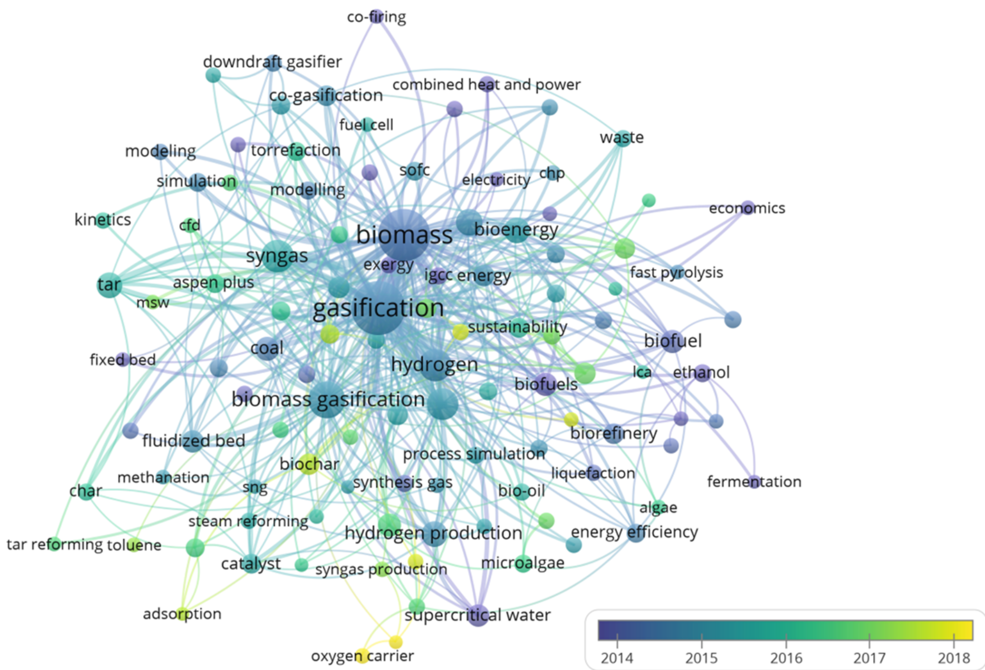

Figure 6. Keyword networks and their time evolution as community detection were associated with the global study of biomass gasification.

the overall effectiveness of biomass gasification, gasification efficiency, sustainability, and deep processing of gasification products will be the research trends in the future.

4. CONCLUSIONS

Biomass gasification is a technology that uses renewable energy sources to produce biochar and vinegar liquor in addition to electricity and heat applications. Additionally, biomass energy is available in large quantities in most parts of the world. The present work provided an overall scientific review of the current status and trends regarding biomass gasification research from 2006 to 2020. It drew several critical findings related to the nature of the biomass gasification field. Such results in biometrics studies of biomass gasification investigation reveal the growing interest of the scientific community over the past decade. From 2006 to 2020, the overall number of papers on biomass gasification presented a trend of consistent increases, which was 3222 papers retrieved from

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200 journals, divided into 48 disciplines. Energy was the most published journal in terms of the number of papers. "Energy & Fuels" represented the main subject classification. China had the highest production featuring 650 papers, representing 20% of the total number of papers in this field, illustrating the crucial role of China in biomass gasification studies. In addition, the USA and China cooperate most intensely.

As evidenced by the keyword cluster, biomass gasification remains an investigation hotspot. Nevertheless, as research has advanced and requirements have increased, developers are focusing on life-cycle assessment, sustainability, and deep processing of gasification products. Knowledge of biomass gasification is expected to continue to increase over the next few years given the growing trend during the research period.

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Author Contributions

L.W. and J.Z. wrote the paper, conceived the idea, and gathered data. S.W. and L.X. supervised the project. H.Q. and H.M. analyzed the results and commented on the manuscript.

Notes

The authors declare no competing financial interest.

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