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Review Article

An Overview of Algae for Biodiesel Production Using Bibliometric Indicators

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Algae are a desirable biodiesel feedstock because they take up little space, have a high algal-cell biomass per unit area, and can sustainably meet a large portion of the world's future energy needs. Using several bibliometric indicators, this study assesses the research productivity of algae for biodiesel production. The dataset was retrieved from the Scopus database using an appropriate keyword search. The VOSviewer v1.6.18 and Biblioshiny in *R*-studio were then utilised for bibliometric analysis and network visualisation. The study found that, with the first article being published in 1990 and an annual scientific growth rate of 14.76%, research on algae for the generation of biodiesel is still in its early phases. Although the possibility of utilising algae to produce biodiesel was originally mentioned in 1990, it was only until 2006 that several researchers started to show an interest in the subject. 101 articles were published in 2015, which is the most ever. The most prolific countries in terms of publications, ongoing collaborations and cooperation, best publishing institutions, and prestigious journals, as well as the most productive researchers and the most highly referenced works in the field, have all been recognised and presented. Finally, a keyword co-occurrence analysis of the subject was presented and discussed to provide research insights into the field. The bibliometric indicators of the study are intended to aid researchers in finding potential research topics, high-quality scientific literature, and suitable journals for publishing research on algae for biodiesel production.

1. Introduction

The world's reliance on fossil fuel energy has been connected to a variety of economic and environmental issues, including air pollution, ecological degradation, climate change, global warming, and an ever-increasing in crude oil prices [1]. Fossil fuel consumption has increased throughout history as a consequence of human population growth and industrialisation, placing a strain on fossil fuel reserves and price trends. At the current consumption rates, the depletion of fossil fuels is expected to pose significant challenges in the near future [2]. Global concern about these challenges has spurred researches on the development of new energy sources as a replacement for fossil fuels, with renewable energy sources from hydropower, wind, solar, and biofuel being presented as viable solutions. Biodiesel is the most widely used biofuel among renewable energy sources due to its advantages for the environment, such as biodegradability and clean burning [3–5]. Because of its similarities to petroleum-based diesel, it is regarded as the ideal alternative for diesel fuel in diesel engines [6, 7]. Furthermore, its adoption has the capacity to lower or eliminate reliance on fossil fuels, resulting in cost savings for the vast majority of nations that depend heavily on petroleum imports for their energy needs [4].

Biodiesel is a fatty acid alkyl ester that may be easily produced by transesterifying triacylglycerol (an oil-based feedstock) with monohydric alcohol [8, 9]. The first generation of biodiesel was produced using edible oil feedstocks such as palm, soya beans, and rapeseed. However, the high production costs of these feedstocks, as well as the competition for land usage between food and biofuel, limit their utilisation as biodiesel feedstocks [10]. As an alternative, second-generation feedstock was derived from nonedible oil feedstocks such as jatropha oil, waste oil, and animal fats. Again, the high pricing, inefficiency in cultivation yields, unsustainable farming techniques, and intrinsic conflict between land usage and feedstock supply pose a threat to their large-scale development [11, 12]. Hence, it was necessary to develop a more promising feedstock as a third-generation feedstock. As a third-generation biodiesel feedstock, algae are aquatic, photosynthetic organisms that use CO_2 and sunlight to generate energy. Algae have the potential to reduce the amount of land required for cultivation while producing more energy per hectare than first and second-generation feedstock [12]. When used as a biodiesel feedstock, algae have several advantages in terms of both economics and the environment. These benefits include the ability to thrive on waste nutrients without much care, high biomass productivity, high photosynthetic efficiency (10–50 times greater than that of plants), the ability to be cultivated in a variety of climates and harvested regardless of season, and the ability to grow quickly and generate a significant amount of biomass with minimal cultivation inputs. Additionally, algae can reduce greenhouse gas emissions by sequestering considerable amounts of CO_2 through photosynthesis when exposed to sunlight. Furthermore, algae are ideal for large-scale production due to their ability to efficiently remove harmful components from wastewater while generating high oil content [12–17]. As a result, studies on cultivation, harvesting, and processing methods for various macroalgae, as well as their potential to produce economically viable biodiesel fuel, have attracted numerous researchers.

Numerous research papers [18–26] as well as review papers [12, 17, 27–35] on algae for biodiesel have been published. Unfortunately, however, there are limited studies on systematic reviews utilising bibliometrics on algae for biodiesel production. A systematic literature review allows one to gain a considerable amount of knowledge about a given subject in a relatively short period [36–38]. Bibliometric analysis is one of the most basic methods for conducting a systematic review of a large number of publications [37, 38]. By analysing trends in publications, such as publisher productivity, publishing dates and locations, and patterns of citation and reference in the literature, bibliometrics may quantitatively evaluate scientific publications and give insights into a field [39]. Bibliometrics has been broadly utilised to analyse patterns in a researcher's or field of study's studies, substantiate the impact of a researcher's or field's research, uncover new and developing fields of research, locate potential research partners, and find relevant sources to publish [39–42]. Researchers, educators, students, libraries, and funding agencies benefit the most from it [43, 44]. When coupled with network mapping techniques, bibliometrics can reveal important patterns in a subject, allowing researchers to identify new trends and contribute to the design and planning of future researches [45]. Recognising the centrality of algae in the production of biodiesel, it is necessary to conduct a systematic study using bibliometric indicators and determine the most active researchers in the field, as well as the most prolific authors, institutions, and countries, as well as the publications with the highest number of citations. As a result, this study offers crucial knowledge about algae for biodiesel production as well as a foundation for a thorough knowledge of issues in the field.

2. Methodology

2.1. Data Source. In this study, a systematic review on the utilisation of algae for biodiesel production was performed using the Scopus database (https://www.scopus.com, Elsevier). Scopus is one of the world's major abstract and citation databases for peer-reviewed literature, providing more consistent and accurate data for bibliometric analysis [46, 47]. In this database, publications are assessed annually to make sure that high standards are maintained. [48]. Additionally, the Scopus database, which has been used in several published bibliometric studies, offers quicker and better assistance for the literature research process [46, 48, 49].

On March 12, 2022, a comprehensive search of Elsevier's Scopus database was carried out with no time constraints using the subfields TITLE-ABS KEY TITLE-ABS KEY ((algae* OR microalgae* OR macroalgae*) AND (biodiesel OR bio-diesel OR bio diesel OR transesterification) AND (methanol OR ethanol)) AND (EXCLUDE (DOCTYPE, "bk") OR EXCLUDE (DOCTYPE, "cr") OR EXCLUDE (DOCTYPE , "no") OR EXCLUDE (DOCTYPE, "dp") AND (LIMIT-TO (LANGUAGE, "English")) to retrieve data for bibliometric analysis of the application of algae for biodiesel production. The search returned a total number of 983 documents. There were 983 documents total in the results of the search. Out of the 983 documents, 955 were in English, 17 in Chinese, 4 in Korean, 2 in Portuguese, 2 in Spanish, 1 in Japanese, 1 in Russian, and 1 in Turkish. In addition, the retrieved documents were eliminated from notes, conference reviews, data papers, and books. The total number of documents was lowered to 931, all of which were written in English. Finally, for bibliometric analysis, the citation and bibliographic data, abstract and keywords, funding information, and other information were exported as a CSV file. Figure 1 summarises the inclusion and exclusion criteria, as well as the search strategy used in this study.

2.2. Bibliometric Analysis. As part of the bibliometric analysis, the study used both VOSviewer (version 1.6.18, Netherlands) and Biblioshiny to undertake scientific mapping analysis and performance analysis. The *R*-studio application bibliometrix has a web-based graphical user interface called Biblioshiny. Biblioshiny is a bibliometrix web interface that provides data importation (https://www.bibliometrix.org/Biblioshiny.html), data frame conversion, data filtering, analytics, and plotting for sources, authors, and documents [50]. Due to its capability to quantitatively display the key information about data, document type, document contents, authors, and author's collaboration, Biblioshiny was primarily used to characterise the obtained database. VOSviewer was utilized for the bibliometric research due to its high graphical renderings of bibliometric information as maps and its adaptability for usage with large-scale data sets [51]. It is one of the best tools for bibliometric data visualisation [51, 52]. The bibliometric maps were created using the co-occurrence keyword, coauthorship, bibliographic coupling, and cocitation analyses. In addition to the co-occurrence analysis, a bibliographic coupling by nation analysis was carried out to determine the significant countries that have contributed to this field of study. The relationships

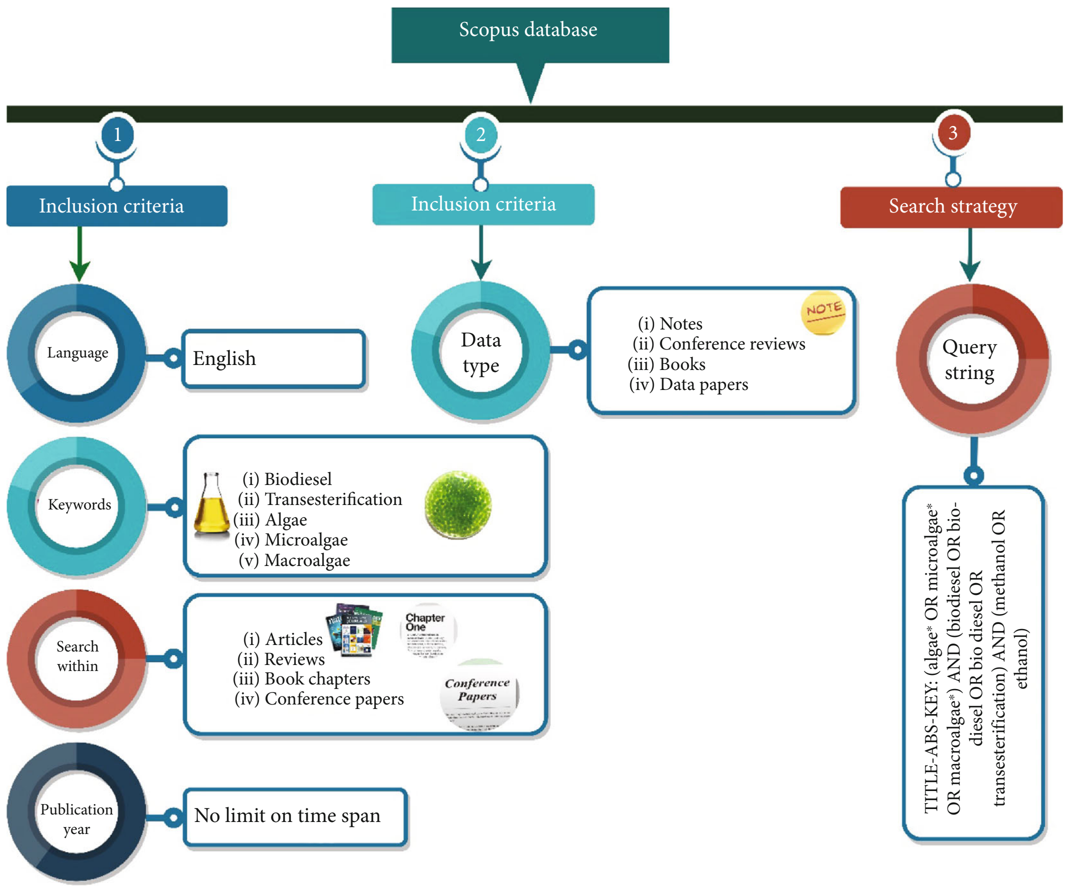

Figure 1: Criteria and search strategy for searching the Scopus database.

between the most important articles were also discovered and highlighted using the "co-citation" technique. With larger nodes and thicker links denoting the significance of those components, each of these studies generates a graphical network of nodes and linkages. A modularity-based clustering method that includes nodes and linkages is used to create VOSviewer maps. The strength of the node connections is represented by the link thickness, and the frequency of considerations is shown by the size of the nodes. Clusters are formed by closely related nodes, and they can be used in word co-occurrence analysis to find theme groups [45, 51]. As a final step, it is crucial to use a thesaurus in VOSviewer to combine related keywords to include the most significant keywords in the analysis. As a result, a thesaurus file was created and used to increase the accuracy of the analysis. For instance, the keywords "Fame," "fatty acid methyl ester," "fatty acid methyl esters," "fatty acid ethyl ester," "fatty acid methyl ester ("fame")," "microalgal biodiesel," "algae biodiesel," "algal biodiesel," and "biodiesel" were all related to the same terminology and were all considered biodiesel. Furthermore, to avoid unnecessary redundancy, the author carefully considered all synonyms before selecting the most appropriate keywords.

3. Results and Discussions

3.1. General Information. The characteristics of the retrieved information from the Scopus database revealed that there were 931 publications published in 347 sources by 2785 authors. Table 1 details the composition and characteristics of the information that was retrieved. There were 2727 authors of multiauthored documents and 58 authors of singled authored documents. Overall, the 931 publications had a total of 37943 references, with the average years from the publication being 6.38, and the average citations per document and average citations/year/doc being 42.03 and 4.844, respectively. From these publications, the total keyword plus and the author's keywords were 5475 and 1633, respectively. The number of single-authored documents was 65, and the average number of documents per author was 0.334. The average number of authors per document was 2.99, and the average number of coauthors per document was 4.19, yielding a collaboration index of 3.15. The collaboration index derived from this analysis shows that 93.01% of the 931 articles on the topic were coauthored by multiple researchers, which may explain why the field has such high research outputs.

3.2. Distribution and Growth Trends for Publications Annually

3.2.1. Characteristics of Annual Scientific Production. A realistic estimation of the research trend in a certain field of study may be established by the number of publications that are issued on an annual basis. The trend in the number of publications may provide clues about the anticipated

Table 1: Characteristics of the retrieved information.

Description	Results
Main information about data	
Timespan	1990 : 2022
Sources	347
Documents	931
Average years from publication	6.38
Average citations per documents	42.03
Average citations per year per doc	4.844
References	37943
Document types	
Articles	688
Book chapters	61
Conference papers	99
Erratum	1
Review	81
Short survey	1
Document contents	
Keywords plus (ID)	5475
Author's keywords (DE)	1633
Authors	
Authors	2785
Author appearances	3898
Authors of single-authored documents	58
Authors of multiauthored documents	2727
Authors' collaboration	
Single-authored documents	65
Documents per author	0.334
Authors per document	2.99
Coauthors per documents	4.19
Collaboration index	3.15

direction of research in the future. To analyse the research trend on the use of algae for biodiesel, a plot of the number of publications and the total number of publications on an annual basis was constructed (Figure 2). Compared to first- and second-generation biodiesel feedstocks, studies on the use of algae for biodiesel production are still in their infancy, growing scientifically at a rate of about 14.76%. The first research on the potential of microalgae as a feedstock for biodiesel production to be published was Nagle and Lemke's [53] study, which examined various solvent systems for extracting lipid from microalgae and studied the effect of key parameters on the transesterification of microalgal lipids [53], but the aforementioned field of study did not start to gain popularity until 2006. 2015 saw the publication of 101 articles, which is a record high. 18 articles have already been published as of March 12th of this year (2022). The cumulative publication curve shows that scholars from around the world have started to pay attention to the topic since 2006. This is evident from the fact that since 2006, the total number of articles has exponentially increased.

3.3. Distribution of Publications by Countries. The 931 documents retrieved in this study were published in 75 countries. The choropleth map with countries and numbers of publications is shown in Figure 3, and the statistics for the selected countries are provided in Table 2. In all, 75 countries published at least one publication on the use of algae in biodiesel production. The highest number of publications (194, 15.95% of the total documents) was from the United States of America (USA), followed by 165 publications (13.57%) from India, 111 publications (9.13%) from China, 63 publications (5.18%) from South Korea, and Malaysia with 60 publications (4.93%). The US may be the nation with the most publications in the field of algae for biodiesel due to the demand for alternative fuels driven by renewable fuel standards (RFS) and increased funding for algal biomass cultivation research and development. Through this funding, research programmes, private projects, demonstration facilities, and businesses of all sizes have been established across the US [54, 55]. Following these top 5 countries in publications are Brazil, Spain, Indonesia, Iran, and the United Kingdom each with 54, 47, 29, 29, and 28 publications, respectively. A total of 28 publications were contributed by each of the remaining nations, for a total of 436 publications, which is 46.83% of the total document published.

Combining the contributions from each country results in 1216 publications overall, which is more than 931, demonstrating the existence of international cooperation on this subject. The countries which have managed to publish 10 or more documents in Table 2 have a nominal GDP of above US $ 286,340. This demonstrates that both developing and developed countries have recognised the potential of algae as a biodiesel feedstock. Surprising in the list, Pakistan with the lowest nominal GDP of US $ 286,340 has managed to publish 14 documents and outshined Saudi Arabia (11 publications, GDP of US $ 804,921), the Russian Federation (11 publications, GDP of US $ 1,710,734), and Germany (10 publications, GDP of US $ 4,319,286) in terms of publications despite their high GDP. The US earned the most citations from the 194 papers produced by the countries and received the most citations (8809). India, China, South Korea, Malaysia, the United Kingdom, Turkey, Taiwan, South Africa, Spain, and Australia are the next ten countries in terms of the number of citations.

The total number of citations (TC), which measures the average impact of each publication, is significantly influenced by the total number of publications (TP) and the average number of citations per publication (AC). Surprisingly, South Africa leads with 16 publications and a TC of 90.56, while the United States of America ranks ninth (45.41). The total link strength (TLS) gives an estimate of the research collaboration between two countries (Table 2). With a TLS of 916, the analysis of TLS revealed that the US seemed to be the best nation in terms of collaborative research on the subject. The US had published documents in collaboration with 14 countries, which were Brazil, Canada, Chile, Colombia, Czech Republic, Finland, France, Germany, Italy, Mexico, New Zealand, Philippines, Portugal, and the United Arab Emirates, as seen in Figure 4. China,

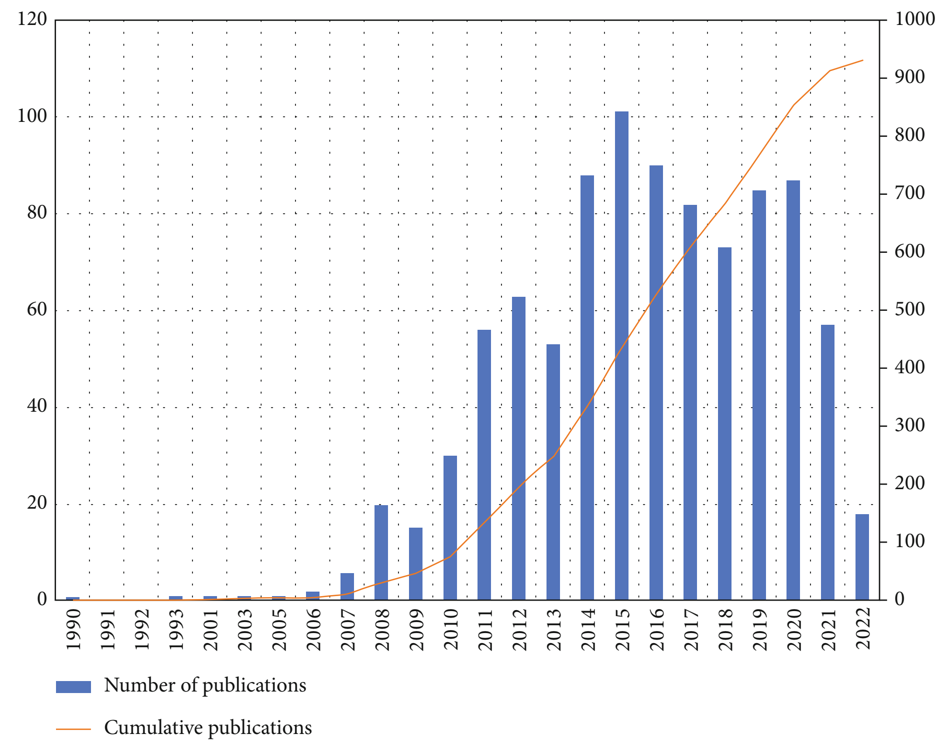

Figure 2: The annual trends in the number of publications on the topic.

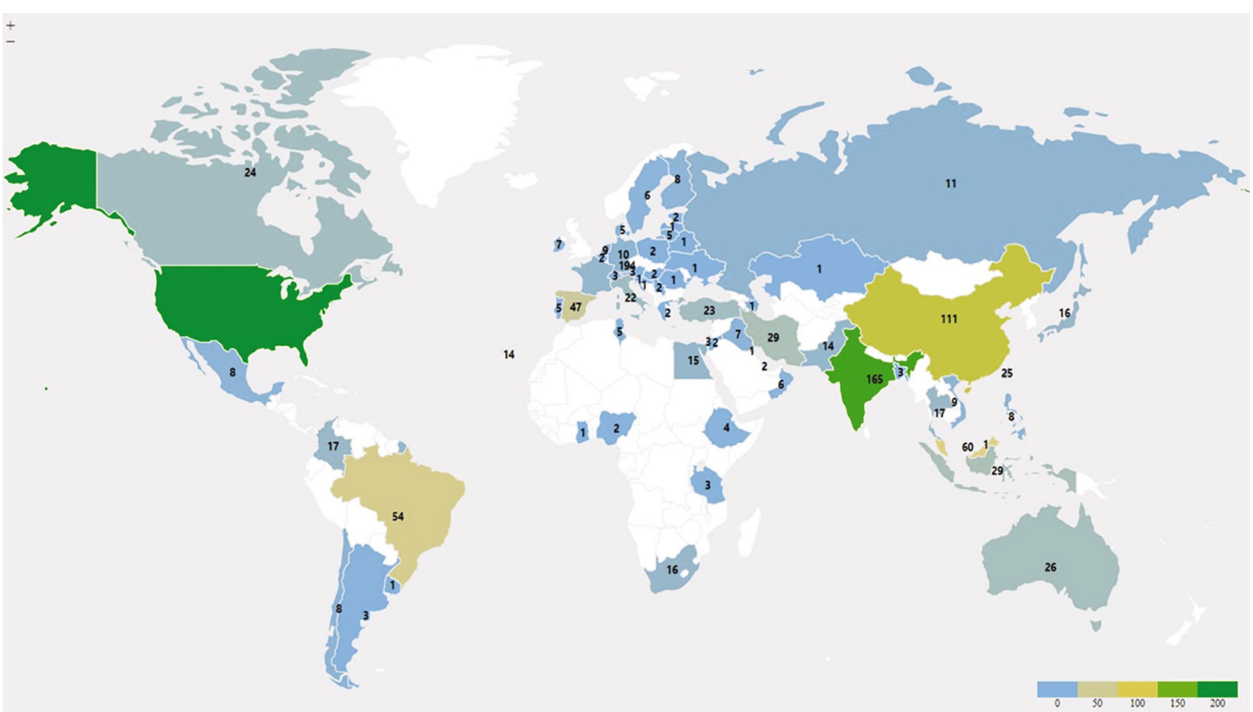

Figure 3: An international choropleth map indicating the volume of publications on algae for biodiesel production.

with a TLS of 805, came in second place. India placed third in collaborative research with a TLS score of 712. With TLS of 515 and 449, respectively, South Korea and Malaysia are in fourth and fifth place. It is evident from the TLS score analysis and the country cooperation network map that the majority of the countries actively cooperate with the United States, China, India, South Korea, and Malaysia on research into algae for biodiesel.

Table 2: Countries with more than 10 published documents.

	Country	TP	Composition (%)	TC	AC	Nominal GDP in US$	TLS
1	United States	194	15.95	8809	45.41	22,675,271	916
2	India	165	13.57	6406	38.82	3,049,704	712
3	China	111	9.13	4710	42.43	16,642,318	805
4	South Korea	63	5.18	3253	51.63	1,806,707	515
5	Malaysia	60	4.93	2911	48.52	387,093.00	449
6	Brazil	54	4.44	1164	21.56	1,491,772	216
7	Spain	47	3.87	1273	27.09	1,461,552	201
8	Indonesia	29	2.38	661	22.79	1,158,783	114
9	Iran	29	2.38	604	20.83	682,859	173
10	United Kingdom	28	2.30	1868	66.71	3,124,650	230
11	Australia	26	2.14	1180	45.38	1,617,543	172
12	Taiwan	25	2.06	1627	65.08	759,104	298
13	Canada	24	1.97	670	27.92	1,883,487	100
14	Turkey	23	1.89	1647	71.61	794,530	174
15	Italy	22	1.81	609	27.68	2,106,287	102
16	Colombia	17	1.40	236	13.88	295,610	25
17	Thailand	17	1.40	330	19.41	538,735	124
18	Japan	16	1.32	494	30.88	5,378,136	114
19	South Africa	16	1.32	1449	90.56	329,529	146
20	Egypt	15	1.23	318	21.20	394,284	89
21	France	14	1.15	583	41.64	2,938,271	62
22	Pakistan	14	1.15	133	9.50	286,340	63
23	Russia	11	0.90	502	45.64	1,710,734	35
24	Saudi Arabia	11	0.90	182	16.55	804,921	52
25	Germany	10	0.82	646	64.60	4,319,286	49
26	Others	175	14.39	8469	48.39		

TP: total number of publications; TC: total number of citations; AC: average number of citations per publication, calculated as =TP/TC; TLS: total link strength.

3.4. Most Productive Institutions. The leading institutions with more than 7 publications on the mentioned subject of study were identified (Table 3). The bibliometric analysis revealed that the 20 institutions produced at least 8 publications over time. A total of 230 documents, or 24.70% of all the publications on the subject, were published by these top institutions, which also received a total of 9371 citations. Out of these institutions, China's Chinese Academy of Sciences published 21 documents that were cited 1106 times. As a result, each document received an average of 52.67 citations. The Korean Advanced Institute of Science and Technology stands in the second position with 18 publications and 776 citations, followed by Universiti Putra Malaysia from Malaysia with 14 publications and 419 citations and New Mexico State University from the US with 13 publications and 969 citations. Despite having only 10 publications and ranking 13th on the list in terms of the number of publications, the Durban University of Technology from South Africa is the top institution with 116.00 average citations per document and then comes National Cheng Kung University from Taiwan, New Mexico State University from the United States, Anna University from India, Universiti Malaya from Malaysia, and the Chinese Academy of Sciences from China, respectively, with 84.36, 74.54, 73.50, 55.45, and 52.67 average citations per documents.

3.5. Authors and Coauthors' Relationship. The quantity of papers produced by the authors and the citation metrics acquired enable identification of the most active researchers in a specific field of study [56]. Therefore, finding the authors who are most influential and active in the study of algae as a biodiesel feedstock is crucial for getting a comprehensive picture of the field. To accomplish this, the authors' output in terms of documents and their metrics for citation is employed. Table 4 lists the 24 authors with at least 6 publications and more than 300 citations, as well as several other authors with fewer publications but with significant citation counts (more than 500 citations). These two sections of the table are intended to show the most active researchers while not overlooking the most significant ones. The ranking is presented according to the author's overall number of publications, not authorship order.

A total of 2785 different authors contributed to the 931 publications were included in this study; 65 of those were single-authored documents. Numerous other significant contributions have been made by various authors since the

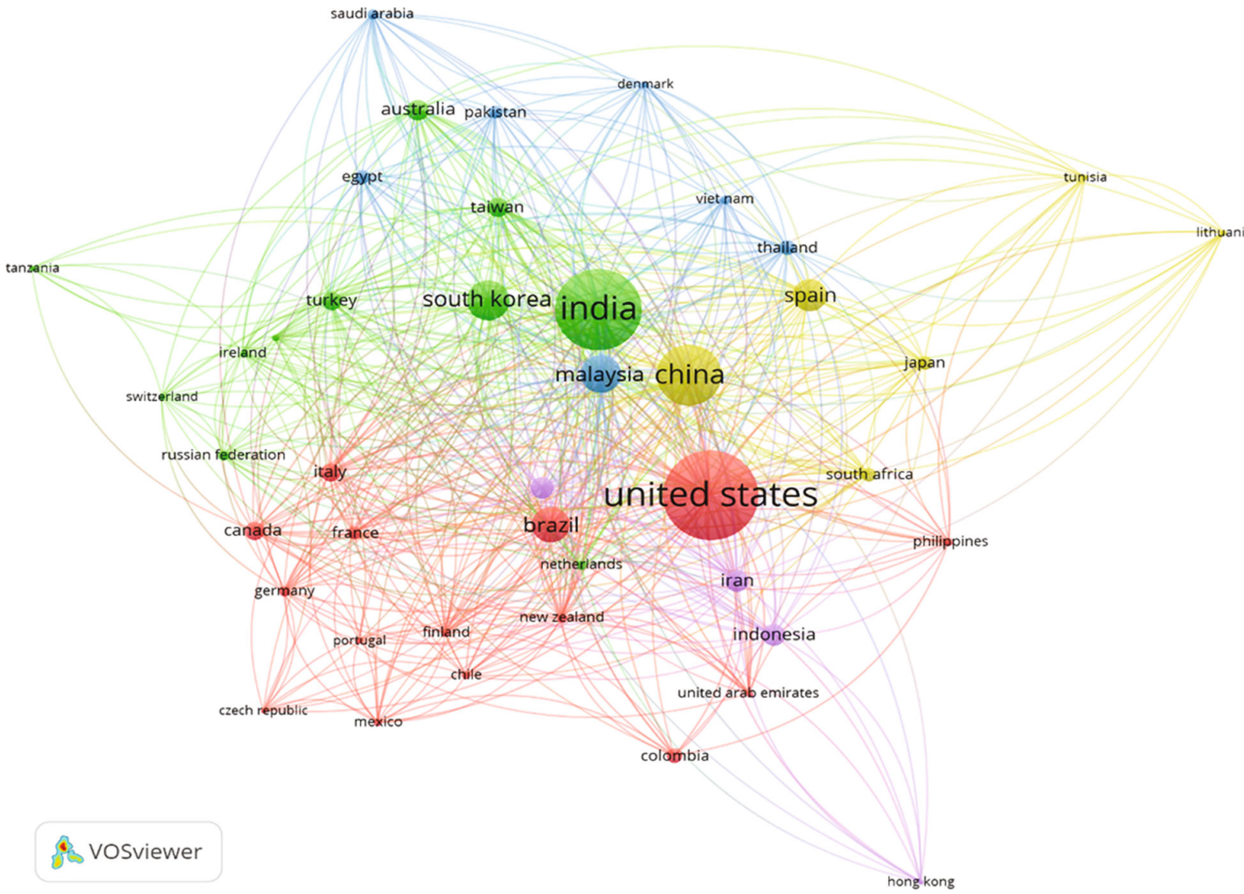

Figure 4: Country cooperation network of countries with at least 50 citations and three publications on the application of algae for biodiesel production.

first publication on the use of algae for the production of biodiesel by Nagle and Lemke [53]. The 12 most prolific authors with more than 8 publications in the studies of algae for biodiesel production were Deng (14 documents), Martín (13 documents), Kafarov (13 documents), Li (10 documents), Grossmann (10 documents), Maceiras (10 documents), Bux (9 documents), Chang (9 documents), Cooke (9 documents), Patil (9 documents), Muppaneni (9 documents), and Liu (9 documents). These 12 authors collectively have 124 publications, or 13.31% of all publications, and 6587 citations. However, in terms of citations, Deng placed seventh, whereas Christ ranked first (documents: 4 citations: 1629), followed by Miao (documents: 3 citations: 1224), Lee (documents: 5 citations: 1169), Bux (documents: 9 citations: 1159), and Lam (documents: 7 citations: 1051). Authors with the greatest impact are identified by the average number of citations per document. Thus, a high-quality article will garner more citations, which can be calculated by calculating the average number of citations per document. Miao has the highest average citation per document (408), followed by Christ (407.25), Singh (268), Lee (233.80), and Rawat (207.80). This suggests that these five authors are the most influential scholars in algae for biodiesel research worldwide.

3.6. Major Research Groups. The author-coauthor relationship may be used to determine which major research groups are engaged in a field of study. By simply mapping the relationships between the authors and coauthors, as illustrated in Figure 5, this may be done effectively and efficiently. The mapping method creates a visual depiction of the linkages, enabling researchers to examine not just the work of a single author but also the relationships with other research groups. In the field of researching algae for biodiesel, there are eight major groups (taking into account at least 8 authors per group). The well-known research groups in the field of study were those of the authors: Deng, Li, Chokshi, Chang, Chang, Maceiras, Wang, Chen, and Oh. With a combined 56 researchers, the research groups led by Deng, Li, Wang, Chen, Oh, Kwon, Chokshi, and Cheng formed the two largest clusters. Although Oh and Cheng did not have a direct link, they were connected through Park. It is quite likely that Park had the chance to work in the labs of both Oh and Cheng while investigating algae for the production of biodiesel. The research groups of Oh and Li were the two largest groups, where 18 researchers were involved in each group in collaborative research. This is followed by the groups of Deng (14 researchers), Wang (12 researchers), Chen (10 researchers), Cheng (9 researchers), Chang (9

Table 3: Top 20 institutions with more than 7 publications.

SN	Institution	Country	TP	TC	TC/TP
1	Chinese Academy of Sciences	China	21	1106	52.67
2	Korea Advanced Institute of Science and Technology	South Korea	18	776	43.11
3	Universiti Putra Malaysia	Malaysia	14	419	29.93
4	New Mexico State University	United States	13	969	74.54
5	Universiti Teknologi Malaysia	Malaysia	12	392	32.67
6	Universidad Industrial de Santander	Colombia	12	63	5.25
7	National Cheng Kung University	Taiwan	11	928	84.36
8	Universidad de Salamanca	Spain	11	207	18.82
9	Universidade de Vigo	Spain	11	224	20.36
10	Carnegie Mellon University	United States	11	315	28.64
11	Universiti Malaya	Malaysia	11	610	55.45
12	Korea Institute of Energy Research	South Korea	11	430	39.09
13	Durban University of Technology	South Africa	10	1160	116.00
14	University of Chinese Academy of Sciences	China	10	254	25.40
15	Universidade Estadual de Campinas	Brazil	10	202	20.20
16	Centro Universitario de la Defensa, Marin	Spain	10	208	20.80
17	Universiti Teknologi PETRONAS	Malaysia	9	165	18.33
18	Zhejiang University	China	9	297	33.00
19	Anna University	India	8	588	73.50
20	Universitas Gadjah Mada	Indonesia	8	58	7.25
	Total		230	9371	

researchers), and Maceiras (8 researchers). It is critical to increase research collaborations and cooperation among the various research groups in light of the collaborations between authors and institutions that have been observed, as this may permit the exchange of crucial data and information among the various research groups. This will contribute to an increase in the amount and quality of research on algae for biodiesel production.

3.7. Major Influential Journals and Publications

3.7.1. Most Influential Journal. The relationship between sources and citations reveals which journals are relevant to researchers and where their findings should be published. Table 5 lists the top journals that have published at least 7 publications on algae for biodiesel. Bioresource Technology was the authors' top choice for publishing their study on the use of algae in the production of biodiesel. This journal has so far published 112 papers, and these papers have been cited in other publications 9827 times. Fuel and Renewable Energy are in second and third place with 47 and 30 papers and corresponding citation counts of 1780 and 1231, while Energy Conversion and Management is in fourth with 28 papers and 1979 citations. Furthermore, Bioresource Technology has the most links overall when compared to the other journals. Their articles received a lot of citations from documents that were published in other journals, as shown by the source-citation relationship map in Figure 6.

The relevance of journal articles may be evaluated by using the average number of citations per publication (AC). In this case, the top 5 journals in terms of the average number of citations per document were Renewable and Sustainable Energy Reviews, Applied Energy, Bioresource Technology, Energy Conversion and Management, and Chemical Engineering Journal. The high average number of citations per document in these journals may be explained by the fact that they published high-quality research, as evidenced by their impact factor of over 9.000.

3.7.2. Most Influential Publications. The number of citations recorded by a publication is commonly regarded as one of the indicators of the publication's impact and provides insight into the quality of the published document. A higher citation metric indicates that the publication is of very high quality and has been cited by many researchers [37]. As a result, although this is not always the case, publications with more citations are typically thought of as landmark publications. In this study, 91 of the 931 investigated publications satisfied the criterion of having at least 100 citations per publication. Table 6 lists the 30 publications that were chosen for further analysis. The top five landmark articles include Chisti [57], Miao and Wu [58], Lee et al. [59], Rawat et al. [60], and Singh and Gu [61].

In the list, the top most cited paper (1507 citations) by Chisti [57] came 18 years later, following the first paper on the subject by Nagle and Lemke [53] with a title "Production of methyl ester fuel from microalgae." Indeed, it is not surprising why Chisti's [57] paper is the top most cited. Chisti [57] evaluated the potential of microalgae in unlocking the potential of biodiesel fuel and compared it with bioethanol made from sugarcane, and concluded that, when compared to bioethanol made from sugarcane, microalgae-based

Table 4: The top productive and influential authors.

SN	Name	Country	Institution	TP	TC	TC/TP	TLS
1	Deng S.	United States	Arizona State University, Tempe	14	972	69.43	411
2	Martín M.	Spain	Universidad de Salamanca	13	333	25.62	13
3	Kafarov V.	Colombia	Universidad Industrial de Santander	13	63	4.85	9
5	Grossmann I.E.	United States	Carnegie Mellon University	10	315	31.50	13
6	Maceiras R.	Spain	Centro Universitario de la Defensa, Marin	10	207	20.70	32
7	Bux F.	South Africa	Durban University of Technology	9	1159	128.78	163
8	Chang J.-S.	Taiwan	National Cheng Kung University	9	904	100.44	140
9	Cooke P.	United States	New Mexico State University	9	890	98.89	350
10	Patil P.D.	United States	New Mexico State University	9	835	92.78	309
11	Muppaneni T.	United States	Arizona State University	9	392	43.56	223
12	Liu J.	United States	American Refining Group, Inc.	9	192	21.33	78
13	Gude V.G.	United States	Mississippi State University	8	745	93.13	284
14	Oh Y.-K.	South Korea	Pusan National University	8	418	52.25	139
15	Lam M.K.	Malaysia	Universiti Teknologi PETRONAS	7	1051	150.14	187
16	Guldhe A.	India	Amity University, Maharashtra	7	447	63.86	130
17	Wang Z.	China	Guangzhou Institute of Energy Conversion of the Chinese Academy of Sciences	7	334	47.71	114
18	Park J.-Y.	South Korea	Korea Institute of Energy Research	7	301	43.00	129
19	Nascimento I.A.	Brazil	Universidade Federal da Bahia	7	233	33.29	16
20	Cheng J.	China	State Key Laboratory of Clean Energy Utilization	7	216	30.86	195
21	Cancela A.	Spain	Universidade de Vigo	7	155	22.14	27
23	Lammers P.	United States	Arizona State University	6	694	115.67	255
24	Yang J.-W.	South Korea	Korea Advanced Institute of Science and Technology	6	300	50.00	209
Other influential authors—ordered by total citations in algae for biodiesel and a minimum of 6 publications and more than 500 citations							
1	Chisti Y.	New Zealand	Massey University	4	1629	407.25	83
2	Miao X.	China	Shanghai Jiao Tong University	3	1224	408.00	78
3	Lee K.T.	Malaysia	Universiti Sains Malaysia	5	1169	233.80	94
4	Rawat I.	South Africa	Durban University of Technology	5	1039	207.80	120
5	Singh A.			3	806	268.67	57
6	Chen C.-Y.	Taiwan	National Chung Cheng University	3	766	255.33	35
7	Nirmalakhandan N.	United States	New Mexico State University	5	694	138.80	255
8	Mannarswamy A.	United States	New Mexico State University	5	629	125.80	217
9	Vasudevan P.T.	United States	University of New Hampshire Durham	3	579	193.00	16
10	Ho S.-H.	China	Harbin Institute of Technology	3	569	189.67	35
11	Mayfield S.P.	United States	Division of Biological Sciences	3	566	188.67	14
12	Demirbas A.	Saudi Arabia	King Abdulaziz University	3	564	188.00	19
13	Lindblad P.	Sweden	Uppsala University	3	519	173.00	9

biodiesel has a higher chance of meeting the demand for liquid transportation fuels in a sustainable manner. The paper also presented the promising future of algal biomass in the production of large quantities of biodiesel by growing algae in photobioreactors and calls for a thorough analysis of production economics to determine competitiveness with fuels made from petroleum.

The second most cited publication (with 1044 citations) was published in 2006 by Miao and Wu [58]. It examined the production of biodiesel from heterotrophic microalgal oil and described for the first time an integrated method for doing so using *Chlorella protothecoides* microalgal oil, which can be grown photoautotrophically or heterotrophically under various culture conditions. The authors further reveal that *C. protothecoides*' heterotrophic development led to the build-up of a significant quantity of lipid in cells, with lipid content reaching as high as 55.20 %. These lipids could be effectively removed from cells using n-hexane. Even though the extracted oil had a high acid value (8.97 mg·KOH/g), acid-catalysed transesterification could still make biodiesel with ease. The article concluded that cultivating microalgae with high lipid content, and possibly bioengineering microalgae to produce biofuels, would be a novel and promising method of producing biofuels in the near future [58]. Lee et al. [59]

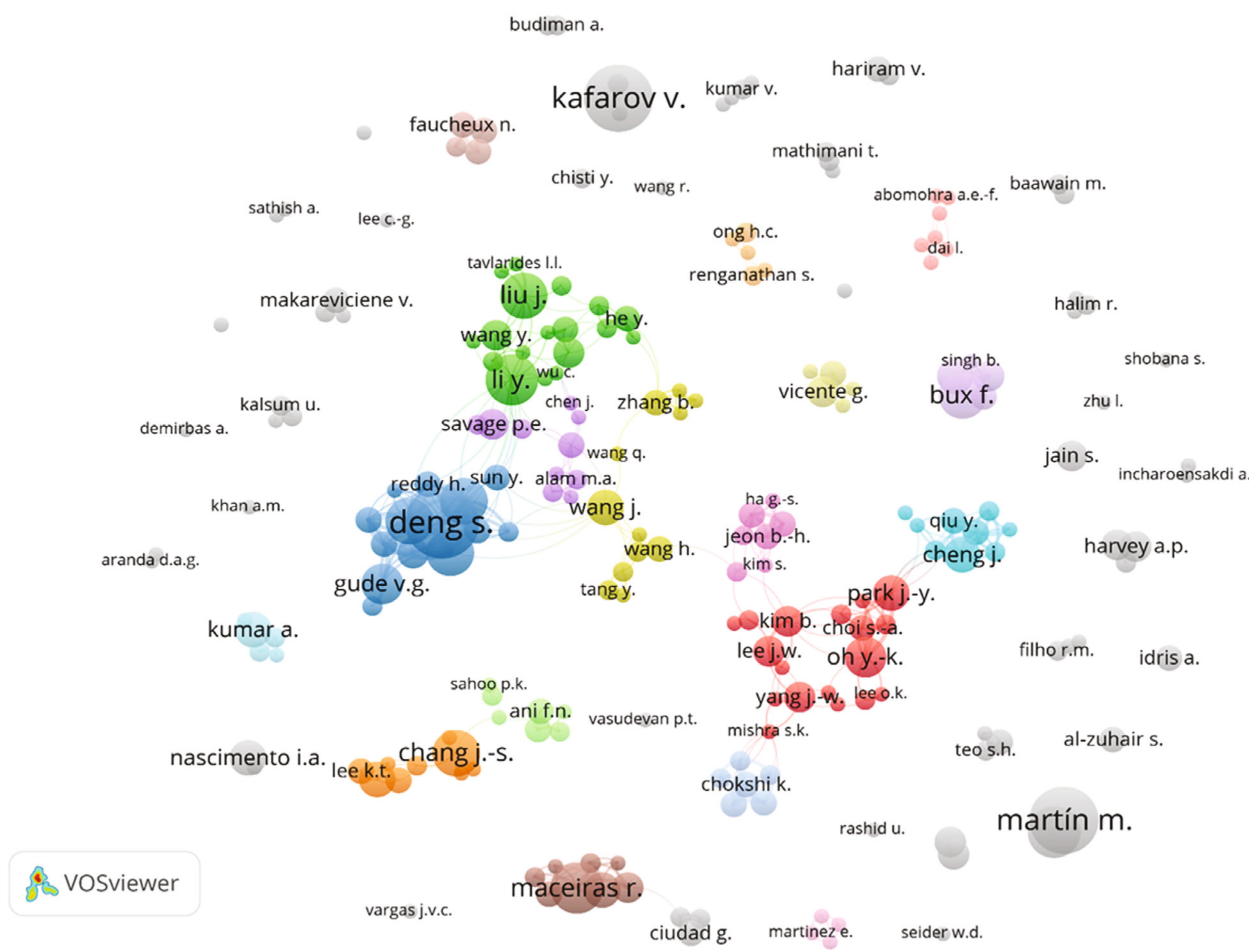

Figure 5: A visualisation network for authors and coauthors of studies on algae for biodiesel production.

publication, which ranked third with 906 citations, was one of the first to compare the extraction of total lipids from *Botryococcus sp.*, *Chlorella vulgaris*, and *Scenedesmus sp.* microalgae using a mixture of chloroform and methanol (1:1) by autoclaving, bead-beating, microwaves, or sonication. Their paper revealed that the efficiency of lipid extraction differs according to the microalgae species and extraction method. Among the investigated species, the highest lipid content was that of *Botryococcus sp.*, and the microwave oven method proved to be the method with the highest efficiency for all the tested species.

Rawat et al.'s [60] publication, which reviewed the potential of microalgae's dual role in phycoremediation of domestic wastewater and biomass production for sustainable biofuel production, ranked fourth with 709 citations. The publication reported that microalgae have aided tertiary treatment in traditional wastewater treatment, as well as BOD and nutrient removal in designed systems such as high-rate algal ponds. Moreover, the publication reported that the existing researches have focused on using final effluent streams with residual nutrients like nitrogen and phosphorus as a resource to harvest microalgae rather than as a waste product. As a result, algae biomass offers advantages for waste water treatment and producing oil for biodiesel. The publications advocate more research into developing technology for algae biomass harvesting and oil extraction, with the potential to use the spent algae biomass to produce a wide range of additional value-added products, including bioethanol or biomethane. The publication by Singh and Gu [61] holds the fifth position with 643 citations. In this work, Singh and Gu [61] investigated the commercialisation potential of microalgae biofuels and concluded that technologies such as tubular photobioreactors have the potential to increase the production of microalgae feedstocks for various fuel productions while also recycling CO_2 for algae culture, reducing pollution and biofuel costs. Because microalgae feedstocks do not compete with land use change or food crops, the extent of their adoption appears promising and calls for more research that will innovate and develop technologies that lower costs while improving yields.

Out of these 5 most cited publications, the publication by Miao and Wu [58] has been cited the most (22 times) by the selected group of 30 documents. This is followed by the publication by Chisti [57], Singh et al. [62], Pragya et al. [63], and Umdu et al. [64] cited 14, 13, 10, and 9 times respectively, by the selected group of 30 documents. This suggests that

Table 5: List of prominent research outlets with at least 7 publications.

SN	Source	TP	TC	AC	Impact factor (2020)	TLS
1	Bioresource Technology	112	9827	87.74	9.642	588
2	Fuel	47	1780	37.87	6.609	268
3	Renewable Energy	30	1231	41.03	8.001	124
4	Energy Conversion and Management	28	1979	70.68	9.709	172
5	Renewable and Sustainable Energy Reviews	19	3082	162.21	14.982	122
6	Applied Energy	16	2443	152.69	9.746	126
7	Energy Sources, Part A: Recovery, Utilization, and Environmental Effects	14	506	36.14	3.447	19
8	Algal Research	13	318	24.46	4.401	49
9	Chemical Engineering Transactions	13	85	6.54	NA	9
10	Energy	13	575	44.23	7.147	43
11	Biomass and Bioenergy	11	232	21.09	5.061	52
12	Energies	10	416	41.60	3.004	21
13	Energy & Fuels	9	353	39.22	3.605	47
14	AIP Conference Proceedings	8	24	3.00	-	6
15	Biomass Conversion and Biorefinery	8	45	5.63	4.987	31
16	Biotechnology and Bioprocess Engineering	8	102	12.75	2.836	13
17	Water Environment Research	8	20	2.50	1.946	10
18	Biofuels	7	35	5.00	2.963	20
19	Biotechnology for Biofuels	7	125	17.86	6.040	17
20	Chemical Engineering Journal	7	320	45.71	13.273	41
21	Computer Aided Chemical Engineering	7	19	2.71	NA	2
22	Journal of Cleaner Production	7	263	37.57	9.297	16
23	Journal of Supercritical Fluids	7	177	25.29	4.577	29
24	Science of the Total Environment	7	186	26.57	7.963	59

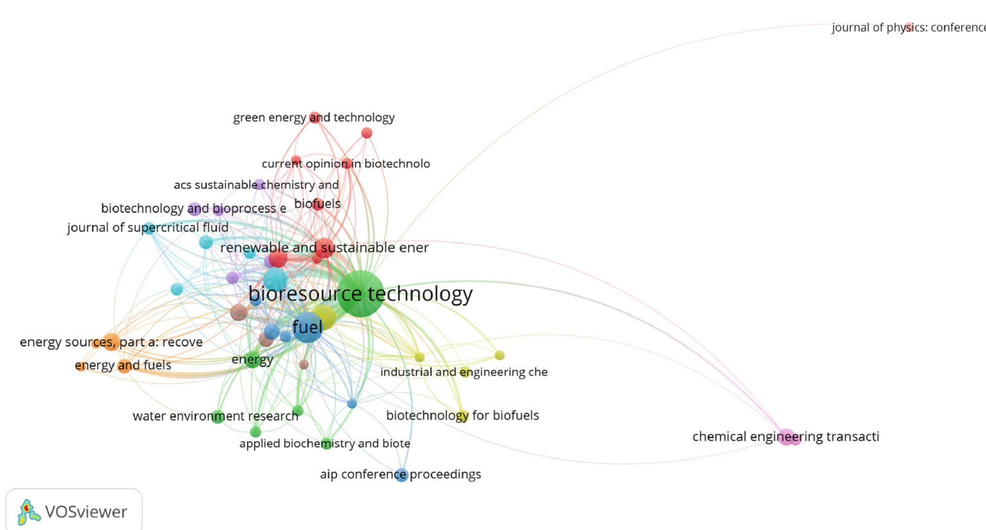

Figure 6: Cocitation network visualisation map for main sources of publications in algae for biodiesel.

other high-quality papers in the field of algae for biodiesel closely follow these 5 publications. As can be seen in Figure 7, there were 12 interconnected clusters, with the most cited papers in each cluster coming from Rawat et al. [60], Patil et al. [23], Ho et al. [65], Amin [66], Lee et al. [59], Nagle and Lemke [53], Pragya et al. [63], Vasudevan and Briggs [67], Lam and Lee [68], Scranton et al. [69], Chisti [57], and Miao and Wu [58].

Table 6: Most influential publications.

SN	Document title	TC	TL	Article
1	Biodiesel from Microalgae Beats Bioethanol	1507	14	Chisti [57]
2	Biodiesel Production from Heterotrophic Microalgal of Oil	1044	22	Miao and Wu [58]
3	Comparison of Several Methods for Effective Lipid Extraction from Microalgae	906	8	Lee et al. [59]
4	Dual Role of Microalgae: Phycoremediation of Domestic Wastewater and Biomass Production for Sustainable Biofuels Production	709	5	Rawat et al. [60]
5	Commercialization Potential of Microalgae for Biofuels Production	643	1	Singh and Gu [61]
6	Microalgae Biofuels: A Critical Review of Issues, Problems, and the Way Forward	635	8	Lam and Lee [68]
7	Effect of Light Intensity and Nitrogen Starvation on CO_2 Fixation and Lipid/Carbohydrate Production of an Indigenous Microalga *Scenedesmus obliquus* CNW-N	518	3	Ho et al. [65]
8	Biodiesel Production—Current State of the Art and Challenges	507	7	Vasudevan and Briggs [67]
9	Use of Algae as Biofuel Sources	488	6	Demirbas [70]
10	Renewable Fuels from Algae: An Answer to Debatable Land Based Fuels	452	13	Singh et al. [62]
11	Review on Biofuel Oil and Gas Production Processes from Microalgae	439	2	Amin [66]
12	Life-Cycle Assessment of Microalgae Culture Coupled to Biogas Production	389	7	Collet et al. [71]
13	Cyanobacteria and microalgae: A Positive Prospect for Biofuels	376	4	Parmar et al. [72]
14	Life Cycle Analysis of Algae Biodiesel	367	6	Sander and Murthy [73]
15	Macroalgae and Microalgae as a Potential Source for Commercial Applications along with Biofuels Production: A Biorefinery Approach	357	6	Suganya et al. [34]
16	A Review on Harvesting, Oil Extraction and Biofuels Production Technologies from Microalgae	357	10	Pragya et al. [63]
17	Biofuels from Algae for Sustainable Development	337	3	Pragya et al. [63]
18	Development of Suitable Photobioreactors for CO_2 Sequestration Addressing Global Warming using Green Algae and Cyanobacteria	331	2	Kumar et al. [74]
19	A Critical Review of Biochemical Conversion, Sustainability and Life Cycle Assessment of Algal Biofuels	304	7	Singh and Olsen [75]
20	Algae Biofuels: Versatility for the Future of Bioenergy	287	6	Jones and Mayfield [76]
21	Development of Suitable Photobioreactor for Algae production-A Review	283	1	Singh and Sharma [77]
22	Optimization of Direct Conversion of Wet Algae to Biodiesel under Supercritical Methanol Conditions	282	7	Patil et al. [23]
23	Second Generation Biofuels: Economics and Policies	275	1	Carriquiry et al. [78]
24	Status and Barriers of Advanced Biofuel Technologies: A Review	272	1	Cheng and Timilsina [79]
25	Biodiesel Production from Algae Oil High in Free Fatty Acids by Two-Step Catalytic Conversion	267	4	Chen et al. [80]
26	Nitrogen Stress Triggered Biochemical and Morphological Changes in the Microalgae *Scenedesmus sp.* CCNM 1077	263	0	Pancha et al. [22]
27	Recent Advances in Liquid Biofuel Production from Algal Feedstocks	254	7	Daroch et al. [81]
28	Producing Docosahexaenoic Acid (DHA)-Rich Algae from Biodiesel-Derived Crude Glycerol: Effects of Impurities on DHA Production and Algal Biomass Composition	254	2	Pyle et al. [82]
29	Production of Biodiesel from Algae Oils	250	0	Demirbaş [20]
30	Transesterification of *Nannochloropsis oculata* Microalga's Lipid to Biodiesel on Al2O3 Supported CaO and MgO Catalysts	249	9	Umdu et al. [64]

3.8. Mostly Used Keywords. One of the most important data sources for research trends is author keywords. The use of author keywords has been demonstrated to be essential for monitoring and evaluating the development of science in the field of study [83]. Keyword analysis can help researchers gain a better understanding of the current state of research, future issues, and research needs [84]. Using VOSviewer and a thesaurus file, 83 of the 1633 total authors' keywords with a minimum frequency of more than 4 occurrences were selected. The type of analysis was set to "co-occurrence," and the unit of analysis was "authors keywords." The 50 most frequently used keywords are listed in Table 7.

In Figure 8, the network map of author keyword co-occurrence is displayed. The size of the circle corresponding to each keyword denotes its frequency of occurrence, and each keyword is represented as a node or a circle. A larger node indicates that a keyword was used more frequently in the scientific publications under consideration.

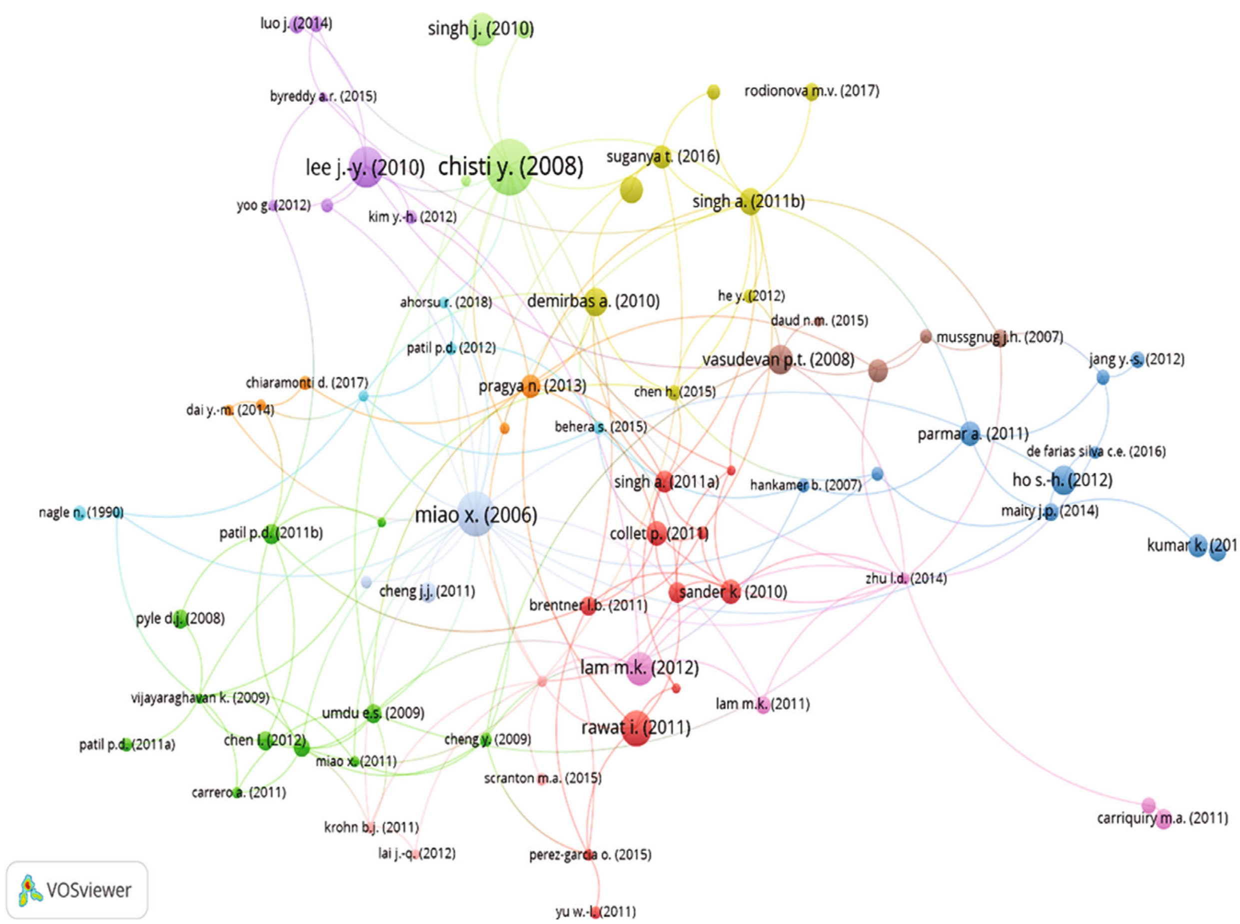

Figure 7: Relation between publications that received at least 100 citations.

As a result, the keywords with the largest nodes are the most important in this study. The relationship between any two terms is represented by a curve; the stronger the relationship (link strength), the thicker the line [52]. Different colours have been used to highlight term clusters in the network to highlight their co-occurrence in various publications. Using the colours red, green, blue, yellow, purple, and light blue, six clusters were found. Cluster 1 (red) had the most keywords (19), followed by cluster 2 (green), which had 18, cluster 3 (blue), which had 14, cluster 4 (yellow), which had 13, cluster 5 (purple), which had 11, and cluster 6 (light blue), which had 8. Even though these clusters are not fully distinct, they provide a broad overview of the many issues that literature favours. These six clustered keywords, the following six pivotal research directions, have been extracted: From these 6 clustered keywords, the following six important research areas have been identified: biodiesel production techniques, algae biomass cultivation, algae lipids and fatty acid composition, algae harvesting and lipid extraction, algae as a feedstock for biorefineries, and an evaluation of the sustainability and life cycle of using algae for biodiesel production, as explained in the subsequent sections.

3.8.1. Biodiesel Production Methods. It is necessary to modify the bio-oils made from algae biomass because they differ from diesel fuels in their properties. Several methods have been proposed for converting bio-oils from algae biomass into bio-oils for producing a fuel similar to diesel from fatty acids, including direct use and blending, microemulsions, thermal cracking, and transesterification. Of these, methods' transesterification is the method of choice as it produces biofuel which is similar to diesel, i.e., Biodiesel [85, 86]. Moreover, algal biodiesel production via the transesterification method is more cost-effective than biodiesel produced from other feedstocks [31]. The transesterification of bio-oils from algae biomass can occur in one or two steps, with acidic and/or basic catalysts being used. The yield of biodiesel varies greatly depending on the process and the type of algae used [87]. Several authors have reported two step transesterification process for algae feedstocks [20, 24, 88–90]. The extracted algae oil is transesterified into biodiesel using alkalised or acidified methanol in a two-step process. Dewatering, drying, solvent extraction, oil degumming, transesterification, esterification, neutralisation, and product purification are typically involved in the production of algal biodiesel using a two-step transesterification process [89, 91].

Alternately, in situ transesterification, which can tolerate high amounts of water in the feedstock and does away with the solvent extraction process, can be used to produce algal biodiesel. This method produces biodiesel by directly contacting alcohol that contains a catalyst with algal biomass.

Table 7: Most frequently occurring keywords.

SN	Keyword	Occurrences	Total link strength
1	Biodiesel	465	997
2	Microalgae	283	584
3	Transesterification	146	331
4	Algae	87	237
5	Extraction	76	177
6	Lipids	55	164
7	Ethanol	47	174
8	Biomass	45	98
9	In situ transesterification	42	96
10	Biorefinery	34	132
11	*Chlorella vulgaris*	31	74
12	Microwave irradiation	26	67
13	Optimization	26	62
14	Heterogeneous catalyst	23	64
15	Lipase	23	50
16	Algae oil	22	53
17	Fatty acids	18	30
18	Fermentation	18	43
19	Microalgae oil	18	37
20	Biogas	17	53
21	Response surface methodology	17	34
22	Catalysis	15	35
23	Hydrogen	15	100
24	Renewable energy	15	18
25	Wastewater	15	30
26	Bio-oil	14	46
27	Biohydrogen	14	42
28	Cell disruption	14	35
29	Methanol	13	22
30	Wet microalgae	13	20
31	Kinetics	12	35
32	Ultrasound	12	30
33	Pyrolysis	11	37
34	Cyanobacteria	10	25
35	Esterification	10	25
36	Ionic liquid	10	26
37	Sustainability	10	22
38	Butanol	9	73
39	Emission	9	21
40	Feedstocks	9	74
41	Lignocelluloses	9	85
42	Methane	9	69
43	*Nannochloropsis oculata*	9	21
44	Process integration	9	10
45	Supercritical methanol	9	27
46	Wet algae	9	22
47	*Chlorella protothecoides*	8	17

Table 7: Continued.

SN	Keyword	Occurrences	Total link strength
48	Ultrasonication	8	19
49	*Chlorella sp.*	7	14
50	Photobioreactor	7	24

Since one of the main reasons that has hindered the commercial production of biodiesel from algae is the solvent extraction and drying steps, which typically consume 90% of the process energy in a two-step transesterification [91, 92], in situ transesterification has the potential to be a more cost-effective alternative method of producing algal biodiesel because it simplifies the conversion process by shortening the process [25, 91, 93, 94]. The presence of a suitable catalyst during this process has proven essential for the increased yield of biodiesel [95, 96]. Thus, a good number of authors have worked on acid catalysed in situ transesterification [87, 93, 94, 97] while others have worked on base catalysed in situ transesterification [21, 87, 94, 98, 99]. High levels of free fatty acid concentration, however, trigger a neutralisation reaction with alkali catalysts that results in the production of soaps. This is why it has been suggested to use acid catalysts to produce biodiesel from microbial biomasses such as microalgae [100, 101]. An alternative to the in situ transesterification process is the in situ supercritical transesterification process.

Supercritical transesterification is a promising method for producing biodiesel from algae with relative environmental and economic benefits. This method successfully breaks the cell walls of microalgae by applying high pressure (15–30 MPa) and temperature (240–385°C), allowing lipids to be extracted and converted into fatty acid methyl esters (FAMEs) in a single step without the use of a catalyst, ensuring that the end product is not washed and thus no polluting effluents are produced [23, 102, 103]. Additionally, the presence of water and free fatty acids, which can be found in high concentrations in the algal biomass, does not reduce the effectiveness of the supercritical reaction but rather enhances it [23, 104]. While the direct supercritical methanol treatment of algae does away with the need for a solvent to extract the oil before transesterification, it still necessitates a unit operation to separate the biodiesel produced from the nontransesterifiable material after the supercritical process, which reduces the profitability of the overall process. The supercritical transesterification can proceed using either supercritical ethanol [100, 105, 106] or supercritical methanol [23, 107]. Unfortunately, the main barriers to scaling up and commercialization are high temperatures and pressure [99].

The use of biocatalysts based on immobilized lipases in the synthesis of biodiesel is seen as a viable technique for cost reduction [108]. Lipases are biotechnological catalysts that may act in a broad range of temperature, pressure, and pH settings, among others. As a result, they can catalyse a wide range of reactions in aqueous and nonaqueous fluids, as well as in a wide range of industrial applications [109].

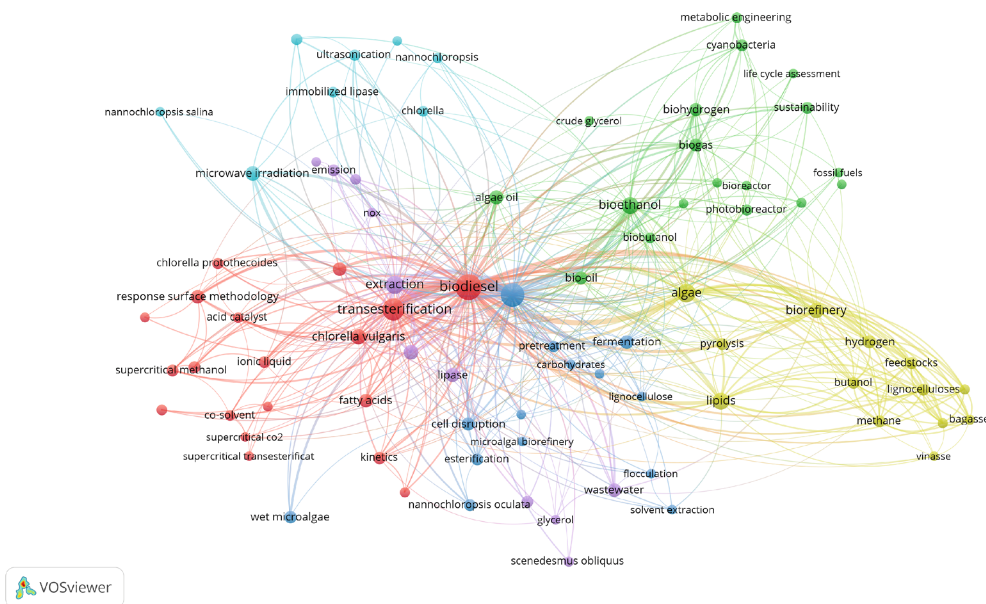

Figure 8: The author keyword co-occurrence networks.

The enzymatic transesterification route has been proposed for the production of biodiesel because it has less stringent requirements for feedstock purification, simplifies the process of separating products, allows for the reuse of catalyst, requires only mild reaction conditions (20-50°C), and has the potential to improve the properties of enzymes through bioengineering [108–110]. Several authors including Kim et al. [111], Kim et al. [112], López et al. [113], Tran et al. [114], Kim et al. [111], Kim et al. [112], and Bayramoglu et al. [115] have worked on transesterification of algae species such as *Dunaliella salina*, *Nannochloropsis gaditana*, *C. vulgaris* ESP-31, *Aurantiochytrium sp. KRS101*, *Botryococcus sp. Nannochloropsis gaditana*, *Scenedesmus quadricauda*, and *Chlorella pyrenoidosa* for biodiesel production using various biocatalysts such as immobilized lipase *P. antarctica*, Novozym 435, Lipase *Burkholderia* sp. C20, immobilizied on nanocomposite $Fe_3O4–SiO_2$, Novozym 435, Novozym CAL-B, and Lipase *Candida rugosa* and reported a promising FAME yield ranging from 88% to 96.4% . Despite these encouraging findings, the enzymatic transesterification process is still constrained by low reaction rates, high enzyme costs, and low enzyme stability in the presence of excess alcohol and glycerol formation during the reaction [108, 116]. This calls for additional research in order to develop more affordable and reliable biocatalysts before scaling up this technology.

3.8.2. Algae Biomass Cultivation. An easy and affordable method for algal cultivation is open pond cultivation [117, 118]. In an open pond cultivation technique, external nutrients are usually delivered into a water tank or bigger earthen bank ponds. Natural light is necessary for photosynthesis, and CO_2 is obtained in the atmosphere. A paddlewheel serves as the circulation and mixer for the algal cells and nutrients in the pond, which is often constructed in the style of a raceway or track. In order to prevent the ground from absorbing the liquid, the raceways are often made of poured concrete or are simply excavated into the ground and lined with plastic [117, 119]. Channel baffles reduce loss and wasted space while allowing the flow to navigate curves. Algal broth is harvested after it has circulated through the loop, and the medium is poured in front of the paddlewheel [119]. The fact that open ponds are simpler to build and maintain than closed systems is one of their principal benefits. There are, however, substantial limitations because of the cells' inefficient use of light, water loss through evaporation, CO_2 escape into the atmosphere, and large surface requirements [19, 117]. Furthermore, biomass productivities are lower than those reached in closed systems due to inadequate control over growth conditions, reliance on the local environment, and ease of predator contamination and other rapidly growing heterotrophic organism [77, 120].

As an alternative, several bioreactors have been proposed for intensive algal production, with the photobioreactor proving to be the pioneer. In contrast, to open pond cultivation, closed photobioreactors provide better control over culture conditions such as CO_2 supply, water supply, optimal temperatures, efficient light exposure, culture density, pH levels, and mixing rates [77]. As a result, photobioreactors are required for large-scale biomass production and to overcome the inherent disadvantages of open cultivation.

A photobioreactor (PBR) is a closed, illuminated culture vessel with a synthetic controlled atmosphere and nutrient feed systems that promote biomass growth and lipid production. It is a closed structure that is isolated from the outside environment and cannot exchange gases or pollutants [121]. The ultimate goal of any PBR is to reduce the cost of biomass production. This can be accomplished by optimising the PBR's model, controlling environmental factors, and minimising contamination risk [117]. In this case, a PBR design is desired for its ability to utilise light most effectively, provide consistent lighting, reduce mutual shadowing, and facilitate rapid CO_2 and O_2 mass transfer. A typical PBR system consists of four phases: microalgal cells in a solid phase, growth medium in a liquid phase, gaseous phase (CO_2 and O_2), and light-radiation field that is superimposed [117, 122]. Different photobioreactor configurations, such as tubular reactors, flat-plate reactors, and vertical column reactors with bubble columns or air-lift columns, have been proposed [77, 121, 123]. The air-lift reactors are good for industrial processes, due to the low level and homogeneous distribution of hydrodynamic shear with medium that circulates in a cyclic pattern through channels built for this purpose. In contrast, tubular designs that are horizontal or vertically inclined are more suited to outdoor culture due to the large illumination surface created by the arrangement of the tubes [120, 124, 125]. In comparison to other bioreactors, flat-plate photobioreactors can attain cell densities that are significantly greater while consuming a small amount of power at a high mass transfer with a good photosynthesis efficiency [120, 126]. Despite the fact that there have been studies on the development of PBRs for algae cultivation, there is still a need to advance the technology in order to increase their efficiency and develop a model that can be scaled up while requiring less energy. Large-scale algal production for biodiesel necessitates the development of transparent equipment with a high illumination surface, mass transfer rates, and biomass yields as well as lower space requirements while taking into account variables like strain type, environmental conditions, and production cost.

Microalgae production often calls for inorganic nutrients that are offered in media mixtures. When producing microalgae on a large scale, these commercial media become expensive because a large quantity of premade media is needed for cultivation. Instead, wastewater has been suggested as a potential solution to this economic dilemma [30, 127]. The nutrients found in waste water, including nitrates, phosphates, ammonium, and urea, as well as essential trace levels of vitamins and trace metals like iron, cadmium, and zinc, all support the growth of microalgae [30, 128]. Similarly, studies have shown that this ability gives a dual purpose for algae cultivation: water purification, CO_2 capturing, and generating biomass to produce biofuels [129]. Several microalgae species including *Chlorella*, *Scenedesmus*, *Phormidium*, *Aulacoseira granulate*, *Cyclotella meneghiniana*, *Botryococcus*, *Chlamydomonas*, and *Spirulina* have been cultivated for biofuel production from wastewater treatment and have shown promising results [13, 130, 131]. In some studies, species like *Cyclotella meneghiniana* when cultivated in wastewater have been reported to have high lipid levels comparable to genetically engineered cyanobacteria [30]. Wastewater, therefore, has the potential to produce microalgae with low input and thereafter provide a means of making a sustainable and profitable biodiesel business. Unfortunately, wastewater might be contaminated with viruses or bacteria, which will end up affecting biomass production and downstream processing [35, 68]. In this situation, wastewater must first undergo several pretreatment steps such as heat treatments, filtration, and UV irradiation before being used as a media. To lower the possibility of contamination, the culturing system should also be cleaned often [131]. Another challenge is the variation in the composition of wastewater from various sources, as the presence of toxic chemicals and high levels of nutrients in some cases inhibits the growth of microalgae and the photosynthesis process due to the presence of colour [30].

3.8.3. Algae Lipids and Fatty Acid Profile. Fatty acid methyl ester (FAME), the main component of biodiesel, is produced when biologically generated lipids are transesterified [32]. Therefore, lipid content has a significant impact on the biodiesel production process and product quality [132]. Polar lipids containing phospholipids and glycolipids may produce biodiesel with high levels of phosphorus and sulphur. These polar lipids may also have an impact on the transesterification process by emulsifying and depleting the catalyst [133]. Depending on the development phase, algae have different lipid yields, with the lowest yields occurring in the late logarithmic phase and stable or rising in the stationary phase. The majority of lipids generated during logarithmic growth are polar membrane lipids based on glycerol, which support cell structure. Triacylglycerol TAGs are neutral lipids that are used for storage but have no structural function. Since cell division ceases and photosynthetic energy is instead used to produce TAG under adverse conditions, the amount of TAG produced rises [134]. Depending upon microalgae strain and cultivation conditions, the algal biomass' total lipid content ranges from 1 to 75%, with values typically exceeding 40 % under nutrient stress circumstances. Due to their extremely low lipid content (up to 4.5%w/w), macroalgae are not as suitable for the production of biodiesel as microalgae. [135]. Microalgae produce a wide variety of substances that resemble lipids, including glycerolipids, sterols, hydrocarbons, and waxes [124, 125]. The most prevalent and well-known class of lipids found in microalgae are glycerolipids. These have a glycerol backbone with one, two, or three fatty acids (FAs) groups attached, which is what distinguishes them [135].

(1) Lipids in Macroalgae. Depending on how their photosynthetic pigmentation differs, macroalgae have been classified into three main groups: red (*Rhodophyta*), brown (*Phaeophyta*), and green (*Chlorophyta*). Globally, red algae have the most species (6000), followed by green algae (4500) and brown algae (2000) [27, 28]. Studies on the utilisation of algae as macroalgae for biodiesel are fewer than those of microalgae due to their comparatively low per hectare yield [19] and very low quantities of oil [136]. Therefore, the selection of the right species with relevant properties such as biomass and fatty acid productivities is essential for success in macroalgae biotechnology. As a result, selecting strains with high lipid productivity is critical for successful macroalgal biodiesel production [137]. Although total lipid content is a possible sign of a feedstock's suitability for biodiesel production, fatty acid content and profile are more important in determining its applicability for a specific end-use [138]. Unfortunately, to date, biodiesel production from macroalgae appears to be less appealing when compared to microalgae biomass with high lipid content. The lipid

content of macroalgal species is relatively low, ranging from 1 to 5% of dry matter [139]. Several studies have evaluated different macroalgae species, including *C. sertularioides*, *Sargassum boveanum*, *Sirophysalis trinodis*, *Laurencia obtuse*, *Jania rubens*, *Acanthophora specifera*, *Padina boryana*, *Gracilaria multipartite*, *Ulva intestinalis*, *Gracilaria vermiculophylla*, *Dictyota dichotoma*, *Ulva lactuca*, *Ulva linza*, *Cladophora fracta*, *Enteromorpha compressa*, *Spatoglossum macrodontum*, *Derbesia tenuissima*, and *Dictyota bartayresii* as biodiesel feedstocks [27, 28, 137, 138, 140] and reported significant variations in biomass production, lipid content, and fatty acid profile in these species. Both environmental factors (such as light intensity, ocean salinity, and temperature) and genetic differences between species have been associated with variances in fatty acid composition and lipid content. In general, brown species have more lipids than green variants [141, 142]. Compared to high lipid content microalgae biomass, macroalgae appear to be more competitive as a feedstock for bioethanol and bio-oils [27, 28].

(2) Lipids in Microalgae. In contrast, macroalgae have received less attention for biodiesel production because of the low amount of TGA in their lipids, making them a better feedstock for biogas and bioethanol than biodiesel [27, 28, 31, 137]. Microalgae have been extensively researched as a potential feedstock for biodiesel production [29, 31, 33, 98, 143, 144]. Microalgae are a diverse category of eukaryotic organisms, with around 300,000 species documented to date based on extrapolation from large and species-rich taxa [145]. Microalgae are very popular among the scientific communities because of their promises, but still, very few strains are well studied if compared with the total reported strains. Microalgal cells may create a wide range of lipid classes. The lipid content and lipid productivity are the most crucial factors in determining whether microalgae have the ability to produce biodiesel [30]. These lipids are classified as polar or neutral based on their chemical structures and polarity. Polar lipids, which frequently contain phospholipids and glycolipids, serve as membrane structural components in most circumstances. Under a variety of stress conditions, TAGs are typically observed to accumulate as a form of energy storage [146]. Only TAGs are readily transesterified into biodiesel using traditional techniques, despite the fact that practically all forms of microalgal lipids may be extracted. Due to the wide variety of lipids, algae, and microalgal strains, choosing the oleaginous microalgal strains best suited for biodiesel production will require screening a large number of microalgal strains [146–148]. A strategically chosen strain can aid not only in the production of higher-quality products but also in the reduction of the number of processing steps required for recovery. The following are the major steps in strain selection: (a) product of interest, (b) credible media selection, (c) cultivation characteristics, and subsequent selection of growth system/modules. Different microalgae species have so far had their total lipid content and free-fatty acid profiles studied for potential lipid production for biodiesel. The microalgae species studied include *Botryococcus braunii*, *Chlorella vulgaris*, *Chlamydomonas sp.*, *Desmodesmus brasiliensis*, *Scenedesmus obliquus*, *Botryococcus terribilis*, *Coelastrum microporum*, *Kirchneriella lunaris*, *Chlamydocapsa bacillus*, *Pseudokirchneriella subcapitata*, *Ankistrodesmus fusiformis*, *Ankistrodesmus falcatus*, *Dunaliella sp.*, *Chlorella emersonii, Amphora sp.*, *Nannochloropsis oculate*, *Graesiella emersonii MN877773*, *Nannochloropsis sp.*, *Porphyridium cruentum*, *Scenedesmus obliquus CNW-N*, *Dunaliella tertiolecta ATCC 30929*, *B. braunii IPE 001*, *B. braunii UK 807-2*, *B. braunii FACHB 357*, *B. braunii Showa*, *Isochrysis zhangjiangensis*, *Chlorella vulgaris ESP-31Scenedesmus sp. LX1*, *Neochloris oleabundans UTEX 1185*, *Monoraphidium sp. FXY-10, UTEX LB1999*, *C. vulgaris FACHB1068*, *Botryococcus sp.*, *Scenedesmus sp.*, *Chlorella vulgaris P12*, and *Tetraselmis subcordiformis* [29, 31, 148–154]. In general, the lipid/fatty acid content ranges from 8% to 71.4%, with *Dunaliella tertiolecta ATCC 30929* being one of the species producing the highest amount of lipids (60.6–67.8% of dry weight), while *Nannochloropsis salina*, *Scenedesmus obliquus*, *Nannochloropsis gaditana*, *Chlorella sp.*, *Chlorella protothecoides*, *Nannochloropsis oculate*, and *chlorella vulgaris* are the most studied species.

3.8.4. Alga Oil and its Fatty Acid Profile. In comparison to plant oils, algae lipids have a more diverse FAs composition [155, 156]. The fatty acid profile of the feedstock affects biodiesel quality factors like cetane number, exhaust emission, the heat of combustion, cold flow, viscosity, oxidative stability, viscosity, and lubricity. These factors depend on the number of double bonds, degree of unsaturation, and carbon chain branching in the oil [157, 158]. A high polyunsaturated fatty acid (PUFA) concentration has been associated with a low cetane number in biodiesel, which leads to poor ignition quality, increased viscosity, and sedimentation. High SFAs, on the other hand, have a dual effect, improving oxidative stability but also lowering cold flow characteristics, necessitating the use of a cold flow improver [158, 159]. As a result, it is necessary to select a feedstock containing an appropriate mixture of different types of fatty acids from algae [134]. Most species of microalgae produce fatty acids with chains of 12, 16, and 18 carbons, while some can synthesise fatty acids with up to 24 carbon atoms. Although polyunsaturated fatty acids (PUFAs) can also be present, TAGs mostly contain saturated (SFAs) and monounsaturated fatty acids (MUFAs), such as C14:0 (myristic acid), C16:0 (palmitic acid), C16:1 (palmitoleic acid), C18:0 (stearic acid), and C18:1 (oleic acid) [135]. Although the types and quantities of fatty acids differ greatly among algae, the presence of palmitic acid (C16:0), stearic acid (C18:0), oleic acid (C18:1), lauric acid (C18:2), and linolenic acid (C18:3) makes these fatty acids the most prevalent ones used in the production of high-quality biodiesel [135, 160].

3.8.5. Harvesting and Lipid Extraction. The harvesting process, which adds 20 to 30% to the cost of producing feedstock, is one of the biggest challenges in using algae for biofuel production [26, 161, 162]. The fact that algal cells only make up around 0.1% of the total culture volume in a typical outdoor pond presents a substantial technological difficulty for harvesting algae. Photobioreactors (PBRs) can create cultures at higher densities; although, they still have cell densities of less than 1%. The problem with this extremely diluted system is that only a small portion of the overall volume needs to be collected for further processing. Pumping such massive amounts of water results in significant energy costs [161]. The amount and quality of lipids produced from algae are also significantly impacted by the harvesting method [27, 28]. Because of the high cost caused by the technological constraints in the harvesting process, it has become a challenge to establish a productive method. Different harvesting strategies and optimization methods have been proposed including physical (centrifugation, gravity sedimentation, filtration, and flotation), chemical, biological, and electrical methods.

(1) Centrifugation. Algae cell harvesting has been done using a variety of centrifuges with varying efficiencies, either in a one-or two-step process that includes biomass preconcentration [12] and proven to be rapid and reliable with high recovery for practically all types of microalgae [12]. Unfortunately, the centrifugation process on large scale is energy intensive and requires high capital investment and operation costs. Furthermore, processing large volumes of water with a relatively low concentration of total suspended microalgae solids in water (0.04%-0.07%) takes time and energy, and the intense gravitational force and shear stresses in the process may cause cell structural damage [12, 14, 163].

(2) Gravity Sedimentation. One of the most affordable techniques for separating solids from liquid before further processing is gravity sedimentation. Because of its ability to handle large volumes, it has been widely used in wastewater and sludge treatment. The method is economically attractive as it requires a low amount of energy, low design cost, and less skilled operators [164]. Regrettably, the presence of a negative charge on the surface prevents microalgae with particle sizes less than 30 μm from settling due to gravity necessitating additional thickening [152, 153, 165]. Therefore, gravity sedimentation is only advantageous for settlement of colonial and larger microalgae as a preconcentration step for use with other harvesting methods [165]. As a result, when choosing harvesting methods, consideration must be given to the size, density, and economic value of the desired products [166]. Although Lamella separators have been utilised to improve harvesting rates as an alternative to gravity sedimentation, they are primarily used in the autoflocculation process [167].

(3) Flotation. Unlike gravity sedimentation, the flotation method works well for algae species that may not have a significant settling velocity for gravitational separation. As a result they float on the water's surface. In the flotation method, air or gas bubbles are used to bring suspended particles to the surface of a liquid, where collection can be done [168]. Because of the low density and self-floating characteristics of some microalgal species, this method can be faster and more effective than sedimentation. Flotation separation has demonstrated efficient harvesting of both fresh water and marine microalgae [166]. Several flotation methods for algae harvesting have been proposed and evaluated, including dissolved air flotation, dispersed air flotation, electrolytic flotation, and ozonation-dispersed flotation [164]. Among these, ozone flotation has proven to be more effective than other methods because it can improve lipid recovery. Ozone flotation may increase the effectiveness of cell flotation by altering the cell wall surface and/or releasing active substances from microalgal cells [164].

(4) Filtration. Filtration has been investigated as a potential harvesting method, with a wide range of filter and membrane types to choose from [14]. The process, like gravity sedimentation, is based on the size of the algae to be harvested, i.e., it is species-dependent [165]. Despite the fact that the method is a simple and effective process that also has the potential to be integrated with other methods to improve efficiency, it has only been tested on a laboratory scale. When filtration is used on a large scale, it frequently results in membrane clogging or fouling if the medium is directly filtered, the creation of compressible filter cakes, and significant maintenance costs, all of which restrict its desirability [164, 165].

(5) Flocculation. Flocculation is regarded as one of the best methods for harvesting microalgal biomass [169, 170]. Its applications, however, have encountered a number of economic and technical challenges, including high energy costs, flocculant toxicity, and inability to scale up [171]. After the addition of flocculants, the aggregation of unstable and microscopic microalgae particles is induced by surface charge neutralization, electrostatic patching, and/or bridging. The resulting agglomerates can then be easily separated using gravity-induced settling or any other traditional separation method [172]. Several flocculation methods, including physical, chemical, and biological flocculation, have been investigated as a preconcentration step for harvesting microalgal cells [12, 164, 173]. The ions in the chemical flocculants have the potential to negatively charge microalgal cells since they are negatively charged, resulting in efficient harvesting. Inorganic polymers such as polyelectrolyte and polyaluminum chloride; inorganic flocculants like $FeCl_3$, $Fe_2(SO_4)_3$, $AlCl_3$, and $Al_2(SO_4)_3$; and organic polymers like chitosan, cellulose, surfactants, and some synthetic fibres are used in chemical flocculation [12]. The most widely used and promising inorganic flocculants with ionic charges for harvesting algal biomass are $Al_2(SO4)_3$ and $FeCl_3$ which have the potential to be scaled up and used for different types of microalgal cells [167]. Unfortunately, these inorganic particles may continue to accumulate on the surface of microalgae, damaging the cells and interfering with lipid extraction. Along with their various detrimental impacts, inorganic flocculants can also hinder the recycling of culture medium and contaminate downstream operations. Since a large dosage is used, inorganic flocculants are expensive per unit of harvested microalgae [12, 14]. On the other hand, organic flocculants can be either anionic, cationic, or nonionic. Popular organic flocculants that have been extensively studied, particularly in wastewater treatment, include

chitosan, cationic starch, surfactants, and cellulose, as well as synthetic flocculants like polyacrylamide [164, 174]. However, utilising anionic and nonionic polymers alone does not effectively flocculate microalgae since their surfaces are negatively charged [175]. Contrarily, cationic polymers can reduce the electronegativity of microalgae and serve as a link between cells, enabling algal cells to aggregate more successfully. Additionally, pH, cell density in suspension, and microalgae surface charge all have an impact on the flocculation strength of organic flocculants [174, 175]. For microalgae harvesting to be cost-effective, an analysis of the flocculation harvesting's financial costs is essential. Although organic flocculants perform well in microalgae harvesting, likewise, a high organic flocculant dosage is required to obtain maximum recovery efficiency [174]. Therefore, environmental and economic factors should be considered before selecting an appropriate flocculation strategy. Alam et al. [176] suggested that bioflocculation is a more appealing alternative to chemical flocculation in microalgae harvesting since it has the potential to be environmentally benign and requires low energy inputs. Due to its popularity, numerous studies have been conducted to increase the efficiency and applicability of bioflocculation technologies. Most methods, however, have only been tried in the lab, and no one has yet successfully applied these technologies to large-scale microalgal harvesting. However, the majority of techniques have only been tested in laboratories, and no one has yet been successful in using these technologies for extensive microalgal harvesting [174].

(6) Ultrasound Flocculation. In this process, microalgae cells in suspension are forced to the ultrasonic wave nodes by high-frequency standing acoustic waves, forming agglomerates that quickly settle in the fluid due to gravity when the ultrasounds are turned off. Unlike other harvesting techniques, the cells are not sheared, and no chemicals are used [177]. The method may achieve a maximum filtration efficiency of 75% while consuming around 3.6 kWh/m^3 of energy [178]. When chitosan is added, the technique can achieve removal efficiencies of up to 98.5% with 100 W of ultrasound power [174, 179, 180]. Hincapié Gómez and Marchese [178] attempted to improve the process by coupling the acoustophoretic force, acoustic transparent materials, and inclined settling and were successful in achieving a filtration efficiency of 70% and a concentration factor of 11.6 at a flow rate of 25 mL·min^{-1} and energy consumption of 3.6 kWhm^{-3}. Nevertheless, despite its potential, the investigations into ultrasonic flocculation so far have only examined this method in a lab or pilot plant context [174, 177–180] for process optimization and scaling up; more researchers are therefore required.

(7) Electrocoagulation-Flotation. During this procedure, negatively charged microalgae cells prefer to migrate to the positively charged anode and lose their negative charge. Once this happens, molecular attraction forces take control, and the algae start to form flocs that can be easily separated using conventional sedimentation techniques [174, 181, 182]. This method is preferred to chemical flocculation because it is less expensive, takes less time to separate, and may not cause as much contamination of residual biomass with metallic hydroxides [183, 184]. Because their ions are liberated from a sacrificial anode by electrolytic oxidation, aluminium and iron electrodes are frequently utilised in electroflocculation. In an electric field, these electrodes can release Al^{3+}(aq) and Fe^{3+}(aq) ions, respectively. The Al^{3+}(aq) and Fe^{3+}(aq) ions spontaneously undergo hydrolysis to form hydroxides and/or polyhydroxy compounds that can operate as an active surface to adsorb negatively charged microalgal cells [14, 184]. When the performances of the two electrodes are compared, iron electrodes have a lower current efficiency than electrodes made of aluminium, which explains why they have a lower harvesting efficiency [174]. Even though electroflocculation microalgae have been the subject of several studies, their widespread use is still hampered by a high energy need.

(8) Magnetic Separation. Mathimani and Mallick [14] have identified magnetic particle separation as a promising approach for microalgal harvesting. In this technique, the microalgal cells are exposed directly to magnetite (Fe_3O_4) nanoparticles, which generate flocculation when there is a magnetic field. This allows the microalgal cells to be separated from the media. Furthermore, by attaching magnetic beads to nonmagnetic target cells, it is possible to quickly detach them from the medium. Magnetic cell separation technology has advanced quickly due to its excellent benefits, including low cost, easy operation, high selectivity, high throughput, robustness, and good biocompatibility [185, 186]. Various aspects of the magnetic separation of microalgae process have been studied, including the synthesis of efficient magnetic reagents, the separation process, particle-cell aggregate detachment, magnetic particle reuse, and the development of an effective magnetic separator. Different types of magnetic particles, including naked magnetic particles and surface functionalized magnetic particles, have been developed and have shown promise when used for microalgae cell separation [187]. Although magnetic separation methods have demonstrated a high potential for successful microalgae harvesting due to properties such as low energy consumption, fast separation, and reusability of medium and magnetic particles [187], the need for an acidic environment, the abundance of magnetic particles, and the additional process of recovering algae cells from magnetic particles restrict the commercialization of this approach [188].

3.8.6. Algae as Biorefinery Feedstocks. Biorefinery is an industrial process that converts biomass into a variety of biochemicals, materials, and energy products [189]. It aims to extract the most value from a specific biomass type to reduce waste pollution into the environment while also increasing the profitability of bioproducts. Microalgae cultivation, harvesting, drying, cell disruption, lipid extraction, and conversion into biofuels are ideal for biorefineries. Many researchers have assessed the potential of the biorefinery concept for the environmentally friendly processing of algae biomass for biofuels and value-added products, and they have concluded that the use of the biorefinery concept has the potential to increase the economic viability of microalgae biomass valorisation [189–194]. Algal biorefinery concepts enhance resource recovery, process effectiveness, and cost-effectiveness beyond economic benefits to create valuable bioproducts in a circular economy [193]. The choice of algae strain has been shown to have a significant impact on the selection of any algal biodiesel-based biorefinery. In this scenario, bioreactors must have vital characteristics including high lipid generation, high lipid productivity, high cell density, suppression of undesirable strains, self-flocculation, and high resilience to hydrodynamic and environmental stress. The production of lipids is the most important of them, since a strain with a high capacity for lipid accumulation will significantly affect the economics of scale [195].

Several biorefinery approaches have been proposed to maximize the benefits of the various microalgal components. The innovative microalgal biorefinery concept has four paths for producing high-value products: biodiesel-bioethanol-biogas, bioethanol-biogas, biodiesel-biogas, and biogas [189]. An algae biorefinery's technology is built to generate the desired products. For instance, high oil content algae will be utilized to produce biodiesel, which entails growing and harvesting microalgae, rupturing biomass cells, and extracting lipids. The spent microalgal biomass from lipid extraction could then be further valorised to various applications through direct use in biosorption, fertiliser, and feed supplement or by a biochemical process such as anaerobic digestion for biogas production; fermentation for bioethanol production; or thermochemical process such as pyrolysis for bio-oil or biochar; hydrothermal liquefaction process for bio-crude; and gasification process for syngas [193, 196]; although, the processing of algae biomass in a biorefinery holds tremendous promise [195]. However, most microalgae biorefineries are not profitable due to the untapped new value-added products from microalgal biomass [193]. Furthermore, algae biomass-based biorefineries are a relatively new technology that requires substantial financial investments in research and development (R&D) and advocates for public and private policies, large-scale demonstrations, deployment strategies, and assurance of continuous and sustainable production of algae biomass [197, 198]. The economic feasibility and uncertain environmental performance of an algae biorefinery are the primary constraints to its deployment. The harvesting and drying of biomass activities, which frequently demand a significant quantity of energy, have a significant impact on cost-competitiveness. A large-scale algae biomass-based biorefinery facility linked to a wastewater treatment facility could reduce the cost of producing biofuel, making it commercially and environmentally viable. Chemical genetics, genetic engineering, metabolic engineering, and microalgal omics applications can aid in the development of commercially viable microalgal biorefineries and pave the way for a carbon-neutral society [197].

3.8.7. Sustainability and Life Cycle Assessment in Algae for Biodiesel. The ability of algae to potentially store significant amounts of CO_2 from the environment and reduce GHG emissions in comparison to petroleum diesel is well established. Additionally, because they have the capacity to recycle the CO_2 that is emitted during each stage of the production of microalgal biodiesel inside their system, they are regarded as an environmentally sustainable resource [33, 143, 144, 199]. Examining the life cycle and energy balance of the production of microalgae biomass on a large scale is necessary to analyse the environmental effects of algae-derived biodiesel technology and the profitability of such undertakings [199–201]. The life cycle assessment (LCA) of biodiesel made from algae utilising closed and open system cultivations has been the subject of several studies [202–204] with Garcia et al. [205] conducting a meta-analysis of the life cycle greenhouse gas balances of microalgae biodiesel. Studies on LCA have shown that there is a lot of variation in the technologies taken into account as well as the methodological decisions made, making it impossible to draw reliable conclusions. This may indicate inconsistent findings on biodiesel's effectiveness in comparison to a rival fuel (petroleum diesel) [199]. In some studies, for example, the average GHG emissions reported were more than twice as high as fossil diesel, while some studies showed large benefits [205]. Although several researchers have proposed a framework for the environmental effects of producing algae biodiesel, there is still a great deal of variation in the LCA results due to differences in the life-cycle assessment (LCA) assumptions, life-cycle impact assessment (LCIA) included items, and system boundaries (considered in the LCA) [199]. This necessitates a more thorough LCA methodology to appropriately assess the environmental advantages of producing algae biodiesel as a substitute for traditional fossil fuels.

3.9. Recommendations for Future Research. If algae-based biodiesel can be generated effectively on a large scale, it could be the greatest option for replacing fossil-based fuel while providing significant economic and environmental benefits. However, despite significant advances in laboratory scale investigations, challenges in the areas of production economic feasibility, technological developments, and environmental pollution remain, posing new research opportunities. Therefore, to unlock the potential of algae for biodiesel production, the following areas have been recommended for further research:

(i) Algal cultivation studies should be concentrated on the selection of different varieties that are resistant to pathogens and pests and can accumulate large amounts of lipids. This could be accomplished, for example, by conducting research into various types of algae species, optimizing culture conditions for high growth rate and lipid productivity, and genetic engineering

(ii) More research is needed on new technology for the separation and harvesting of microalgae biomass since the physical harvesting methods now in use need dewatering large amounts of microalgal suspension, which uses a lot of energy and takes a long time

(iii) Since the application of various products made from algal biomass biorefinery has only been tested on a small scale, more research is needed to expand production in real-world engineering applications. By utilizing all types of products, such as vitamins, proteins, biochar, nutraceuticals, and pigments, the commercial interest in and use of biorefinery-based production can be increased, which could lower overall production costs and increase the profitability of the process

(iv) The economics of the process are critical to the commercialization of algae-based biofuels. Likewise, the ease of implementation is a key factor in determining whether a new technology or method succeeds. In order to reduce the number of stages involved in the production of biodiesel from algae, studies are required to develop simpler, better, and more economical methods. This is due to the fact that the systems utilized for producing algae are a complex composite of several subsets of systems (such as production, harvesting, extraction, and drying systems), suggesting that any change in a process step will have an impact on economics

(v) Studies on the closed PBR culture system are required in order to investigate low-cost, durable, and environmentally friendly PBR construction materials and to further optimize the process parameters in order to create an economically viable algal production system and achieve higher biomass and lipid productivity

(vi) More research on technoeconomic evaluation and life-cycle assessment is required to evaluate the commercial feasibility and environmental sustainability of algal potential for biodiesel generation

4. Conclusions

A successful study of bibliometric indicators for algae for the production of biodiesel was accomplished through the use of the Scopus database and VOSviewer to analyse the network visualisation and reveal relationships and collaboration among authors, coauthors, nations, and institutions, as well as keyword co-occurrence and cocitation of cited references. The most productive organisations, top journals in terms of publications and citations, prolific researchers and influential publications, average number of citations per document, most productive countries, and most commonly used keywords in the field were all identified. The study bibliometric indicators are expected to be useful to researchers in identifying potential research topics, high-quality academic literature, and suitable journals for publishing research on algae for biodiesel production. The fact that this study was limited to works indexed in the Scopus database, as well as the fact that the data and figures are time-dependent and subject to change, for example, total citations of any publications and other such information are a limitation. As a consequence, the results obtained by using different bibliographic databases may change slightly.

Abbreviations

AC: Average number of citations per publication
BOD: Biological oxygen demand
FA: Fatty acid
FAME: Fatty acid methyl ester
GDP: Gross domestic product
GHG: Greenhouse gases
LCA: Life cycle assessment
LCIA: Life cycle impact assessment
MUFA: Monosaturated fatty acids
PBR: Photobioreactor
PUFA: Polyunsaturated fatty acids
SFA: Saturated fatty acids
TAG: Triacylglycerols
TC: Total number of citations
TLS: Total link strength
TP: Total number of publications
VOSviewer: Visualization of Similarities Viewer.

Data Availability

The Scopus extracted dataset used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares no conflicts of interest regarding this work.

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