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Development of bioenergy technologies: A scientometric analysis

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A R T I C L E I N F O

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A B S T R A C T

Bioenergy has the potential to substitute the current demand for fossil fuels in various applications. Recovering energy from bio-based materials due to environmental considerations has been adopted as a policy objective by governments and international organizations, which led to both vast financial investment and scientific research, especially in the last two decades. So far, various feedstocks and technologies have been scrutinised by the research community, although not all of them are commercially adopted due to sustainability considerations. This study employs scientometric analysis to survey the progress of scientific development in the field of bioenergy from 1966 to 2022, using ten parameters including publication year, type of document, categories, countries, affiliations, document citations, co-authorship, author citation networks, journal citation networks, and keywords. A total of 51,905 scientific documents were collected from the Web of Science, involving more than 96,000 authors from 162 countries. The dispersion of studies followed an ascending distribution with a sharp increase in the second half of the 2000s. The evolution of keywords in terms of burst strength confirmed the advancements of technologies from primary first-generation to advanced fourth-generation bioenergies. Based on the evolution of science in this area, it is concluded that integrated sustainability assessment studies, covering technical, economical, environmental, and social aspects, are needed to bridge the gap between abundant theoretical endeavours and limited commercial use of this energy source.

1. Introduction

Increasing demand for energy resulting from industrialization [1,2], uprising price of conventional fossil fuels [3], as well as their environmental impacts [4] and biodiversity concerns [5] have made it inevitable to accelerate the substitution of fossil fuels by alternative renewable and clean energy sources. Bioenergy is regarded as a promising and environmentally-friendly energy source, with the potential to satisfy future needs for sustainable sources of energy [6–9]. Bioenergy refers to any type of fuel derived from organic, biological, or plant sources, called biomass [10]. Generally corresponding to the origin of organic feedstocks and conversion technologies, biomass energy is classified into four generations.

First-generation, which are also known as conventional biofuels, are obtained from carbohydrate-rich crops like sugar cane, sugar

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beet, wheat, barley, corn, rice, or oil-bearing crops like rapeseed, sunflower, soybean, olive, palm, peanut, coconut, as well as animal fats [11]. Most advanced technologies, such as fermentation of sugar or starch [12], and transesterification of vegetable oils and animal fats [13,14], can be applied to generate final products of bioethanol or biodiesel, as a substitute for gasoline and diesel, respectively.

Second-generation biofuels come from lignocellulosic feedstocks, such as forestry [15] and agricultural residues [16], and municipal and industrial organic waste [17], as well as non-edible energy crops [18], such as jatropha, miscanthus, switchgrass, etc. Generally, second-generation biofuels are produced via physical, biochemical, or thermochemical processes. Briquetting [19], pelletizing [20], or extracting fiber from biomass residues [21] are the main physical processes that turn waste biomass into useable and efficient solid fuels for combustion. However, more advanced conversion technologies are derived through biochemical and thermochemical routes. Pretreatment of biomass is the main stage in a biochemical process, in which the structure of lignin, cellulose, and hemicellulose are broken into fermentable sugar through acid or enzymatic hydrolysis [22]. Anaerobic digestion of organic materials like manure also is among the most common biochemical degradation techniques which results in biogas, a promising substitution for natural gas [23]. Finally, the main thermochemical processes for the extraction of second-generation biofuels are pyrolysis [24] and gasification [25]. Heating up the plant biomass at high temperatures (300–900 °C) in the absence of air is known as pyrolysis and, in the presence of air, oxygen, steam, or carbon dioxide, as gasification. These thermochemical processes result in two main products: bio-oil and syngas for fuel [26] and one byproduct: biochar [26], which can be applied to soil [27].

Microalgae (unicellular) and macroalgae (multicellular) are promising third-generation biofuel feedstocks that contain a high amount of lipid biomolecules [28,29]. These aquatic biomass capture a high volume of carbon dioxide and produce oxygen and oil through photosynthesis [29,30]. The oil content, which is much higher than that of lignocellulosic biomass, can be converted into many kinds of biofuels, such as bioethanol, biodiesel, biobutanol, and propanol, via thermochemical or biochemical processes [31].

Finally, fourth-generation biofuels refer to the fuels obtained from genetically-modified microorganisms, such as micro/macro-algae and cyanobacteria, aiming to enhance biofuel yield [32] and eliminate carbon emissions [33]. As energy demand increases, apart from being feedstocks for producing biofuels in the form of solid, gas, or liquid states, microorganisms and enzymes also convert chemical energy in microbial fuel cells [34] and have catalytic performance in enzymatic biofuel cells [35], respectively. However, the focus of the current study is only on the former and does not include biofuel cells.

Bioenergy research with the aim of aiding the development of reliable energy sources being applicable at a commercial scale through removing technical, economic, social, and environmental obstacles have been published in scientific journals and formed the basis of policy guidelines. However, many countries are still far away from using bioenergy sustainably despite an abundance of biomass resources [36]. Slow diffusion of bioenergy technologies between theoretical attempts at the lab scale and commercialized manufacturing at the real scale has occurred due to many factors such as technical immaturity [10], socio-economic inefficiencies [37], lack of competitiveness against fossil fuels [38], inadequate investment [39], environmental considerations, as well as the nature of entrepreneurship [36,40]. To address the gap identified above, it is critical to address the prerequisites for the applicability of research results for widespread industrial use. As a result, this scientometric analysis was devised.

Scientometric analysis, which has recently gained a lot of attention in various scientific disciplines, is a practical tool for measuring the progress of a specific field of science in a given period of time [41]. In fact, the scientometric analysis aims to uncover the general trend or developments of a particular scientific subject via visualization of the attempts made by the research community including researchers, institutions, laboratories, faculties, universities, scientific publishers and journals, and public institutions.

Recently published scientometric articles in many different areas confirm the importance of mapping progress. For some examples, adopting a scientometric analysis, Marzouk and Elshaboury (2022) conducted a review of the research on embodied energy in the construction industry [42]. Khalaj et al. (2020) analyze the studies that had been done in the green synthesis of nanomaterials aiming to illustrate knowledge transferring in this area [41]. In another study, Olawumi and Chan (2018) provide valuable information on the main efforts made in the assessment of sustainability concepts in different areas [43]. Zheng et al. (2021) build a knowledge framework on the research in the Intracranial Aneurysms Magnetic Resonance Angiography domain [44]. In a review paper, Chen et al. (2021) illustrated the research efforts on the environmental impacts of construction [45], while Esfahani et al. (2021) aim to map the knowledge in the domain of energy security [46]. Demolition waste and microalgae-based wastewater treatment is also the subject of a scientometric study by Li and Zhu (2021) [47]. There are also some examples of systematic scientometric studies in the domain of bioenergy with various dimensions and a spectrum of keywords covering different periods of literature. For example, Konur (2012) [48] analyzed 6474 references targeting the studies on bioenergy production from 1980 to 2010. The search terms of *"biomass"* in the title and *(biofuel* or "bio-fuel*" or fuel* or bioenergy or "bio-energy" or energy or biomethan* or "bio-methan*" or methan* or bioethanol* or "bio-ethanol*" or ethanol* or biodiesel* or "biodiesel*" or diesel* or biogas* or "bio-gas*" or gas or biooil* or "bio-oil*" or oil* or bio-hydrogen* or hydrogen* or synfuel* or syngas* or synoil* or "syn-gas" or "syn-fuel*" or "syn-oil*" or "renewable energy" or "green energy" or "biorefin*" or "bio-refin*" or refinery)* in the topic were applied to collect the study data [48]. A year after, the intersection of organic farming and bioenergy was subject to another scientometric study by Siegmeier and Möller (2013) [49]. They investigated 46 English articles from the period 1980–2012, collected through a combined search of *("agriculture OR farm*"), ("organic agriculture" OR "organic farm*"), and ("bioenergy*" OR "biofuel*" OR "bioethanol*" OR "biodiesel*" OR "biogas*" OR "anaerobic digestion")* in topic field. In another scientometric study, Coelho et al. (2014) explored the literature on producing biofuels from macroalgal biomass through a scientometric study. For this purpose, 160 published documents gathered from the years 1945–2013, using the search terms of *"macroalgae" or "seaweed" and "biofuel*" or "green energy*" or "renewable energy*" or "hydrogen*" or "biohydrogen*" or "bio-oil*" or "pyrolysis*" or "biogas*" or "bioenergy" or "biomethan*" or "bioethanol*" or "biodiesel*"* in topic [50]. Perea-Moreno et al. (2019) targeted the research status and trends in biomass as renewable energy by analyzing relevant documents in Elsevier's Scopus database during 1978–2018 [51]. Research on the production of biodiesel from 2001 to 2019 is also subject to a bibliometric study by Andreo-Martínez et al. (2020) [52]. They collected 608 scientific articles from WOS, Science Citation Index Expanded (SCI-E), searching *("biodiesel" OR "bio-diesel" OR "bio diesel") AND ("Supercritical transesterification" OR "Supercritical condition*" OR "Supercritical methanol" OR "Supercritical ethanol" OR "Supercritical alcoholysis")* in all databases. Chubur et al. (2022) [53] analyzed the literature on the utilization of microbiological methods for producing biogas. Scientific documents were obtained from Scopus and web of science using keywords including *biogas, bioprocess, anaerobic digestion, cavitation, electrolysis, and pretreatment* [53]. Finally, Gómez-Marín and Bridgwater (2021) conducted a systematic scientometric review to illustrate the status of bioenergy research in the UK during 2005–2019 [54]. Still, the need to identify obstacles to the advancement of science in the field of bioenergy to promote the commercialization of novel technologies remains. In this sense, the present study explores the bioenergy literature using the scientometric methodology to measure the efforts made by the research community, governments, and international organizations with the purpose of identifying the opportunities and threats of transmitting knowledge to real-scale commercialization.

2. Methodology

In this study, an advanced search was carried out in the Web of Science (WoS) Core Collection database, including three indices of Science Citation Index Expanded (SCI- EXPANDED), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (A&HCI), to collate the research items in the field of bioenergy and biofuels from the beginning of WOS publications to 2022.

Four branches of the search were performed using the keywords "bioenergy", "bio-energy", "bioenergies", "bio-energies", "biofuel*", "bio-fuel*", "biodiesel", "bioethanol", "biogas", "bio oil", "bio-oil", "biohydrogen", "biomethane", "biomass", "energy", and "energies". The first branch consists of all the research items (including "articles", "review articles", "editorial materials", "letters" and "notes") which provide "biofuel*" or "bio-fuel*" in their title, and "biomass" or "energy" or "energies" or "bioenergy" or "bio-energy" or "bioenergies" or "bio-energies" or "biodiesel" or "bioethanol" or "biogas" or "bio oil" or "bio-oil" or "biohydrogen" or "biomethane" in their topic. The second branch includes "bioenergy" or "bio-energy" or "bioenergies" or "bio-energies" in the title and "biomass" or "biofuel*" or "bio-fuel*" or "biodiesel" or "bioethanol" or "biogas" or "bio oil" or "bio-oil" or "biohydrogen" or "biomethane" in the topic. The third branch of items results from the search of "biomass" in the title and, "bioenergy" or "bio-energy" or "bioenergies" or "bio-energies" or "biofuel*" or "bio-fuel*" or "biodiesel" or "bioethanol" or "biogas" or "biooil" or "bio-oil" or "biohydrogen" or "biomethane" in the topic. Finally, the fourth branch includes the research documents covering "biodiesel" or "bioethanol" or "biogas" or "bio oil" or "bio-oil" or "biohydrogen" or "biomethane" in their title. It is worth mentioning that documents containing "* fuel cell*" or "biofuel cell*" or "bio-fuel cell*" in their title, were excluded from the searched branches by placing the word "not" before these keywords. Naturally, overlaps between the four branches were removed by placing the word "or" between them (full syntax of the search query is provided in the supplementary information, text S1). It is important to select and combine appropriate keywords so that both relevant research items are found and overcrowding is avoided [41,48]. For example, if the documents were only limited to titles including "bioenergy" or "bio-energy" or "bioenergies" or "bio-energies", there would be many studies irrelevant to the topic of this study, such as [55].

By screening the WoS outputs, relevant research items were identified and analyzed according to the "publication years", "type of documents", "categories", "countries", "affiliations" and "citations". Then the items are saved as a "Marked list" to further transfer to CiteSpace software (version 6.2.R2) [56]. Additional analyzes, including "co-authorship", "citation networks" and "keywords analysis", were performed, adopting four scientometric parameters.

i) Citation counts: Total number of citations that an author, individual article, or a specific journal has received during a particular period.
ii) Citation frequency: Citation counts divided by the years.
iii) Citation burst: An indicator that represents a surge of attention to the publications in multiple years as well as a single year [43]. Suppose there are n batches of items, where in, the consist of rt relevant items from a total of dt then citation burst is calculated using Eq. (1):

$$CB(i, r_t, d_t) = -\ln\left[\binom{n}{k} P_i^{r_t} (1 - P_i)^{d_t - r_t}\right] \tag{1}$$

iv) Betweenness centrality: An index that shows the degree of centrality of a node, by calculating the shortest distance of a node with other related nodes (higher degree of centrality, higher betweenness centrality) [57]. It is determined using Eq. (2).

$$BC\ (k) = \sum_{i \neq j \neq k} \frac{\Delta_{ij}(k)}{\Delta_{ij}} \tag{2}$$

where, Δ_{ij} represents the number of shortest connecting links between nodes i and j, and $\Delta_{ij}(k)$ is the number of shortest links that traverse the node k.

3. Results

Through an advanced search of WoS (on the date 12-06-2023), 51,905 research items (including "articles", "review articles", "editorial materials", "letters" and "notes") were found in the period of 1966–2022, using combinations of keywords "bioenergy", "bio-energy", "bioenergies", "bio-energies", "biofuel*", "bio-fuel*", "biodiesel", "bioethanol", "biogas", "bio oil", "bio-oil", "biohydrogen", "biomethane" "biomass", "energy", and "energies, refined in the English language. In the following sections, the results for ten measurement techniques of the bibliographic records according to the scientometric methodology are presented and illustrated.

3.1. WoS analysis

3.1.1. History of publications

The frequency of the published documents by year is illustrated in Fig. 1. Dispersion of the number of studies follows an ascending distribution, starting with a slight uprising in the late 1990s and early 2000s, followed by a sharp bump in the late 2000s and early 2010. At the beginning of the second half of the 2010s, the rate of increase in the number of publications decreased, although it grew significantly again in 2019. After reaching the peak of the study period, in 2021, the number of publications in 2022 has declined by 7% compared to the previous year.

In the 1960s and 1970s, only 31 papers were registered, followed by 233 publications in the 1980s. In the 1990s, the number of publications doubled compared to the previous decade and increased significantly in the 2000s to 4123 publications. The decade starting from 2010 had the highest contribution in the whole period of 1966–2022, with 31,945 published research documents. After reaching the highest record of 5262 in the year 2021, the number of publications declined to 4917 items in 2022.

3.1.2. Type of documents

The distribution of the different types of documents in the field under study is shown in Fig. 2. As can be seen in the figure, the majority of the documents were published in the form of Articles (89%), followed by Review articles (10%), and other types (including Editorial Material, Notes, and letters) (1%).

3.1.3. Categories

Table 1 represents the WOS output of how published documents of all types in the subject of the present study are placed in different categories. "Energy Fuels" with a total of 24,875 published items, ranks first among various categories, followed by "Engineering Chemical" with 12,743 items, "Biotechnology Applied Microbiology" with 10,077 items, "Environmental Sciences" with 9141 items, and "Green Sustainable Science Technology" with 6554 items, etc.

3.1.4. Contribution of countries

The performance of countries based on the production of the scientific content in the field of bioenergy is shown in Fig. 3 and Table 2. Among 162 countries that have contributed to generating scientific publications, China has had the highest participation rate, 17%, with a total number of 9026 publications. The United States, with 8108 publications, has received the second position. India, Brazil, the United Kingdom, Spain, Malaysia, Germany, South Korea, and Italy, have occupied the third to tenth places with a total number of 6306, 3394, 2531, 2294, 2277, 2192, 1973, and 1880 publications, respectively (Fig. 3 and Table 2).

3.1.5. Affiliations

Contribution of the top ten affiliations/institutions in the production of science in the field of study is presented in Table 3. According to the WOS outputs, "United States Department of Energy (DOE)" had the highest participation rate among all institutions by conducting 2.51% of the 51,905 publications. "Indian Institute of Technology (IIT)" is in the second place with a 2.5% participation rate, followed by "Chinese Academy of Sciences" with a rate of 2.39%.

3.1.6. Highly cited articles

Table 4 presents the WoS report of the top 20 highly cited documents in the period under study, 1966–2022. It is worth mentioning that most of these articles are related to the period 2006–2010. Indeed, these articles have had a substantial influence on forming the

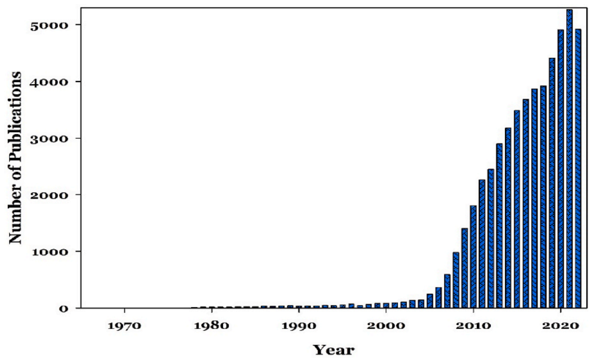

Fig. 1. Distribution of the WOS publications in the field of bioenergy, throughout 1966–2022.

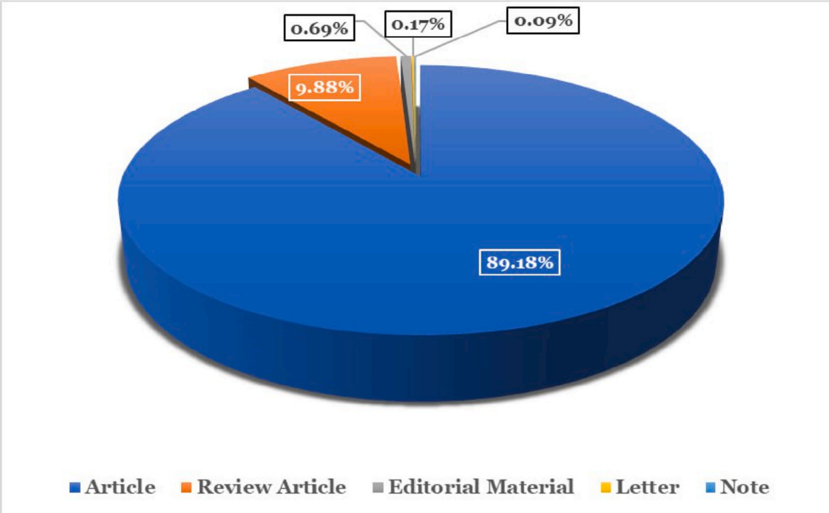

Fig. 2. Contributions of the variant types of documents in the study field. Articles make up the largest share (89%).

Table 1
Ranking categories based on the frequency of published documents.

Ranking	Categories	Frequency
1	Energy Fuels	24,875
2	Engineering Chemical	12,743
3	Biotechnology Applied Microbiology	10,077
4	Environmental Sciences	9141
5	Green Sustainable Science Technology	6554
6	Agricultural Engineering	5800
7	Engineering Environmental	4323
8	Chemistry Physical	3254
9	Chemistry Multidisciplinary	3.247
10	Thermodynamics	3179

current scientific trend of bioenergy studies.

3.2. CiteSpace analysis

3.2.1. Co-authorship

More than 96,000 authors have been involved in the production of WOS content in the field of bioenergy. According to the results attained from CiteSpace software (see Table 5), "Haji Hassan Masjuki" has had the best performance in terms of the number of publications with a total number of 161 publications in this specific field (corresponding to the defined search of keywords). "Gopalakrishnan Kumar" with 133 and "Irini Angelidaki" with 129 research documents have taken second and third positions, respectively. A co-Authorship network that reveals the cooperation between authors in establishing publications has been shown in Fig. 4, and Fig.S1 (clearer image by removing the overlaps) in supplementary information. The performance of each individual author has been shown with the node size (bigger node, more release) [56]. The cooperation between the authors is also shown by lines [56]. In addition to the strong networks forming in the center, some isolated points are also visible in the margins.

3.2.2. Co-citation

3.2.2.1. Co-cited authors. The author co-citation network reveals the relationship between distinct authors by identifying the number of times their published works have been cited in the same research items. In fact, the author co-citation parameter can represent the influence of the author on a particular field of study [41]. Three metrics including "citation frequency", "citation burst" and "betweenness centrality" have been applied in this study to examine the authors' impact on bioenergy studies. Fig. 5, and Fig.S2 (clearer image by removing the overlaps) in the supplementary information, illustrate the authors' co-citation network in the bioenergy field.

In terms of citation frequency, "A Demirbash" with a frequency of 5357 citations has the highest position. Then "Gerhard Knothe" and "Yusuf Chisti" with 3636 and 2211 citations received the second and third places, respectively (see Table 6). In addition, citation burst, which reveals an upsurge of attention to the authors' articles over a period of time, has been analyzed to measure the impact of

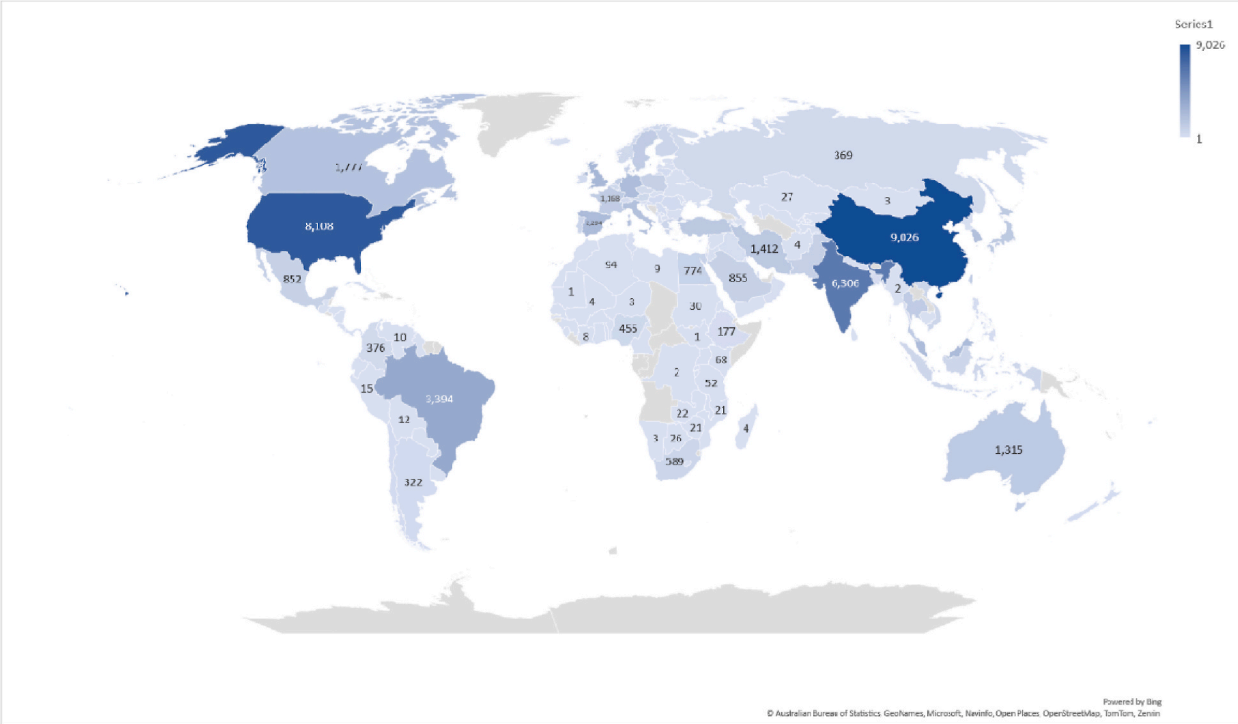

Fig. 3. Global map of the contribution of countries. China is the largest producer of the scientific content in the field of bioenergy.

Table 2
Top ten countries regarding the contribution in the scientific production in the field of bioenergy.

Ranking	Country	Number of documents	Share (%)
1	China	9026	17.39
2	United States	8108	15.62
3	India	6306	12.15
4	Brazil	3394	6.54
5	United Kingdom	2531	4.88
6	Spain	2294	4.42
7	Malaysia	2277	4.39
8	Germany	2192	4.22
9	South Korea	1973	3.80
10	Italy	1880	3.62

Table 3
Top ten organizations regarding the contribution to the scientific production in the field of bioenergy.

Ranking	Affiliations/Organizations	Country	Number of documents	Share (%)
1	United States Department of Energy (DOE)	United States	1305	2.51
2	Indian Institute of Technology (IIT) system	India	1298	2.50
3	Chinese Academy of Sciences	China	1238	2.39
4	National Institute of Technology (NIT) system	India	812	1.56
5	Egyptian Knowledge Bank (EKB)	Egypt	762	1.47
6	United States Department of Agriculture (USDA)	United States	743	1.43
7	Council of Scientific Industrial Research (CSIR)	India	643	1.24
8	University of California system	United States	560	1.08
9	Centre national de la recherche scientifique (CNRS)	France	524	1.01
10	Universiti Malaya	Malaysia	513	0.99

the authors on the advancement of knowledge in the bioenergy field. Table 7 presents the ten authors with the highest citation burst strengths. The strongest burst is recorded for “Fangrui Ma” with a value of 246.31 during 2002–2012, followed by “Bill Freedman” with a value of 196.37 during 1998–2012, and “Martin Mittelbach” with a burst strength of 153.68 during 1996–2012. Finally,

Table 4
Highly cited documents in the subject under study, during the period between 1966 and 2022.

Ranking	Title	Year	Total Citations	Ref
1	Biodiesel from microalgae	2007	6283	[58]
2	The path forward for biofuels and biomaterials	2006	4433	[59]
3	Pyrolysis of Wood/Biomass for Bio-oil: A Critical Review	2006	3889	[60]
4	Biodiesel production: a review	1999	3885	[61]
5	Microalgae for biodiesel production and other applications: A review	2010	3425	[62]
6	Biomass recalcitrance: Engineering plants and enzymes for biofuels production	2007	3278	[63]
7	Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change	2008	3069	[64]
8	Biofuels from microalgae- A review of technologies for production, processing, and extractions of biofuels and co-products	2010	2886	[65]
9	Review of fast pyrolysis of biomass and product upgrading	2012	2880	[66]
10	Pretreatment technologies for an efficient bioethanol production process based on enzymatic hydrolysis: A review	2010	2696	[67]
11	Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances	2008	2606	[68]
12	Pretreatments to enhance the digestibility of lignocellulosic biomass	2009	2559	[69]
13	Land clearing and the biofuel carbon debt	2008	2513	[70]
14	Methods for Pretreatment of Lignocellulosic Biomass for efficient hydrolysis and biofuel production	2009	2368	[71]
15	Technical aspects of biodiesel production by transesterification - a review	2006	2248	[72]
16	Overview of applications of biomass fast pyrolysis oil	2004	2166	[73]
17	Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines	2007	2104	[74]
18	Liquid-phase catalytic processing of biomass-derived oxygenated hydrocarbons to fuels and chemicals	2007	1971	[75]
19	Conversion of biomass to selected chemical products	2012	1910	[76]
20	Production of first and second generation biofuels: A comprehensive review	2010	1902	[68]

Table 5
Top ten authors regarding the number of research documents in WOS in the field of bioenergy.

Ranking	Author	Affiliation	Country	Counts
1	Haji Hassan Masjuki	Department of Mechanical Engineering, University of Malaya	Malaysia	160
2	Gopalakrishnan Kumar	Institute of Chemistry, Bioscience, and Environmental Engineering, Faculty of Science and Technology, University of Stavanger,	Norway	133
		School of Civil and Environmental Engineering, Yonsei University	Republic of Korea	
3	Irini Angelidaki	Department of Environmental Engineering, Technical University of Denmark	Denmark	129
4	Hwai Chyuan Ong	Mechanical Engineering Department, Faculty of Engineering, University of Malaya	Malaysia	126
		Centre for Green Technology, School of Civil and Environmental Engineering, University of Technology	Australia	
5	Jo-Shu Chang	Department of Chemical Engineering, National Cheng Kung University	Taiwan	120
		Center for Bioscience and Biotechnology, National Cheng Kung University		
		Research Center for Energy Technology and Strategy, National Cheng Kung University		
6	Md Abul Kalam	Centre for Energy Sciences (CFES), Department of Mechanical Engineering, Faculty of Engineering, University of Malaya	Malaysia	117
7	Roger Ruan	Center for Biorefining and Department of Bioproducts and Biosystems Engineering, University of Minnesota	USA	106
8	Wei-Hsin Chen	Department of Aeronautics and Astronautics, National Cheng Kung University	Taiwan	106
		Department of Chemical and Materials Engineering, College of Engineering, Tunghai University		
		Department of Mechanical Engineering, National Chin-Yi University of Technology		
9	Pau Loke Show	Department of Chemical Engineering, Faculty of Science and Engineering, University of Nottingham Malaysia	Malaysia	106
10	Keat Teong Lee	School of Chemical Engineering, Universiti Sains Malaysia	Malaysia	99

according to the betweenness centrality criterion, "D.O. Hall" and "A Demirbaş" have the highest centrality of 0.11 followed by "Fangrui Ma" with a centrality of 0.09 (see Table 8).

3.2.2.2. Co-cited journals. Journal co-citation analysis provides important information about the impact of various journals in advancing bioenergy science. Fig. 6, and Fig.S3 (clearer image by removing the overlaps) in supplementary information display the journal co-citation network. Three metrics of "citation frequency", "citation burst" and "betweenness centrality" have been assessed through the CiteSpace program. "Bioresource Technology", "Renewable & Sustainable Energy Reviews" and "Biomass & Bioenergy" have been ranked as the three most effective journals regarding citation frequency with total citations of 33033, 25264, and 24944 respectively (see Table 9). According to the strength of a peculiar influence in a period of time, "Journal of the American Oil Chemists' Society" with a burst of 637.17 during 1998–2013, "Biomass Conversion and Biorefinery" with a burst of 450.86 during 2021–2022, and "Thesis" with a burst of 402 during 2016–2020 were ranked as the top three journals with strongest citation burst (see Table 10). Ultimately, considering the betweenness centrality parameter, "Science" has the highest centrality of 0.07 followed by "Biotechnology and Bioengineering", "Bioresource Technology" and "Applied and Environmental Microbiology" with betweenness centralities of 0.04

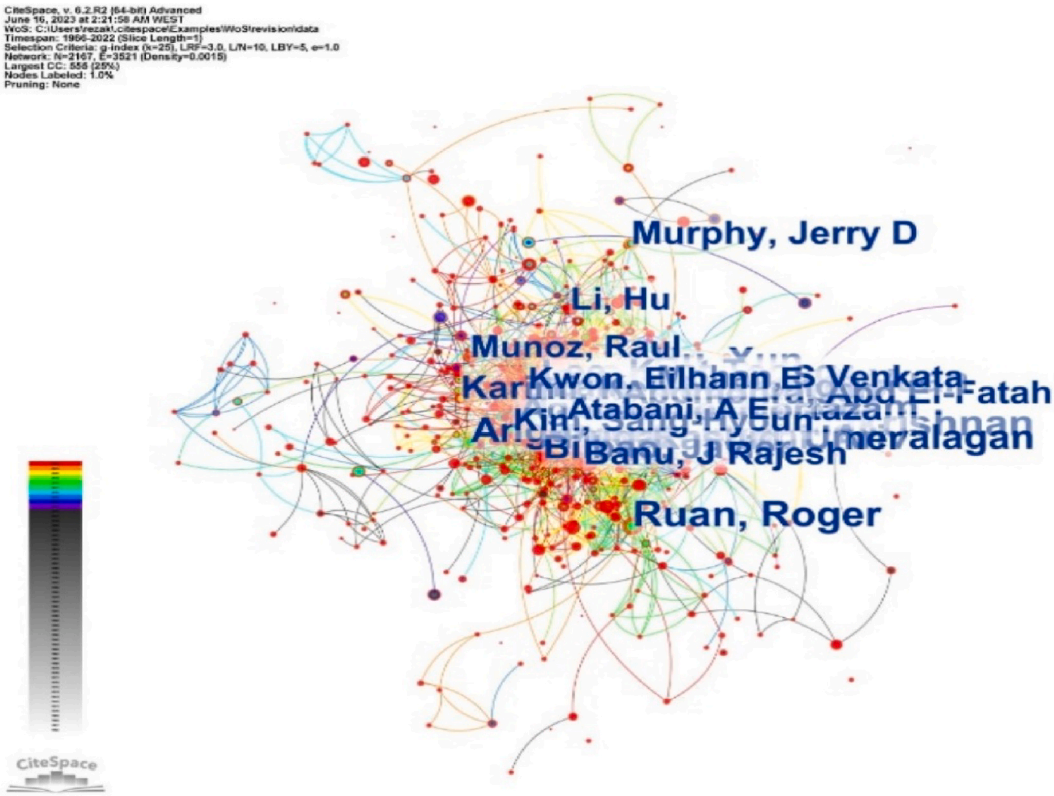

Fig. 4. Co-authorship network which shows the connections between the authors in the production of scientific documents in the field of bioenergy. The node size indicates the contributions of individual authors, and the lines show the frequency of collaboration [43].

(see Table 11).

3.2.3. *Keywords*

Keywordscan greatly describe the domain of a scientific research [43]. Therefore, illustrating the network of keywords to indicate the relationships as well as usage frequency, in addition to mapping the keyword developments in bioenergy literature can build a guideline for the research community about the salient topics in different periods of time to identify gaps and draw a clear path for the future.

The network of keywords has been depicted using CitaSpace software (see Fig. 7 and Fig.S4). It is worth mentioning that both “author keywords” and “keywords plus” have been used in this scientometric study. In Fig. 7, each node represents a keyword that is sized according to the frequency of usage. The links also reveal co-occurring of different keywords. According to the outputs of CiteSpace software (Table 12), “biomass”, “performance ”, “anaerobic digestion ”, “transesterification ”, “optimization ”, “energy ”, “oil ”, “fuel ”, “ethanol” and “conversion” have been the most frequent keywords in bioenergy literature. Moreover, Table 13 ranks the keywords regarding the strength of the burst, specifying the time of occurrence. Three keywords with the strongest burst were “vegetable oils” with a burst of 140.94 during 1996–2011, “esters” with a burst of 139.08 during 1996–2013, and “transesterification” with a burst of 134.61 during 2004–2011.

4. Discussion

In this section, by reviewing the history of the conducted studies in the field of bioenergy, taking into account national and international policy implications, the evolution of the state of the art is discussed. In order to better consider the evolution of studies in the field of bioenergy and biofuel, the discussion in this section is based on the landmarks of the decades, starting from the first decade (the 1960s) to the last decade (2020s) under the study period 1966–2022.

According to the data attained from WOS, the beginning of the scientific attempts to exploit energy from human wastes dates back to 1964 with a study trying to produce an enzymatic biofuel cell [77]. Then, the first article in the domain of the current study, aiming to explore the possibility of using biogas in motor use and its economic importance, has been registered in 1966. In the scope of the searched keywords, scattered studies have been conducted in the 1960s and 1970s and about 31 documents were published, mostly related to the generation of biogas from agricultural waste [78]. which is the most cited article in this period, preliminarily, studies the production of biogas via anaerobic digestion of fruit and vegetable waste. It seems that along with the establishment of the

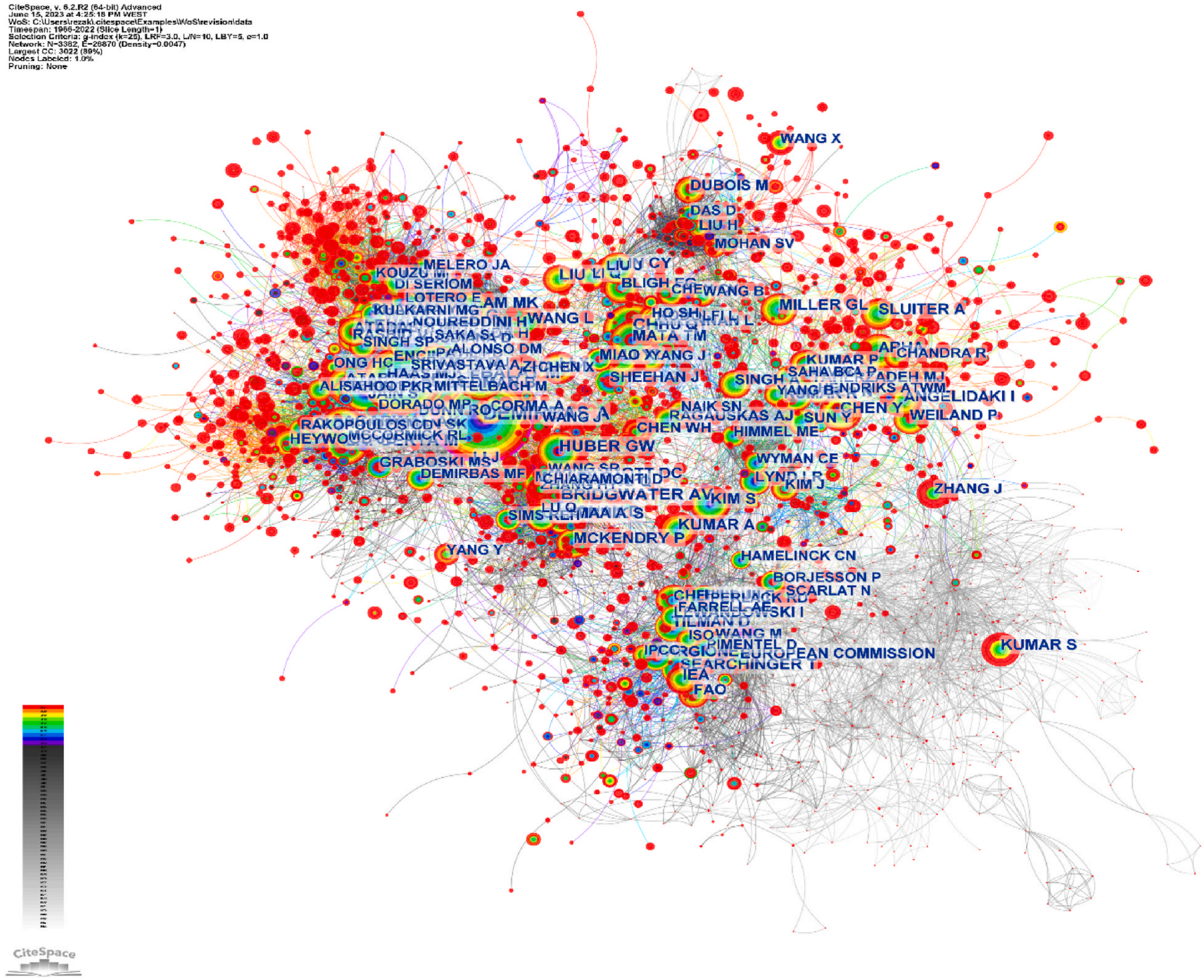

Fig. 5. Author co-citation network shows the relationship between the authors whose works have been cited simultaneously by the third research item. Node sizes indicate the number of citations, and the lines show co-citation frequency.

Table 6
Top ten authors with high citation frequency.

Ranking	Author	Affiliation	Country	Citation frequency
1	A Demirbaş	Department of Industrial Engineering, King Abdulaziz University Department of Renewable Energy, Sila Science, Trabzon	Saudi Arabia Turkey	5357
2	Gerhard Knothe	National Center for Agricultural Utilization Research, Agricultural Research Service, U. S. Department of Agriculture	USA	3636
3	Yusuf Chisti	Institute of Tropical Aquaculture and Fisheries, Universiti Malaysia	Malaysia	2211
4	Anthony V. Bridgwater	Bioenergy Research Group, EBRI, Aston University	United Kingdom	2050
5	Fangrui Ma	Department of Food Science and Technology, University of Nebraska	United States	1985
6	Mustafa Balat	Sila Science and Energy Unlimited Company	Turkey	1816
7	Mustafa Canakci	Department of Automotive Engineering, Kocaeli University	Turkey	1711
8	Yi Wang	State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology	China	1583
9	George W Huber	Department of Chemical and Biological Engineering, University of Wisconsin	United States	1457
10	Lekha Charan Meher	Centre for Rural Development and Technology, Indian Institute of Technology Defence Institute of Bio-Energy Research	India	1397

Table 7
Top ten authors regarding citation burst strength.

Ranking	Author	Affiliation	Country	Burst Strength	Period
1	Fangrui Ma	Department of Food Science and Technology, University of Nebraska	United States	246.31	2002–2012
2	Bill Freedman	Department of Biology, Dalhousie University	Canada	196.37	1998–2012
3	Martin Mittelbach	Institute of Chemistry, University of Graz	Austria	153.68	1996–2012
4	Michael S. Graboski	Colorado Institute for Fuels and High Altitude Engine Research and Department of Chemical Engineering and Petroleum Refining, Colorado School of Mines	United States	120.9	1999–2013
5	Alexander E Farrell	Energy and Resources Group, University of California	United States	115.61	2006–2013
6	Joseph E. Fargione	The Nature Conservancy, Minneapolis, Minnesota	United States	112.28	2008–2013
7	Timothy D. Searchinger	Princeton School of Public and International Affairs, Princeton University,	United States	109.93	2009–2013
8	Hideki Fukuda	Division of Molecular Science, Graduate School of Science and Technology, Kobe University	Japan	109.3	2002–2011
9	John Sheehan	Department of Soil and Crop Sciences, Colorado State University	United States	109.06	2005–2013
10	Mustafa Canakci	Department of Automotive Engineering, Kocaeli University	Turkey	108.21	2003–2011

Table 8
Top ten authors regarding betweenness centrality.

Ranking	Author	Affiliation	Country	Centrality
1	D.O. Hall	Department of Plant Sciences, King's College	United Kingdom	0.11
2	A Demirbaş	Department of Industrial Engineering, King Abdulaziz University Department of Renewable Energy, Sila Science, Trabzon	Saudi Arabia Turkey	0.11
3	Fangrui Ma	Department of Food Science and Technology, University of Nebraska	United States	0.09
4	Donald L. Klass	Entech International, Inc., Barrington,	United States	0.05
5	Anthony V. Bridgwater	Bioenergy Research Group, EBRI, Aston University	United Kingdom	0.05
6	Charles L Peterson	Dept. of Biological and Agricultural Engineering, University of Idaho, Moscow,	United States	0.04
7	Charles E. Wyman	Center for Bioenergy Innovation, Oak Ridge National Laboratory Chemical and Environmental Engineering Department, University of California	United States	0.04
8	Chiu-Yue Lin	Department of Environmental Engineering and Science, Feng Chia University	Taiwan	0.04
9	Victror Nallathambi Gunaseelan	Nallathambi Gunaseelan, Department of Zoology, PSG College of Arts and Science, Coimbatore	India	0.04
10	Michael A. Borowitzka	Algae R&D Centre, Environmental and Conservation Sciences, Murdoch University	Australia	0.04

International Energy Agency (IEA) Bioenergy in the late 1970s (1978) and its supporting policies of bioenergy research, development, and deployment, the number of publications grew so that in the 1980s, the number of WOS publications reached 233 research items (Fig. 1).

The maturity of the studies in bioenergy as an alternative to conventional fuels started in the late 1990s and early 2000s. In the 1990s, concerns regarding greenhouse gas emissions and global warming [79] along with increasing energy demand [80] had driven countries to set up bioenergy research programs to advocate for innovation and knowledge advancement in modern bioenergy technologies to extract energy carriers from biomass, especially in the forms of electricity, biogas, and biofuels for transportation, rather than the only traditional use of biomass for heat and electricity. For example, in 1991, to support and encourage the development of biofuels used in the transportation sector, the Swedish government allocated 120 million crowns for studies in this field. After about six years of research, the results indicated the existence of technical defects in both biofuels and engines, which needed improvements [81]. In fact, the potentials for processing bioethanol and biodiesel from edible crops, which were later called first-generation biofuels, and their pros and cons were subject to tens of research items (for example [82,83]) in this decade so that "vegetable oils", "esters", "rapeseed oil" and "diesel fuel" were among keywords with the strongest burst (Table 13).

European countries were responsible for over 34% of the total 485 publications in the 1990s, while India with 24%, and the USA with 22% had the highest contributions. Surprisingly, China published only nine documents in this decade. The most influential article of this decade is dedicated to "Biodiesel production: a review" [61] which also maintains the fourth place amongst the highly cited documents, with 3885 citations (Table 4). This article reviews alternative approaches attributed to biodiesel production including direct use and blending, microemulsions, pyrolysis, and transesterification. Finally, the largest number of publications belongs to David O Hall [84], who has been the most prolific author of this decade with 11 publications.

In 1997, adopting the "White Paper for a Community Strategy and Action Plan", the European Union set up a goal of doubling the share of renewable energy sources from 6% to 12% in the gross final energy consumption by 2010 [85]. While a major part of the renewable sources of energy in that period was provided by the traditional use of burning woody biomass [26], the White paper

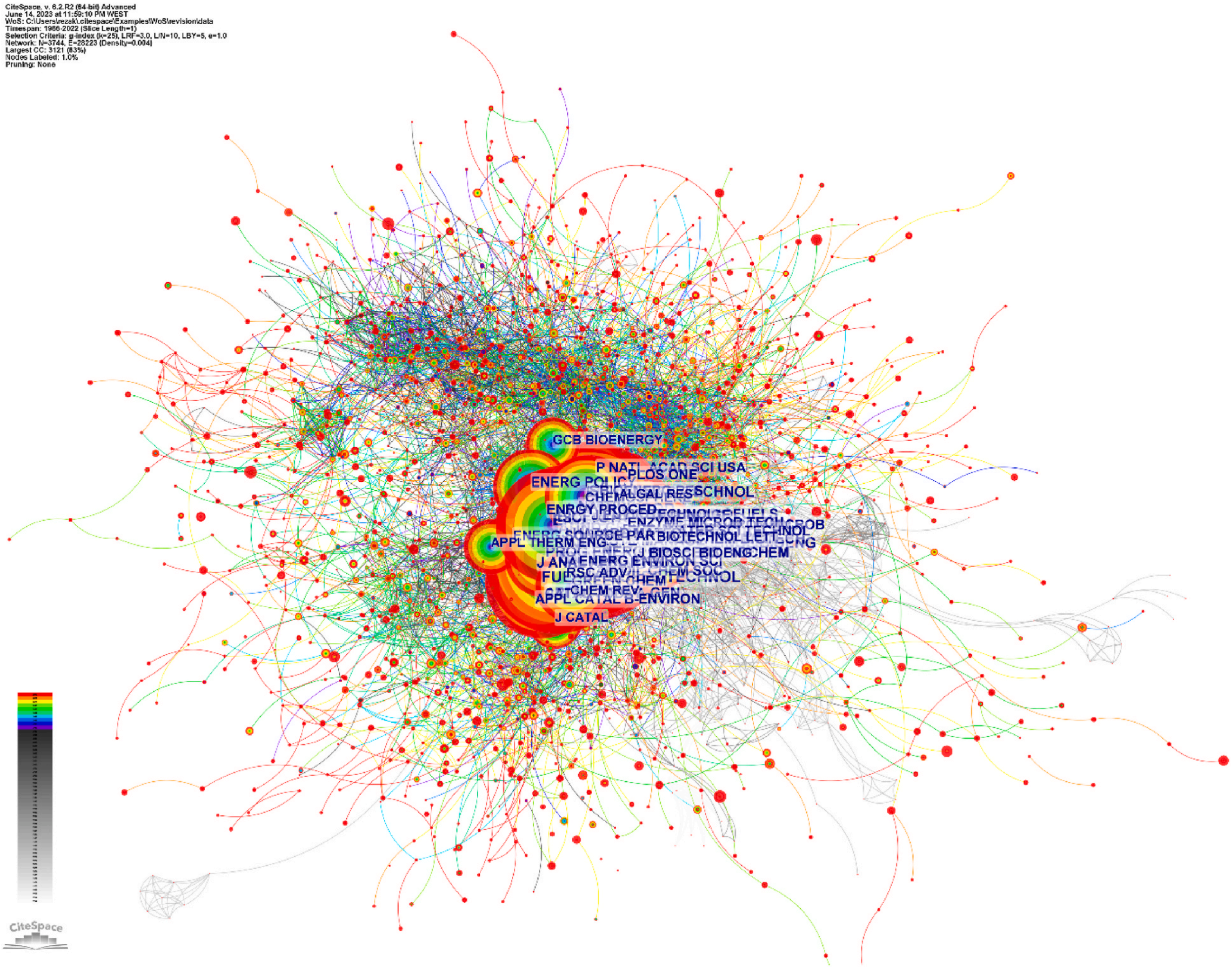

Fig. 6. Journal co-citation network shows the relationship between the journals in which their publications have been cited simultaneously by a research item. Node sizes indicate the number of citations, and the lines show co-citation frequency.

Table 9
Top ten journals with high citation frequency.

Ranking	Journal	Citation Frequency
1	Bioresource Technology	33033
2	Renewable & Sustainable Energy Reviews	25264
3	Biomass & Bioenergy	24944
4	Fuel	22635
5	Renewable Energy	18291
6	Applied Energy	17554
7	Energy Conversion and Management	16437
8	Energy & Fuel	16256
9	Energy	14677
10	Fuel Processing Technology	13731

promoted member states to take steps to increase awareness and knowledge of new biomass energy deployment technologies, and their relative technical, environmental and economic aspects. On the other hand, according to the Kyoto protocol adopted in 1998, the United Nations developed member states agreed to limit their greenhouse gas (GHG) emissions to the individual specified targets [86].

In the 2000s, a total number of 4123 research documents were published in WOS, in the domain of the searched keywords, although around 86% were published in the second half of the decade. Since 2005, the number of studies in the field of bioenergy has risen sharply (Fig. 1). In the meantime, scientific articles made up the majority of the research items. The wide range of studies in bioenergy in the late 2000s can be attributed to the renewable energy policies established worldwide, especially in industrialized countries, to tackle global climate change and provide security of energy supply. At the European-Union level, some major directives

Table 10
Top ten journals regarding citation burst strength.

Ranking	Journal	Burst Strength	Period
1	Journal of the American Oil Chemists' Society	637.17	1998–2013
2	Biomass Conversion and Biorefinery	450.86	2021–2022
3	Thesis	402	2016–2020
4	Journal of the ASABE	383.23	1999–2014
5	Sustainability-Basel	383.02	2021–2022
6	Science of The Total Environment	352.41	2021–2022
7	Energies	352.03	2021–2022
8	Journal of Environmental Chemical Engineering	350.05	2021–2022
9	Science	327.3	2006–2013
10	Processes	307.64	2021–2022

Table 11
Top ten journals regarding betweenness centrality.

Ranking	Journal	Centrality degree
1	Science	0.07
2	Biotechnology and Bioengineering	0.04
3	Bioresource Technology	0.04
4	Applied and Environmental Microbiology	0.04
5	Water Research	0.03
6	Agricultural Wastes	0.03
7	Fuel	0.03
8	Energy Conversion and Management	0.03
9	Journal of the ASABE	0.02
10	Cleaner Production	0.02

had been set in this decade to promote renewable energies. For example, in 2001, the European Parliament made a target of 22.1% for the share of renewable sources of total electricity consumption by 2010 [87]. As a result, following wind power, electricity produced from biomass had the second-largest increase of 89 TW h from 2000 to 2010 [88]. In 2003, also, approval of the Biofuels Directive [89] encouraged member states to move towards supplying a share of 5.75% of the overall transportation fuel use by biofuels or other renewable fuels by 2010 [89], although in reality only 4.4% was achieved [88]. In the United States, the Department of Energy, in 2006, made a target of supplying 30% of the transportation fuels from biofuels by 2025 [59].

All these national and international support programs and policies have encouraged researchers to study bioenergy technologies, their technical and economic issues, environmental impacts, and their capacity to reduce greenhouse gas emissions. So, in a collective effort, in 2005, academic members from around the world, with the statement “Global response to climate change” [90] addressed world leaders in G8, as their nations were responsible for most of the greenhouse gas emissions, to take urgent actions to mitigate climate change consequences and to take this issue into account in all their national and international strategies. These joint science academies were committed to helping governments to deal with climate change challenges at national and international levels [90].

It is noteworthy that seventeen out of the twenty most influential articles, in terms of the number of citations, have been published between 2006 and 2010 (Table 4). Reviewing highly cited articles remarked as influential articles, reliable observations regarding the status of the real application of biofuels, and the state of the studies, influential ideas, theories and methods, and emerging trends, as well as an outlook on the future, are achievable. In the 2000s, the prominent sources of biofuels apart from solid forms of firewood for heating in less developed countries [91] and wood chips and pellets for heating and electricity generation in developed countries [26], for transportation at the commercial level were biodiesel obtained from transesterification of vegetable oils like rapeseed, soybean, sunflower seed, or animal fats and waste grease in Europe, Brazil, Argentina, USA, and China [26], and, in a larger scale, ethanol fermented from sugarcane in Brazil [59], corn in USA [59,74], wheat and sugar beet in Europe [74], corn, wheat, and cassava in China [26], and corn and wheat in Canada [26,92].

However, despite consensus on the need for energy recovery from bioresources, the sustainability aspects associated with biofuels derived from these agricultural crops as the primary source of renewable energy were considered important and in need of being discussed, so that considerable socio-economic and environmental trade-offs [58,62,70,93–96] limited the potential from the commercialization of these energy sources. Inevitably, producing biofuels from edible biomass threatens food security, both in terms of prices and quantity [97]. Competition with the food industry for land and water resources would result in rising prices and food shortages [98], and consequently public discontent [99]. Chisti (2007) [58] shows that supplying only half of the USA transport fuel needs by biodiesel originating from oil crops, waste cooking and animal fat will require extensive areas of oil crop cultivation, unsustainably. Chisti (2007) estimated that 24% of the United States' cropland will need to be devoted to oil palm cultivation to supply only 50% of the demand for transportation fuel. Hill et al. (2006) [94] also display, even by utilizing the entirety of harvested crops, the amount of ethanol and biodiesel extractable from corn and soybean in the USA would be enough only to meet a small portion of the demand in the country. Hill et al. (2006) investigated the costs and benefits of biofuel production and concluded that the economic profitability of capturing energy from these organic sources depends on the oil prices due to the high cost of biofuel production [94].

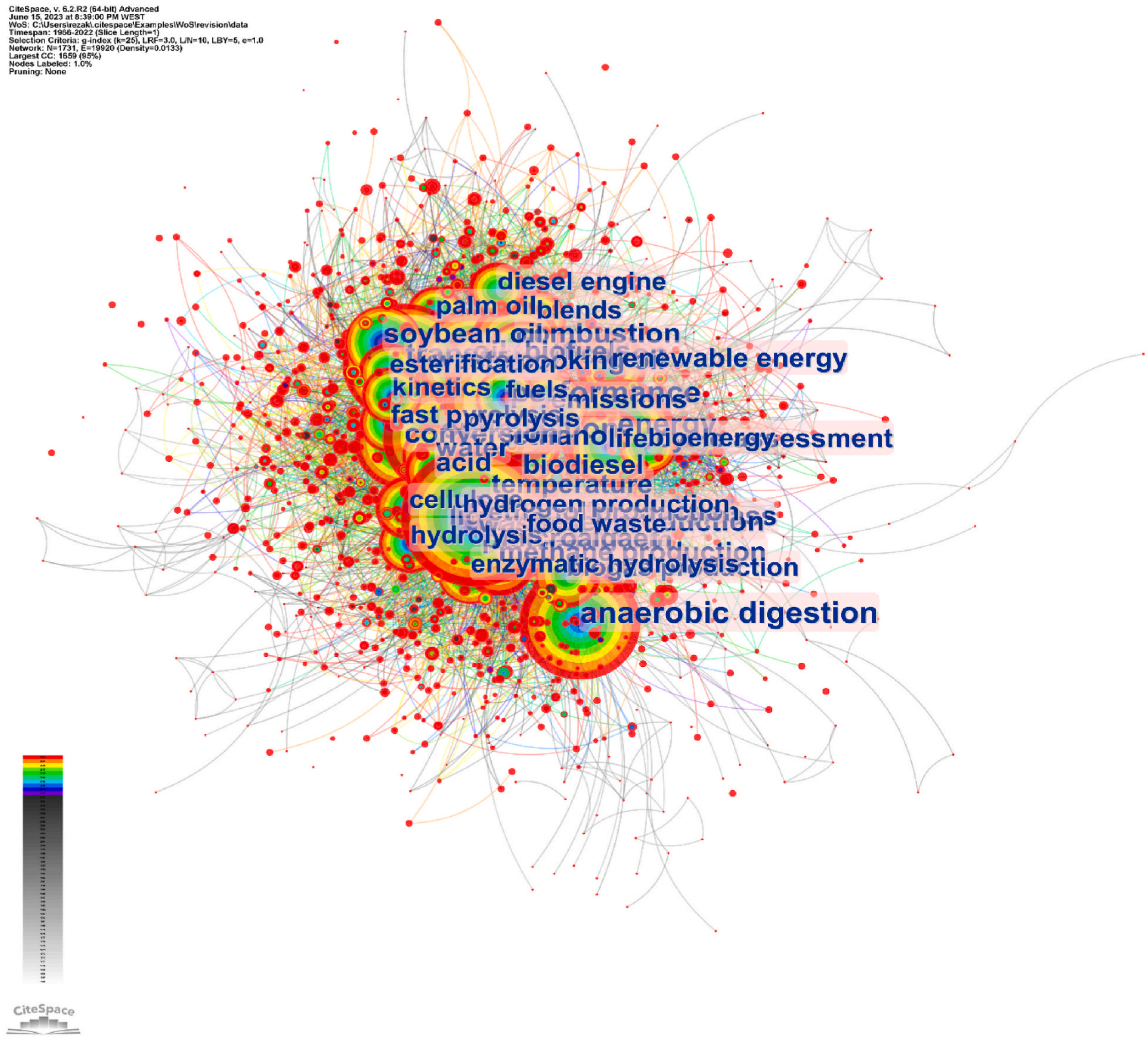

Fig. 7. Network of keywords. Keywords with more than 1000 repetitions are visible in the pictures. Node sizes indicate the frequency, and the lines show the co-occurring frequency.

Concerning the environmental impacts, their results demonstrated the benefits of reducing greenhouse gas emissions by 12% and 41% by replacing fossil fuels with bioethanol and biodiesel, respectively. However [64,70], criticize these kinds of environmental assessments, as they neglect the long-term negative impacts of changing land use from forests and pastures to croplands to produce biofuels. Adopting a worldwide agricultural model, Searchinger et al. (2008) predicted greenhouse gas emissions to double in 30 years and continue to increase for 167 years due to land-use change [64]. Joseph et al. (2008) also address the same problem by raising the issue of "biofuel carbon debt" [70]. This study shows that land-use change in Brazil, Southeast Asia countries, and the USA would increase the emission of carbon dioxide by 420 times more than the annual carbon saving anticipated by replacing the production and consumption of fossil fuels with derived biofuels.

Undesired effects of crop-based biofuels paved the way for the development of more advanced generations of bioenergy technologies to produce biofuel from lignocellulosic biomass (second-generation) or algae (third generation), as were the subject of most of the highly cited studies (Table 4), although not being commercially available technologies in that time. Unlike first-generation, the availability of feedstocks is not a problem in the production of second-generation biofuels, as cellulose is the most abundant biopolymer on earth [100]. However, more advanced biofuel technologies attributed as second-generation technologies were required to ensure taking advantage of non-food biofuel feedstocks [68]. Research afterward focused on the different features of the process to discover techno-economically efficient technologies for generating cellulosic biofuel with minimal environmental impacts. While the development of biofuels from microorganisms was only in the early stage of studying the aspects of lipid metabolism and searching for

Table 12
Top twenty keywords regarding the frequency of usage.

Ranking	Keyword	Frequency
1	biomass	4780
2	performance	3974
3	anaerobic digestion	3537
4	transesterification	3486
5	optimization	3323
6	energy	3142
7	oil	2890
8	fuel	2554
9	ethanol	2436
10	conversion	2387
11	lignocellulosic biomass	2351
12	combustion	2029
13	fermentation	1950
14	growth	1875
15	pretreatment	1844
16	soybean oil	1826
17	biodiesel production	1813
18	biofuels	1720
19	temperature	1715
20	life cycle assessment	1678

Table 13
Top twenty keywords in terms of burst strength.

Ranking	Keyword	Burst	Period
1	Vegetable oils	140.94	1996–2011
2	Esters	139.08	1996–2013
3	Transesterification	134.61	2004–2011
4	Rapeseed oil	123.65	1996–2013
5	Fuel	113.88	2002–2011
6	Diesel fuel	79.85	1996–2012
7	Ethanol	62.82	2008–2013
8	Vegetable oil	59.32	2005–2013
9	Fuels	56.46	2007–2013
10	Circular economy	55.75	2020–2022
11	Methyl esters	53.95	2004–2012
12	Kinetics	51.61	2003–2010
13	Mmethanol	51.42	2007–2012
14	Biofuels	47.27	2011–2013
15	Candida antarctica lipase	41.2	2001–2012
16	Biological hydrogen production	38.29	2004–2014
17	Fuel ethanol	37.45	2007–2013
18	Costs	36.87	2007–2013
19	Supercritical methanol	36.32	2007–2012
20	Corn	34.48	2007–2014

techno-economically efficient techniques of algal cultivation and oil derivation.

The upward trend in the number of studies, especially in the form of articles, continued under USA leadership followed by China in the 2010s (Figs. 1 and 3). In this decade, more studies have been conducted, focusing on advanced methods of generating all types of biofuels, such as bioethanol, biodiesel, biobutanol, bio methanol, biogas, bio-oil, synthetic biofuels, drop-in fuels, or biohydrogen from mostly cellulosic materials and relatively less micro and macroalgae. All of the keywords with a burst over 15 in the 2010s are related to the advanced generations of biofuels, sorted by strength of burst, like "biofuels", "inhibitors", "liquid fuel", "economics", "valorization", "cell wall", "miscanthus", "culture", "algae", "mas-transfer", "co-pyrolysis", "physicochemical property", "biological pretreatment", and "hydrothermal pretreatment".

In the meantime, continuous international agreements to replace fossil fuels with renewable energies have promoted the publication of bioenergy studies. For example, in 2009, the European Union via a renewable energy directive [101] set the target of supplying 20% of the total energy consumption and 10% of the total transportation fuel consumption through renewables by 2020. However, this directive had several substantial amendments, including a modification in 2015 [102] in a way that a maximum of 7% of the transportation fuels can be supplied by traditional crop-based biofuels and the rest 3% must be fed from non-crop-based advanced generations of biofuels or other renewables [102]. Subsequently, in 2018, via another directive promoting the use of energy from renewable sources, the European Union set the target of meeting at least 32% of the final energy consumption and at least 14% of the final energy consumption in the transportation sector through renewable sources by 2030 [103].

The European Commission committed in the "*Roadmap for moving to a competitive low carbon economy in 2050*" [104] to take the path towards a low carbon economy in a cost-efficient way to reach a reduction of greenhouse gas emissions to 80–95% by 2050 comparing to 1990 level, where the role of energy systems is challenged. The potential for supplying 75% of gross final energy consumption by renewable energies by 2050 had been targeted, emphasizing the role of novel renewable technologies, including second and third-generation biofuels [105]. In the United States, the legislation of the Energy Independence and Security Act of 2007 [106] set the volume standards for biofuels in upcoming years, targeting 36 billion gallons of biofuels by 2022, of which 21 billion gallons are produced from non-food advanced biofuels, specifically 16 billion gallons produced from cellulosic materials. Accordingly, the U.S. government allocated 385 million dollars in subsidies to support the development of advanced non-crop-based production of biofuels [107].

Eventually, commercial production of biofuels from cellulosic material for the first time was realized in October 2013 by an Italian company, Beta Renewables, extracting bioethanol from enzymatic hydrolysis of wheat straw and giant reed with a nominal capacity of 20 million gallons per year [26], although being shut down four years later. Several other bioethanol plants had a similar fate in recent years [108]. In fact, the high cost of the pretreatment stage, as well as its technical inefficiencies, had been the main challenges in the large-scale production of biofuels from lignocellulosic materials [109]. Recently, examining different process parameters including storage of biomass [110], pretreatment techniques [109,111], value-added byproducts, process residues usage, etc., as well as integrated biorefinery possibilities [100,112] through lab-scale research projects, have made good progress in overcoming costs and reducing prices. For example, a considerable amount of research has been focused on tackling the main failure of ethanol extraction from lignocellulosic biomass, which had been related to the technical, economical, or environmental limitations of the depolymerization technologies of cellulose and hemicellulose into fermentable sugars [63,111,113]. As a result of advancements, bioethanol extraction via biochemical microbial route, as well as generation of bio-oil through a thermochemical fast pyrolysis process, has been close to the initial stage of commercialization [114].

Despite the large potential of generating biofuels from algae due to high lipid and carbohydrate contents in addition to its high growth rate [115], relatively few studies, around 3800 WOS publications, have been conducted, during 1966–2022, focusing on different dimensions of the sustainability of producing biofuels from these productive sources, as potentially they are more productive than lignocellulosic biomass. Research, in the 2010s and early 2020s, has focused on sustainable biorefineries through which high value-added byproducts derived from protein and mineral contents of algae can reduce biofuel production costs [28,116]. The bulk of the cost of algae biofuels is related to the cultivation and harvesting of algae biomass, processing, and lipid extraction which all are highly energy-consuming [30,116]. Apart from the economical aspects, resolving technical issues, such as the instability of algae biofuel due to the essence of algal lipid, which is highly unsaturated oil, has been subject to algae studies [33] in the last decade. Recently, as an advancement, metabolic engineering of microorganisms has entered the alga biofuel topics under fourth-generation biofuels [116]. The latter aims to introduce more sustainable generations of biofuels via genetically modified microorganisms, to minimize the environmental drawbacks of the previous generations by eliminating carbon emissions, although it still is an infant research endeavor.

In the first three years of the 2020s, the number of articles has progressed considerably. So that 15,088 research documents have been published only in three years, leading by China (Figs. 1 and 3). In addition to China, India, and Malaysia had significant progress in terms of the production of scientific content in recent years. Even two Indian organizations of "Indian Institute of Technology (IIT) system" and "National Institute of Technology (NIT) system" have taken first and third places among the most productive organizations in the last three years, while appropriating the second place by "Egyptian Knowledge Bank (EKB)" (Table 3).

It is worth noting that the keyword of "circular economy" has attracted a lot of attention from bioenergy researchers during 2020–2022 so that with the burst strength of 55.75 has been placed in the tenth position among the keywords with the strongest burst (Table 13). Also "environmental sustainability" has been a highly regarded keyword with a burst strength of 16.98 during 2021–2022. Reviewing the most repeated keywords (Table 12) also gives us an indicator of the desire of the scientific community for more advanced and sustainable generations of bioenergy and biofuels. On the other hand, according to WOS categories of the scientific documents, a significant number of studies have been classified as "Environmental Sciences" and "Green Sustainable Science Technology" (Table 1), having a growth of 6% in the last three years compared to the last decade. It can be concluded that the sustainability of biomass utilization and resource usage to generate environmentally friendly and economically feasible energy systems is of high importance in the research communities in the 2020 decade.

5. Future outlook

Regarding a big gap between abundant theoretical attempts and relatively low real applications, in addition to the need for technical advancements, for bioenergy technology to be a large-scale commercialized energy generator, it is of vital importance to serve all other dimensions of sustainability, including techno-economic, socio-economic, and environmental concerns. Due to the fact that bioenergy can be extracted from several sources and also various industries are involved in the processing of biomass for different applications in the forms of solid, liquid, or gaseous energy, sustainability assessment of bioenergy technologies is of high importance, especially in terms of the current and applicable policies. This requires extensive interdisciplinary collaboration from biology and engineering to economics and social science to study the bioenergy systems in an integrated manner so that eventually reliable energy alternatives to fossil fuels are achievable. Identifying sustainability criteria in different technical, social, economic, and environmental dimensions may have a significant contribution to the development of sustainable bioenergies. Multi-criteria decision-making analysis such as fuzzy-Delphi would be a good practice to prioritize the various identified criteria and subsequently to prioritize efficient methods and processes, ensuring the involvement of experts from different specialized fields. Data shortage is also one of the issues that have been raised widely as bottlenecks to transforming pilot-scale to large-commercial scale bioenergy technologies. Taking advantage of simulation models may be able to alleviate this problem, somehow.

6. Conclusion

The current scientometric study provided a quantitative and qualitative overview of the studies concerning the development of bioenergy (in terms of technical, environmental, economic, social, etc.), and discussed the policy implications in order to identify the obstacles and opportunities of transmitting knowledge to real scale applications. Totally, 51905 research items retrieved from WOS were analyzed via ten scientometric measurement techniques including "history of publication", "type of documents", "categories", "contribution of countries", "affiliations", "highly cited articles", "co-authorship networks", "author co-citation networks", "journal co-citation networks" as well as "keyword analysis". Parameters such as publication counts, citation frequencies, and burst and betweenness centrality were applied to measure the efforts authors and journals have made in scientific production in the studying area. The main conclusion regarding the results achieved in this study is as follows.

1 The dispersion of the number of studies follows an ascending distribution, with a sharp increase starting from the second half of the 2000s. It seems that the high growth of publications over time has resulted from national and international policy objectives to replace fossil fuels with renewable sources of energy.
2 Among 162 countries involved in scientific production in the bioenergy field, China, the United States, and India by far had the most contributions. In addition, taking seven positions of the ten most prolific institutions displays the leadership of these countries in the field of study.
3 Reviewing the highly cited papers which are mostly published in the 2000s and early 2010s, an emerging trend of bioenergy science in the period is observable. The dominant idea in this period, especially in the late 2000s, was the need to use more sustainable biomass resources like lignocellulosic biomass and algae instead of agricultural crops, and efficient technologies to meet the uprising fuel needs.
4 More than 96,000 authors contributed to the production of WOS content in the field of bioenergy. The most prolific author in terms of the number of publications, citation frequency, citation burst strength, and betweenness centrality were "Haji Hassan Masjuki", "A Demirbaş", "Fangrui Ma" and "David.O. Hall", respectively.
5 The journals "Bioresource Technology", "Journal of the American Oil Chemists' Society", and "Science" demonstrated the highest citation frequency, strongest citation burst, and the highest degree of centrality, respectively.
6 Reviewing the most frequent keywords and the evolution of keywords in terms of burst strength provides evidence of the technological advancements from the primary first generation to the advanced second and third generations.
7 Discussing the evolution of studies between 1966 and 2022, it was evident that the sustainability of organic materials and conversion technologies has been the most important factor in preventing or promoting the development of bioenergy technologies. In fact, for a technology to reach the field of commercial scale, it is necessary to enrich all dimensions of sustainability including technical, techno-economic, socio-economic, and environmental aspects.

Author contribution statement

Akram Jahanshahi: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Myriam Lopes: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Miguel Brandão: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Eduardo Anselmo De Castro: Conceived and designed the experiments; Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of competing interest

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e20000.

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