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Review

Catalysis in Biofuel Production and Biomass Valorization: Trends, Challenges, and Innovations Through a Bibliometric Analysis

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Abstract: Biomass valorization and biofuel production are essential strategies for converting renewable organic materials into sustainable energy, addressing the urgent need for alternatives to fossil fuels. This study conducts a bibliometric analysis of 1657 publications from the Scopus database, covering the period from 2010 to December 2024, revealing significant trends in this field. The number of published articles reached 318 in 2024, peaking at 163 articles in 2020, which garnered 7302 citations, indicating robust global interest. China leads the research landscape with 550 publications and 17,577 citations, followed by the United States with 160 publications and 9359 citations. Key journals include "ACS Sustainable Chemistry and Engineering" and "Chemsuschem", highlighting important contributions to the field. The analysis identifies four clusters: the role of lignin and heterogeneous catalysis in biomass conversion; pyrolysis and waste valorization techniques; key chemical intermediates from biomass; and advanced reactions like hydrogenolysis for enhancing product value. The study emphasizes the need for innovative strategies and interdisciplinary collaboration to improve biomass utilization and biofuel production. Future research should focus on developing integrated systems that promote a circular economy, optimize reaction conditions, and explore new biomass feedstocks. Overall, this research significantly advances the understanding of biomass conversion processes and supports the transition to renewable energy solutions, underscoring the critical role of biomass in achieving sustainability goals.

Keywords: bibliometric analysis; biomass valorization; biofuel production; catalysis; valorization; research trends; Scopus database; VOSviewer

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1. Introduction

The rapid increase in global energy demand, driven by industrialization and population growth, poses a significant challenge [1,2]. With a projected world population of 9 billion by 2050, energy demand is expected to rise by 50% [3,4]. Traditional resources like fossil fuels currently provide 80% of the world's energy supply and contribute to 66% of electricity generation, emitting substantial greenhouse gases (GHGs) [5]. This escalating demand, coupled with rising oil prices, has prompted countries to explore alternative energy sources, particularly biofuels [6,7]. Atmospheric CO_2 levels have consistently risen over the past three decades, reaching 410.5 ± 0.2 ppm in 2019, which is 130 ppm higher than pre-industrial levels [5,8]. The World Health Organization reports that air pollution causes approximately 3 million deaths annually, with only 10% of the global population living in areas that meet air quality standards. The Intergovernmental Panel on Climate Change warns that without intervention, GHG emissions could reach levels between 750 and 1300 ppm CO_2 equivalents or higher by 2100. This increase contributes to global warming and climate change [4,9]. The average temperature in 2020 was reported to be 1.2 ± 0.1 °C higher than the baseline of 1850–1900 [9].

In this context, biomass and organic residues are increasingly recognized as valuable resources for bioenergy production. Lignocellulosic biomass offers sustainable alternatives to fossil fuels for generating bioenergy in forms such as biogas, bioethanol, biodiesel, and biohydrogen. Biomass has emerged as the world's third-largest energy resource, following coal and oil [10,11]. It is gaining popularity for power generation due to its potential for long-term sustainability and its near carbon-neutral status, which can significantly reduce net carbon emissions [12,13]. The transportation sector, which accounts for approximately 28% of total global energy consumption, heavily relies on fossil fuels, contributing significantly to GHG emissions [1,14]. This dependence has led to serious environmental issues, including air, soil, and water pollution, negatively affecting public health and exacerbating climate change [15].

Liquid biofuel production contributes to climate change mitigation, agricultural diversity, energy security, and rural development [2,16]. The expansion of the biofuel sector is vital for fostering a sustainable economy by maximizing social, economic, and environmental benefits [2,17]. Research has advanced biofuels through four generations over the past five decades, each characterized by distinct feedstocks and production methods [18,19]. First-generation biofuels are derived from food crops, raising concerns about food security [19,20]. In contrast, second-generation biofuels utilize non-food biomass, such as agricultural residues, reducing competition with food supply [21]. The third generation focuses on advanced feedstocks, including algae, which can provide high energy content and grow in diverse environments [22,23].

Despite the evident social and environmental advantages of biofuels, their economic viability depends on several factors, including feedstock availability, technology, project design, and management [2,24]. The socio-economic effects of biomass utilization are not unequivocally constructive; challenges such as high investment and capital costs, technological maturity, large-scale biomass supply, and regulatory issues must be addressed. Biomass valorization encompasses a range of processes aimed at converting various forms of biomass into valuable products, including biofuels, biochemicals, and bio-composites [25,26]. This approach not only facilitates energy production, but also enhances the economic value of waste materials, contributing to a circular economy [27]. By utilizing agricultural, municipal, and industrial waste, biomass valorization reduces landfill use and environmental pollution while simultaneously creating new economic opportunities [28].

The technologies employed in biomass valorization are diverse, including thermochemical processes like gasification and pyrolysis, biochemical methods such as fermentation and anaerobic digestion, and enzymatic treatments [29,30]. These processes are designed to optimize the extraction of energy and high-value compounds from biomass, addressing the challenges posed by its complex composition [31]. The synergy between biofuel production and biomass valorization is essential for developing a sustainable bioeconomy [16]. By transforming waste into energy and other useful products, these processes contribute to reducing GHG emissions, enhancing energy security, and promoting rural development [32].

In light of these challenges, it is crucial to explore the primary areas of future directions, hotspots, and focus on biomass valorization and biofuel production research. There is an urgent need for further investigation to fill existing knowledge gaps and address emerging health concerns related to exposure from biomass valorization and biofuel production. An in-depth understanding of the research environment is essential for recognizing emerging trends and informing practical applications [33–35]. The bibliometric analysis serves as a robust methodology for systematically evaluating and visualizing published literature, yielding both quantitative and qualitative insights into scientific activities [36]. By utilizing statistical techniques, this analysis scrutinizes articles, books, and their citations, revealing patterns of research productivity across individuals, institutions, and countries [37]. Such insights contribute to a nuanced understanding of current research dynamics and facilitate the forecasting of future advancements. Moreover, co-citation analysis enhances bibliometric methods by elucidating the interrelationships among documents, thereby aiding in the identification of new research frontiers [38]. However, the data should be interpreted with caution, considering the potential biases and limitations inherent in citation-based metrics. It is crucial to balance these metrics with qualitative assessments of research quality and impact.

This study employs bibliometric methods to analyze literature on biomass valorization and biofuel production from the past 14 years, focusing on the knowledge base, key developments, and future trends. The novelty of our study lies in its thorough temporal bibliometric analysis of literature related to biomass valorization and biofuel production from 2010 to 2024, a period marked by significant advancements in research and technology. This analysis quantitatively assesses critical dimensions, including publication trends over time, leading journals in the field, and the geographical distribution of research efforts across different countries and funding sponsors. Additionally, we examine the contributions of prominent universities and explore co-citation networks to elucidate collaborative relationships among authors and identify key influencers in the research landscape. By highlighting the most cited publications, our analysis sheds light on foundational studies that have shaped the discourse on biomass valorization and biofuel production. Furthermore, this comprehensive assessment identifies key research topics and emerging themes, revealing gaps in the literature and suggesting new avenues for exploration. Ultimately, our research enhances the understanding of the current state of biomass valorization and biofuel production research in the context of environmental and water pollution, contributing to the development of effective strategies for mitigating these critical challenges. This work not only addresses important gaps, but also sets the stage for future investigations into innovative solutions for environmental and water pollution.

2. Methods

2.1. Data Sources and Bibliometric Methodology

This study employed the PRISMA checklist for its literature review methodology, adhering to PRISMA guidelines while deliberately excluding meta-analysis techniques from our analysis [23,38]. The bibliometric analysis serves as a valuable tool in systematic literature reviews, facilitating the development of a comprehensive and replicable database [35]. Its widespread adoption is attributed to its capability to provide an integrated overview of research sectors, outputs, organizations, and trends [36,39]. This method is particularly effective for reviewing extensive scholarly data, elucidating the relationships between journal citations, and offering insights into existing or emerging fields of study [39]. Furthermore, the bibliometric analysis supports ongoing research and development while highlighting its implications, making it a favored approach across various scientific disciplines [40].

To investigate trends and advancements related to biomass valorization and biofuel production, this paper employed a bibliometric analysis. Data were extracted from the Scopus database, covering the period from 2010 to December 2024. The Scopus database was chosen for its comprehensive coverage of all fields of study and its extensive collection of relevant published articles [36]. The literature search utilized the following query string and keywords: "(TITLE-ABS-KEY ((“Catalysis”) AND (“Biofuel Production” OR “Biomass Valorization” OR “Biomass Valorization”)) AND PUBYEAR > 2010 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE, “English”)) AND (LIMIT-TO (DOCTYPE,“ar” OR DOCTYPE,“re”)) AND (LIMIT-TO (SRCTYPE,“j”) OR LIMIT-TO (SRCTYPE,“p”)))". The research methodology is shown in Figure 1.

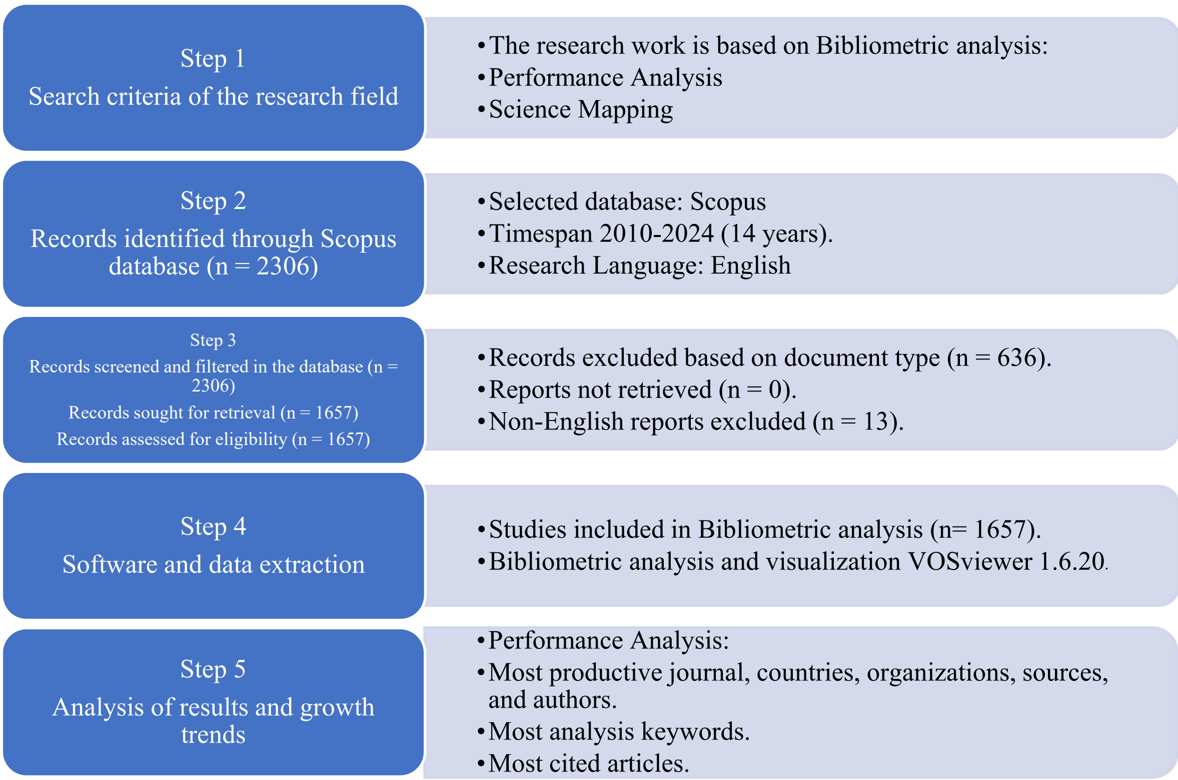


Figure 1. Research methodology.

After data extraction and organization from the Scopus database, Comma-Separated Values (CSVs) files were created for further analysis. To ensure the reliability and precision of the data during the source selection phase, multiple filtering procedures were implemented. These procedures involved the elimination of duplicate entries, and the application of defined inclusion and exclusion criteria based on language, document type, and source. Following the segmentation and evaluation of records, a comprehensive analysis of source names, authors, and funding agencies, and their affiliations was conducted for each year. The quality of the documents was further assessed through a review of their titles, abstracts, and keywords. Incomplete or inaccurate records were systematically discarded through a stringent filtration process to enhance the dataset's integrity. As a result, the dataset was refined to include only peer-reviewed journal articles published in English, ultimately reducing the total number of publications to 1657.

2.2. Visualization Procedure

In bibliometric studies, constructing and visualizing bibliometric maps significantly enhances the readability and identification of relationships among diverse sources. This methodology facilitates the analysis of findings and aids researchers in comprehending the structure of bibliometric results. To analyze these findings and familiarize ourselves with bibliometric patterns, we utilized VOSviewer version 1.6.20 for data processing. VOSviewer is an open-source, user-friendly software specifically designed for the visualization and networking of bibliometric data [41]. The choice of VOSviewer for data processing and analysis was based on its capacity to manage extensive networks and its advanced text-mining capabilities [41]. This software enables the identification of relationships and trends within the literature by generating bibliometric maps that visualize connections between selected articles [41]. A notable strength of VOSviewer is its dynamic label management, which adapts to algorithmic requirements, effectively displaying co-occurrences [41]. Our analysis focused on three primary aspects: the journals in which the articles were published, the author keywords utilized in the papers, and the countries of origin. These elements provide a comprehensive overview of the research landscape, making them essential for bibliometric investigations [42,43]. Key parameters for the analysis included publication counts, average normalized citations, and total link strength (TLS). These metrics are instrumental in assessing the visibility and impact of articles within the academic community [42].

Upon conducting the search, we retrieved a total of 1657 documents, comprising journal articles. These publications originated from 306 unique sources. The literature on this topic was significantly enriched by contributions from 7163 authors affiliated with 3901 distinct institutions globally. Geographically, authors from 84 countries made substantial contributions to this body of knowledge. The collective impact of these 1657 documents is highlighted by a total of 56,729 citations, underscoring their significance within the academic community. An analysis of author-supplied keywords provided further insights into the research focus, revealing a diverse range of 3618 unique terms. Table 1 summarizes the key bibliometric findings from the literature concerning biomass valorization and biofuel production.

Table 1. Summary of key bibliometric results (2010–2024).

Description	Findings
Publications	1657
Authors	7163
Countries	84
Publication Venues	306
Authors' Affiliations	3901
Author Keywords	3618
Total Citations	56,729

3. Results and Discussion

3.1. Trends in Publication and Citation for Biomass Valorization and Biofuel Production Research

The annual count of published articles is a critical metric for assessing trends in scientific research development. Concurrently, analyzing citation frequency provides essential insights into the quality and influence of these articles within the academic community. Figure 2 presents a detailed overview of publication trends related to biofuel production and biomass valorization from 2010 to 2024, revealing a significant overall increase in the number of publications during this period.

In 2010, only nine articles were published, which collectively received 4639 citations. This indicates that even early research made substantial contributions to the field. The number of publications gradually increased in subsequent years, reflecting a growing interest in biofuel production and biomass valorization. By 2011, the count reached six published articles, amassing 680 citations. This upward trend continued, with 15 articles published in 2013, garnering 1008 citations and signaling a growing recognition of the topic. A notable surge in output began in 2014, when 33 articles were published, resulting in 3550 citations. This increase underscored the expanding interest in research within this domain. The following year, 2015, saw a rise to 39 published articles, accumulating 3895 citations, further demonstrating the field's growing importance. In 2016, the number of publications increased to 51, with total citations reaching 4934. This trend continued in 2017, with 64 articles published and 4006 citations recorded. The year 2018 marked a significant leap, as 110 articles were published, resulting in 6203 citations, highlighting sustained interest and investment in research.

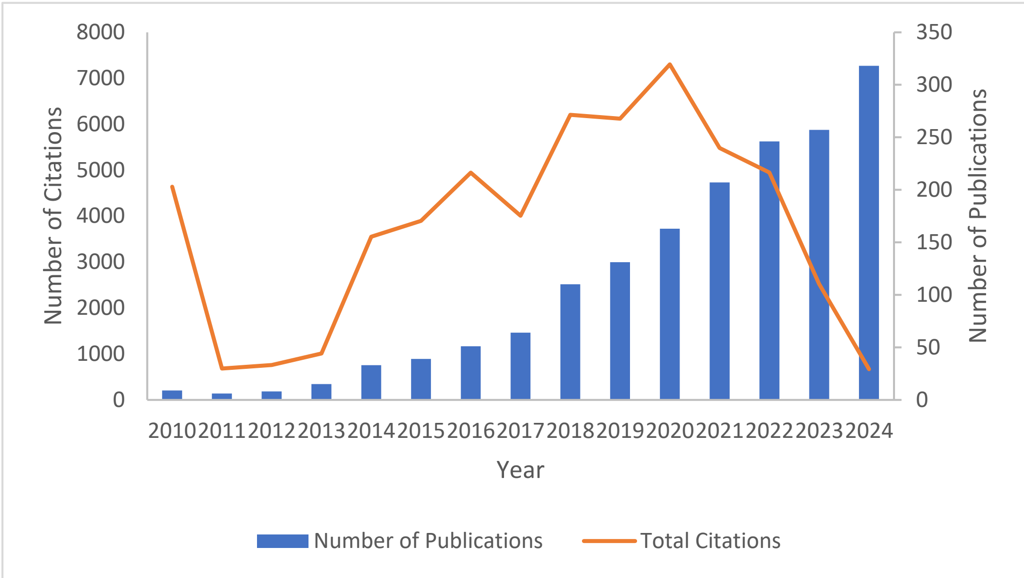


Figure 2. Analysis of total citations and annual publications on the topic of biofuel production and biomass valorization, as determined by the Scopus database until December 2024 (n = 1657).

In 2019, publication numbers increased to 131, which received 6117 citations, reinforcing the trend of substantial research output. The peak publication year was 2020, with 163 articles yielding 7302 citations, indicating a robust interest in biofuel production and biomass valorization. However, in 2021, despite the number of published articles soaring to 207, total citations declined to 5480. This may suggest a shift in research focus or a potential saturation of existing studies. The trend of fluctuating citation counts continued into 2022, with 246 publications and 4964 citations, indicating a significant volume of research output, albeit with reduced impact compared to earlier years. In 2023, the number of publications rose to 257, but citations dropped to 2523, suggesting that more recent research may not have achieved the same level of recognition as prior works. Finally, in 2024, the count of published articles reached 318, while citations fell to 668, indicating that newer publications have yet to gain traction within the academic community.

Overall, the data illustrate a clear upward trend in research on biofuel production and biomass valorization, underscoring heightened awareness and concern regarding these subjects. However, the variability in citation counts signals fluctuations in the impact and quality of publications over the years, necessitating further investigation into the factors influencing these trends.

Figure 3 illustrates the trends in publication outputs related to biomass valorization and biofuel production across seven primary Scopus subject categories. A search within the Scopus database yielded a total of 2306 research documents published from 2010 to December 2024 on the topics of biomass valorization and biofuel production. Among these, the predominant type is "articles", which accounted for 1670 publications, or 72.42% of the total. The remaining categories included "review articles" (19%), "book chapters" (4.42%), and other formats (such as "books", "conference articles", "non-English language documents", and "non-journal publications"). Given that "articles" and "review articles" constituted most of the output, the other categories were excluded from further analysis.

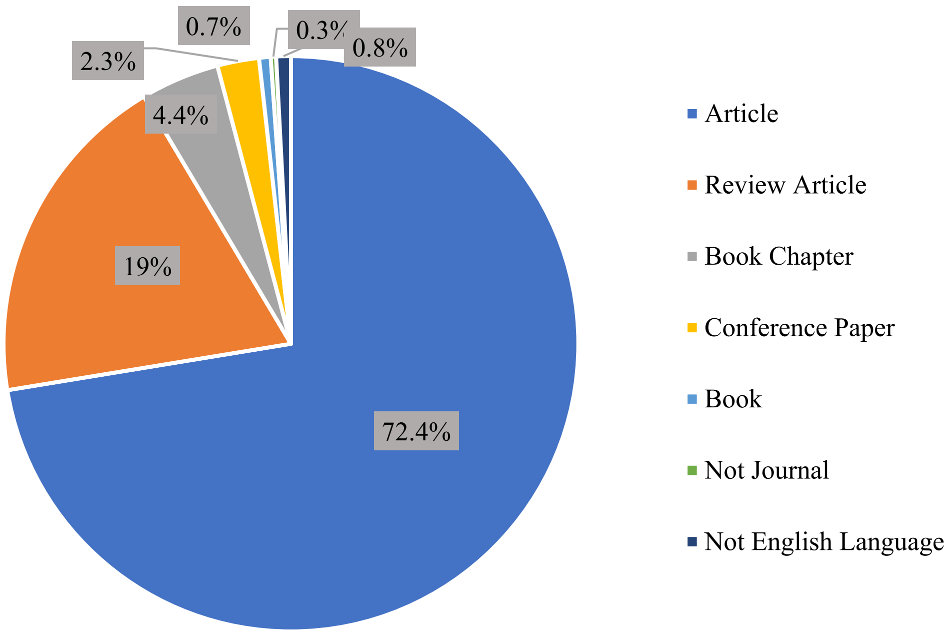


Figure 3. Categorization of documents related to biofuel production and biomass valorization.

3.2. Leading Journals for Articles of Biofuel Production and Biomass Valorization

Table 2 presents a detailed overview of the top 14 journals cited in biofuel production and biomass valorization research, highlighting essential metrics such as SCImago Journal Rank (SJR), H-index, total link score (TLS), publication counts, and total citations. The data indicate a significant concentration of research output in high-impact journals, underscoring their pivotal role in advancing knowledge in this domain.

Table 2. The top 14 sources by citation count for biofuel production and biomass valorization research.

Source Journal	TLS	No. of Documents	Total Citations	H-Index	SJR
ACS Sustainable Chemistry and Engineering	12,539	95	3721	173	1.664
Chemsuschem	10,289	75	3433	201	2.045
Green Chemistry	10,207	70	3296	272	1.878
ACS Catalysis	5660	42	2575	293	3.847
Bioresource Technology	4644	76	2818	364	2.576
Chemical Engineering Journal	4330	60	2088	309	2.852
Catalysis	4066	44	587	274	1.720
Catalysis Today	3787	31	1163	240	1.022
Applied Catalysis B: Environmental	3419	35	2524	328	5.112
Fuel	2908	40	927	256	1.451
Chemcatchem	2703	32	699	129	1.034
Industrial Crops and Products	2368	32	500	173	0.907
Biomass Conversion and Biorefinery	2023	30	282	45	0.595
Renewable Energy	859	28	886	250	1.923

The table provides bibliometric data on various journals in sustainability, catalysis, biomass conversion, and renewable energy, from 2010 to 2024. Journals like ACS Sustainable Chemistry and Engineering, Chemsuschem, and Green Chemistry stand out with high total citations, H-index values, and SJR scores, indicating their significant impact and broad recognition in the field. In contrast, journals such as Biomass Conversion and Biorefinery and Renewable Energy show lower citation counts and SJR values, suggesting they are either newer, more specialized, or still establishing their academic influence. The data highlight a diverse range of journals, from well-established ones with broad appeal to emerging and niche outlets with specialized focus areas.

In summary, Table 2 illustrates a distinct trend where high-impact journals dominate the discourse on biomass valorization and biofuel production research. Notably, "ACS Sustainable Chemistry and Engineering" is recognized for its substantial volume of publications, while "Environmental Science and Technology" stands out for its significant citation impact. The concentration of both publications and citations within these journals underscores their crucial role in advancing the scientific understanding of biomass valorization and biofuel production, highlighting the necessity for continued research in this vital area.

To further explore the network of international collaborations in biomass valorization and biofuel production research, a network diagram was constructed using VOSviewer. In this diagram, the journals engaged in the research are represented as labeled nodes, with connecting lines illustrating the contributions of each journal to the collective body of work. The size of each node corresponds to the total citations received by publications from that journal, while the thickness of the lines indicates the strength of collaborative relationships between the journals [44]. This visualization offers valuable insights into the dynamics of global cooperation in the field of biomass valorization and biofuel production research. The primary sources identified in this study consist of journals that published a total of 28 articles in this domain between 2010 and 2024. Figure 4 depicts that 14 of these sources meet the established criteria for inclusion.

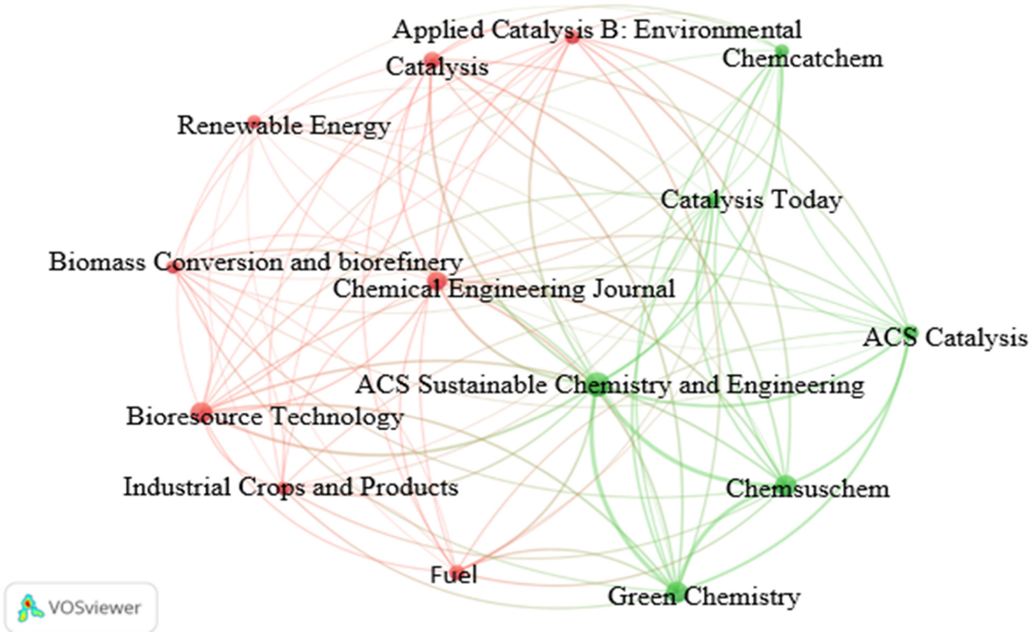


Figure 4. Co-occurrence map of journals published in 2010–2024 that have more than 28 articles related to biomass valorization and biofuel production.

This analysis underscores a robust network of high-impact journals committed to biomass valorization and biofuel production research, highlighting the essential role these platforms play in disseminating significant research findings. The variation in citation counts among these journals reflects their influence and points to specific areas of focus, suggesting that researchers should carefully consider these metrics when selecting appropriate venues for their publications. The prominence of journals such as "ACS Sustainable Chemistry and Engineering", which boasts the highest number of publications, and "Environmental Science and Technology", noted for its substantial citation impact, illustrates the diverse opportunities available for researchers to make meaningful contributions in this critical field. These journals not only facilitate the sharing of knowledge but also shape the future directions of research in biomass valorization and biofuel production.

3.3. Distribution of Research on Biomass Valorization and Biofuel Production by Country

The bibliometric analysis presented in Table 3 provides a detailed overview of the leading countries contributing to research in biomass valorization and biofuel production. These data include critical statistics such as citation counts, TLS, and the number of publications for each nation.

Table 3. Leading 12 countries through publishing biomass valorization and biofuel production research from 2010 to 2024.

Country	TLS	No. of Publications	Total Citations
China	80,059	550	17,577
Spain	24,371	167	4787
United States	41,214	160	9359
India	17,547	151	3156
Italy	16,509	115	2085
Republic of Korea	25,945	107	3922
United Kingdom	25,596	104	3513
France	14,025	98	3020
Germany	14,705	83	2574
Hong Kong	28,728	75	3773
Taiwan	14,198	52	1562
Brazil	5839	51	465

The results indicate that China leads the field with 550 publications and a total of 17,577 citations, establishing itself as the most significant contributor to biomass valorization and biofuel production research. Following China, the United States ranks second, with 160 publications and 9359 citations, demonstrating a strong research output in this area. Hong Kong and Republic of Korea also play notable roles, with 75 publications and 3773 citations, and 107 publications with 3922 citations, respectively, indicating a robust engagement with this critical environmental issue. Several key factors contribute to China's dominance in this research area such as strong governmental support and funding, abundant biomass resources, research collaboration and international partnerships, large research workforce and institutional capacity building, etc. [44].

Overall, these findings suggest a diverse range of countries actively engaged in biomass valorization and biofuel production research, each contributing uniquely to the discourse, with varying levels of publication output and citation impact. These data highlight the global relevance of this research area and the potential for continued collaboration across nations.

Overall, these data illustrate a diverse international landscape in biomass valorization and biofuel production research, characterized by varying levels of academic output and impact. China emerges as the leading country in terms of publications, followed by the United States, which also ranks high in citation impact. This indicates a well-established research infrastructure and significant scholarly engagement in environmental studies related to biomass valorization and biofuel production. Notably, China not only has the highest number of publications, but also the most citations, reflecting the substantial influence of its research in this field. The United States follows closely in terms of citations, underscoring the importance of its contributions. Countries like Hong Kong, Republic of Korea, the United Kingdom, and Spain demonstrate a growing interest in this critical area, indicating that global efforts are underway to address the challenges posed by biomass valorization and biofuel production contamination. Overall, these findings highlight the importance of international collaboration in advancing knowledge and strategies related to biomass valorization and biofuel production.

The network analysis identified 12 countries that show significant engagement in the study of biomass valorization and biofuel production, as depicted in Figure 5. Countries represented by larger nodes and thicker connecting lines hold central positions within the network, reflecting their influential roles in this research area. This visualization provides valuable insights into the global research landscape, emphasizing the key contributors who are advancing knowledge and management strategies related to biomass valorization and biofuel production. Understanding these dynamics is crucial for recognizing collaboration patterns and identifying the leading players in this important field of environmental science.

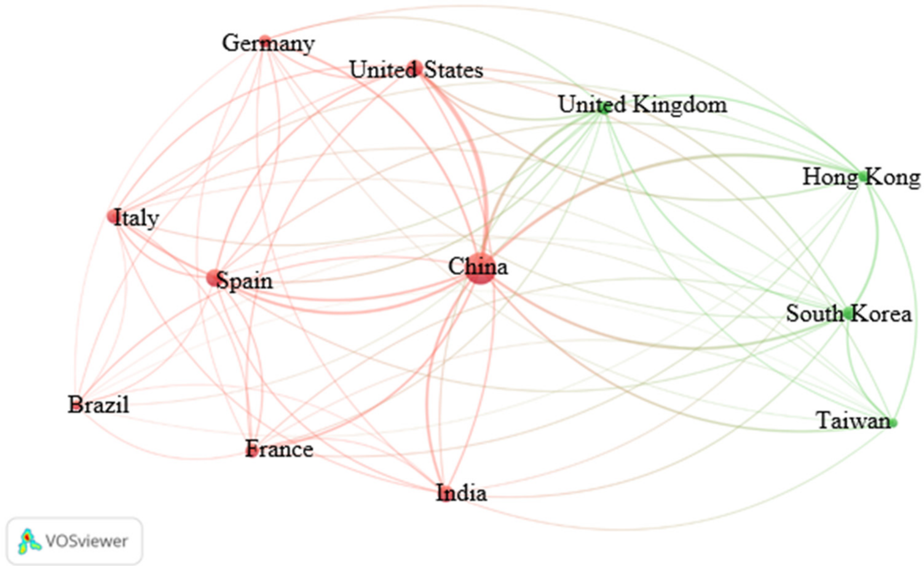


Figure 5. A network visualization displaying the primary nations taking part in the biomass valorization and biofuel production research.

The bibliometric analysis underscores the global dedication to addressing the challenges related to biomass valorization and biofuel production. Various countries have emerged as key contributors to this essential field of research. To identify the leading institutions engaged in studies on biomass valorization and biofuel production, a comprehensive map was developed using data from 1657 publications obtained from the Scopus database, as illustrated in Figure 6.

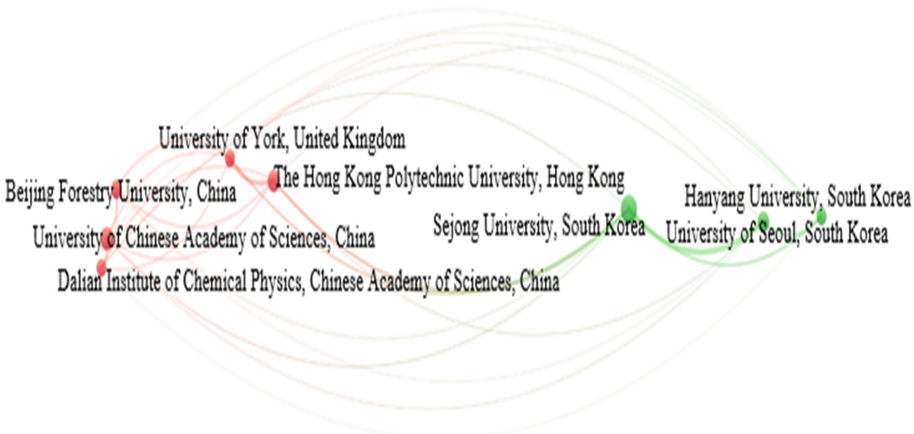


Figure 6. A network visualization showcasing the main universities involved in biomass valorization and biofuel production research.

The initial dataset primarily listed affiliations by departments or colleges rather than specifying the universities or research institutions. As a result, it was necessary to reorganize this information to accurately reflect the universities or research entities involved, as presented in Table 4.

Table 4. Top eight affiliations and universities according to the authors' affiliation.

Affiliation	Institute	Country	TLS	Total Citations	No. of Documents
Department of Environmental and Energy	Sejong University	Seoul, Republic of Korea	2533	1204	29
Department of Civil and Environmental Engineering	The Hong Kong Polytechnic University	Hung Hom, Hong Kong	1711	1436	18
Green Chemistry Centre of Excellence, Department of Chemistry	University of York	York, United Kingdom	1604	998	11
School of Environmental Engineering	University of Seoul	Seoul, Republic of Korea	1565	356	15
Department of Earth Resources and Environmental Engineering	Hanyang University	Seoul, Republic of Korea	555	112	11
University of Chinese Academy of Sciences	University of Chinese Academy of Sciences	Beijing, China	509	1259	20
Cas Key Laboratory of Science and Technology on Applied Catalysis	Dalian Institute of Chemical Physics, Chinese Academy of Sciences	Dalian, China	454	213	11
Beijing Key Laboratory of Lignocellulosic Chemistry	Beijing Forestry University	Beijing, China	400	543	13

Among the leading institutions in biomass valorization and biofuel production research, the "Department of Environmental and Energy at Sejong University" in Seoul, Republic of Korea, stands out with 29 publications and 1204 citations, highlighting its significant contributions to this critical field. Following closely is the "Department of Civil and Environmental Engineering at The Hong Kong Polytechnic University", which has produced 18 publications and accumulated 1436 citations, indicating its valuable role in addressing environmental challenges. The "Green Chemistry Centre of Excellence at the University of York" in the United Kingdom has published 11 articles that received 998 citations, reflecting its important contributions to green chemistry in relation to biomass.

Additionally, the "School of Environmental Engineering at the University of Seoul" has 15 publications and 356 citations, showing its active engagement in this research area. The "Department of Earth Resources and Environmental Engineering at Hanyang University", also in Republic of Korea, has contributed 11 publications with 112 citations, while "the University of Chinese Academy of Sciences" in Beijing, China, has 20 publications and 1259 citations, reinforcing its role in advancing research in biomass valorization. The "Dalian Institute of Chemical Physics", specifically its CAS Key Laboratory of Science and Technology on Applied Catalysis, has published 11 articles with 213 citations, emphasizing its contributions to applied catalysis research. Lastly, the "Beijing Forestry University", through its Beijing Key Laboratory of Lignocellulosic Chemistry, has produced 13 publications with 543 citations, showcasing its focus on lignocellulosic materials.

The main strength points for these institutions are as follows: leading in biomass catalysis; strong government funding; collaborations with industry; advanced catalytic research;

interdisciplinary studies integrating environmental sciences, specializing in biomass pyrolysis; bio-oil upgrading and extensive biomass conversion research; strong academic impact. However, the weakness and areas that need to be improved relate to biofuel adoption and regulatory challenges that slow down large-scale production; research on next-generation biofuels (like algae-based fuels) has slowed down due to inconsistent policy support; and the high cost of sustainable biofuels remains a key barrier to scaling up research.

Overall, these institutions represent a diverse array of contributions to the field, reflecting varying levels of research output and impact. Collectively, they enhance our understanding of biomass valorization and biofuel production and underscore the importance of collaborative efforts in this vital area of study.

3.4. Co-Citation Network of Authors in Biomass Valorization and Biofuel Production Research

Co-citation author network analysis is a recognized bibliometric technique that systematically maps existing literature [45]. This method identifies authors who are frequently cited together, thereby uncovering conceptual frameworks and thematic interconnections within a specific research area. In this study, we employed VOSviewer to perform a detailed co-citation network analysis, which provided insightful perspectives on the relationships among publications centered on biomass valorization and biofuel production.

Table 5 outlines the most prolific researchers in the field, indicating their publication counts and total citations. For example, Kwon, E.E. leads with 42 publications and 1114 citations, followed by Tsang, D.C.W., who has 33 publications and an impressive total of 2996 citations. Other noteworthy contributors include Jung, S. with 28 publications, Ok, Y.S. with 24, and Yu, I.K.M., Li, H. and Tsang, Y.F., each contributing 19 publications.

Table 5. Most prolific researchers in biomass valorization and biofuel production (2010–2024).

Author	Publications	Total Citations	University	Country
Kwon, E.E.	42	1114	Hanyang University	Republic of Korea
Tsang, D.C.W.	33	2996	Hong Kong Polytechnic University	Hong Kong
Jung, S.	28	414	Kyung Hee University	Republic of Korea
Ok, Y.S.	24	2318	Korea University	Republic of Korea
Yu, I.K.M.	19	1896	The Chinese University of Hong Kong	Hong Kong
Li, H.	19	396	Guizhou University	China
Tsang, Y.F.	19	199	The Education University of Hong Kong	Hong Kong

In contrast, Table 6 highlights the most influential researchers based on citation impact. Here, Bruijnincx, P.C.A. stands out with only three publications, but an exceptional total of 4265 citations. Weckhuysen, B.M. and Zakzeski, J. also show significant impact with four and two publications, respectively, garnering 4153 and 4053 citations. Tsang, D.C.W. appears again, reaffirming his importance in both publication volume and citation impact, alongside Ok, Y.S. and Yu, I.K.M., who are also notable in this context.

A comparison of these two tables reveals several authors who exhibit both high publication output and considerable citation impact. Notably, Tsang, D.C.W. and Ok, Y.S. appear in both tables, illustrating their dual influence through extensive research contributions and substantial citation counts. Yu, I.K.M. is also featured in both, highlighting his role in advancing the field.

This overlap underscores the significance of these researchers in shaping the intellectual landscape of biomass valorization and biofuel production. Their substantial publication outputs, coupled with high citation figures, emphasize their positions as key contributors to advancing knowledge in this vital area of environmental science. The insights gained from this co-citation network analysis not only clarify the current research landscape, but also reveal the collaborative dynamics among these influential authors.

Table 6. Most influential researchers by citation impact in biomass valorization and biofuel production (2010–2024).

Author	Publications	Total Citations	University	Country
Bruijnincx, P.C.A.	3	4265	Utrecht University	The Netherlands
Weckhuysen, B.M.	4	4153	Utrecht University	The Netherlands
Zakzeski, J.	2	4053	University of California	USA
Jongerius, A.I.	2	4053	Utrecht University	The Netherlands
Tsang, D.C.W.	33	2996	Hong Kong University	Hong Kong
Ok, Y.S.	24	2318	Korea University	Republic of Korea
Yu, I.K.M.	19	1896	Hong Kong University	Hong Kong
Beckham, G.T.	9	1748	National Renewable Energy Laboratory	USA

3.5. Top Cited Publications in Biomass Valorization and Biofuel Production Research

Citation analysis is a vital method for elucidating the intellectual connections among publications, especially when one study references another. This approach aids in identifying key research articles within a specific academic discipline and allows for the examination of citation trends and patterns [36]. In this study, we conducted a citation analysis of papers published in the field of biomass valorization and biofuel production. Table 7 presents the top 19 articles ranked by citation counts, with the rankings determined solely by their adherence to the criteria set forth by the Scopus database. This analysis offers valuable insights into the most significant and influential publications in this area. The studies discussed highlighted the significant relationship between biomass valorization and biofuel production, emphasizing advancements in converting biomass into renewable fuels and chemicals. Citation analysis has identified key publications that underscore the vital role of biomass valorization in producing renewable energy sources.

For instance, Zakzeski et al. [46] underscored the significance of catalytic lignin valorization, which is crucial for transforming biomass into valuable products, while You et al. [47] developed a method that integrates oxidative biomass upgrading with hydrogen production, utilizing an Ni_3S_2/Ni foam electrocatalyst to convert biomass substrates into high-value products while efficiently generating hydrogen. This integration enhances biomass valorization and supports biofuel production by maximizing energy conversion and minimizing hazardous by-products. In addition, the studies by Van den Bosch et al. [48] and Linger et al. [29] highlight effective methods for fractionating lignocellulosic materials. Van den Bosch et al. [48] established a catalytic biorefinery process that converts birch sawdust into valuable phenolic compounds and carbohydrate pulp, facilitating advancements in biofuel applications. Linger et al. [29] focused on utilizing (*Pseudomonas putida*) to convert lignin-derived aromatic compounds into medium-chain-length polyhydroxyalkanoates (mcl-PHAs), which can be further upgraded into fuels and chemicals. Furthermore, Cha and Choi [25] demonstrated the integration of biomass valorization with hydrogen production by oxidizing 5-hydroxymethylfurfural (HMF) into 2,5-furandicarboxylic acid (FDCA) in a photoelectrochemical cell, showcasing a promising method for converting biomass intermediates into valuable chemicals.

Moreover, Foong et al. [27] highlighted the potential of microwave pyrolysis to convert biomass waste into engineered activated biochar, addressing reactor design challenges to enhance the production of value-added products. Vardon et al. [49] successfully engineered (*Pseudomonas putida*) to convert lignin-derived compounds into cis, cis-muconic acid, which can be hydrogenated to adipic acid using Pd/C as a catalyst, demonstrating the potential of lignin valorization in biorefineries. Wu et al. [50] introduced a solar energy-driven lignin-first approach, using cadmium sulfide quantum dots to cleave β-O-4 bonds in lignin at room temperature, converting it into functionalized aromatics while preserving cellulose and hemicellulose. The studies also address challenges such as metal leaching in catalytic systems. Han et al. [51] utilized ultrathin Ni/CdS nanosheets for the photocatalytic conversion of biomass intermediates into valuable products while producing hydrogen, emphasizing the impact of reaction conditions on conversion rates. Liu et al. [30] demonstrated an efficient electrochemical process for producing glucaric acid and hydrogen from glucose using nanostructured NiFe catalysts, marking a significant advancement in biomass valorization. Démolis et al. [52] reviewed alkyl levulinates as bio-based alternatives to petrochemicals, while Ferrini and Rinaldi [26] presented a biorefining method using catalytic hydrogen transfer reactions to isolate lignin bio-oil from plant biomass. Cao et al. [53] reviewed renewable hydrogen production through biomass gasification, emphasizing the need for improved efficiency in thermochemical processes.

The studies by Huang et al. [54] highlight the necessity of optimizing catalyst characteristics to improve biomass valorization and biofuel synthesis. Behling et al. [55] focus on the heterogeneous catalytic oxidation of lignin, addressing its potential as a valuable chemical source despite being underutilized. Rambabu et al. [56] present an eco-friendly method to synthesize multifunctional zinc oxide nanoparticles from date pulp waste, demonstrating their effectiveness in degrading hazardous dyes and antibacterial applications for wastewater treatment. Li et al. [28] develop iridium single-atom catalysts on nitrogen-doped carbon, achieving superior activity for formic acid oxidation due to the isolation of iridium sites. Lastly, Luo et al. [57] introduce PdMo bimetallene as an efficient electrocatalyst for oxygen reactions, showcasing high performance and stability. Together, these studies advance the understanding of biomass conversion and catalysis, supporting sustainable energy solutions.

These collective studies not only address various methodologies for biomass conversion, but also highlight the necessity of optimizing catalyst characteristics, as noted by Dutta et al. [58] in their review of gamma-valerolactone synthesis from levulinic acid using non-noble metal catalysts. This comprehensive body of research contributes to a more sustainable approach to energy production, demonstrating the pivotal role of biomass as a key resource in the transition to renewable fuels.

Among the top publications in biomass valorization and biofuel production research, a significant study is "The catalytic valorization of lignin for the production of renewable chemicals", authored by Zakzeski, J. and published in 2010 in the "Chemical reviews" [46]. This influential paper has garnered 3788 citations. The study emphasized the significance of catalytic lignin valorization for producing renewable chemicals, positioning it as a crucial component of biomass. This study is directly related to biomass valorization and biofuel production, as it explores how lignin, a major component of biomass, can be converted into valuable chemicals and fuels. The research reviewed various catalytic strategies, noting that reduction systems typically yield bulk chemicals with lower functionality, while oxidation systems produce fine chemicals with higher functionality. These findings are essential for advancing biomass valorization, as they provide insights into how lignin can be transformed into usable products. The key challenges identified include the complexities of native lignin and its interactions with contaminants, which can hinder catalyst performance. The authors advocate for using model compounds that closely resemble lignin's functional groups to facilitate better comparisons of catalytic activity. This approach is vital for developing effective catalysts that can be applied in biorefineries, as it aligns with the goals of biomass valorization. The study stresses the importance of improving separation processes in biorefineries to enhance the efficiency of biomass-derived product streams. By drawing parallels between the evolution of petroleum refineries and the emerging field of biorefineries, the authors suggest that innovation in catalytic technology can transform lignin from a low-value by-product into a high-value feedstock for various chemicals and biofuels [46].

Table 7. The top 19 most-cited articles.

First Author	Year	Title	Source	Citation	Ref.
Zakzeski, J.	2010	The catalytic valorization of lignin for the production of renewable chemicals.	*Chemical reviews*	3788	[46]
You, B.	2016	A general strategy for decoupled hydrogen production from water splitting by integrating oxidative biomass valorization.	*Journal of the American Chemical society*	733	[47]
Van den Bosch, S.	2015	Reductive lignocellulose fractionation into soluble lignin-derived phenolic monomers and dimers and processable carbohydrate pulps.	*Energy and Environmental Science*	728	[48]
Linger, J. G.	2014	Lignin valorization through integrated biological funneling and chemical catalysis.	*Proceedings of the National Academy of Sciences*	658	[29]
Cha, H. G.	2015	Combined biomass valorization and hydrogen production in a photoelectrochemical cell.	*Nature chemistry*	612	[25]
Foong, S. Y.	2020	Valorization of biomass waste to engineered activated biochar by microwave pyrolysis: Progress, challenges, and future directions.	*Chemical Engineering Journal*	581	[27]
Vardon, D. R.	2015	Adipic acid production from lignin.	*Energy and Environmental Science*	506	[49]
Wu, X.	2018	Solar energy-driven lignin-first approach to full utilization of lignocellulosic biomass under mild conditions.	*Nature catalysis*	473	[50]
Han, G.	2017	Visible-light-driven valorization of biomass intermediates integrated with H2 production catalyzed by ultrathin Ni/CdS nanosheets.	*Journal of the American Chemical Society*	430	[51]
Liu, W.J.	2020	Efficient electrochemical production of glucaric acid and H2 via glucose electrolysis.	*Nature communications*	404	[30]
Démolis, A.	2014	Synthesis and applications of alkyl levulinates.	*ACS Sustainable Chemistry and Engineering*	402	[52]
Ferrini, P.	2014	Catalytic biorefining of plant biomass to non-pyrolytic lignin bio-oil and carbohydrates through hydrogen transfer reactions.	*Angewandte Chemie*	386	[26]
Cao, L.	2020	Biorenewable hydrogen production through biomass gasification: A review and future prospects.	*Environmental Research*	379	[53]

Table 7. *Cont.*

First Author	Year	Title	Source	Citation	Ref.
Behling, R.	2016	Heterogeneous catalytic oxidation for lignin valorization into valuable chemicals: What results? What limitations? What trends?	*Green chemistry*	358	[55]
Rambabu, K.	2021	Green synthesis of zinc oxide nanoparticles using Phoenix dactylifera waste as bioreductant for effective dye degradation and antibacterial performance in wastewater treatment.	*Journal of Hazardous Materials*	333	[56]
Huang, X.	2014	Catalytic depolymerization of lignin in supercritical ethanol.	*ChemSusChem*	332	[54]
Li, Z.	2020	Iridium single-atom catalyst on nitrogen-doped carbon for formic acid oxidation synthesized using a general host–guest strategy.	*Nature chemistry*	318	[28]
Luo, M.	2019	PdMo bimetallene for oxygen reduction catalysis.	*Nature*	317	[57]
Dutta, S.	2019	Green synthesis of gamma-valerolactone (GVL) through hydrogenation of biomass-derived levulinic acid using non-noble metal catalysts: A critical review.	*Chemical Engineering Journal*	306	[58]

The second most cited study, "A General Strategy for Decoupled Hydrogen Production from Water Splitting by Integrating Oxidative Biomass Valorization", by You, B. (2016), has received 733 citations and was published in the "Journal of the American Chemical Society" [47]. This research explores the combination of oxidative biomass upgrading with decoupled hydrogen (H_2) generation from water splitting. Traditional water electrolyzers produce hydrogen and oxygen (O_2) simultaneously, necessitating gas separation and suffering from low energy conversion efficiency due to the slow anodic oxygen evolution reaction (OER). The study introduces a novel hierarchically porous Ni_3S_2/Ni foam bifunctional electrocatalyst (Ni_3S_2/NF), which facilitates the oxidative upgrading of biomass substrates like ethanol, benzyl alcohol, and 5-hydroxymethylfurfural (HMF). This method allows for the oxidation of these organics to valuable liquid products with much lower overpotentials than OER, particularly emphasizing the conversion of HMF to 2,5-furandicarboxylic acid (FDCA), which has favorable thermodynamics and is more valuable than O_2. By integrating H_2 production with HMF oxidation, the required cell voltage is reduced by approximately 200 mV, achieving a current density of 100 mA cm^{-2}. The Ni_3S_2/NF catalyst exhibits excellent durability and high Faradaic efficiencies for both H_2 and FDCA production. This approach not only mitigates risks associated with H_2/O_2 mixtures and reactive oxygen species (ROS), but also maximizes energy conversion efficiency while generating high-value products. Overall, the study advances biomass valorization by transforming biomass into valuable chemicals while simultaneously producing hydrogen, enhancing the potential for renewable energy applications and contributing to biofuel production. The findings suggest a pathway to improve energy efficiency and economic viability in sustainable biomass utilization and renewable energy generation [47].

The study titled "Reductive lignocellulose fractionation into soluble lignin-derived phenolic monomers and dimers and processable carbohydrate pulps", authored by Van den Bosch, S, has received 728 citations and was published in “Energy & environmental science” in 2015 [48]. This research investigated a catalytic biorefinery process for the reductive fractionation of lignocellulose, focusing on efficiently converting birch sawdust into soluble lignin-derived phenolic monomers and dimers, as well as processable carbohydrate pulps. The study employed a Ru on carbon catalyst (Ru/C) in methanol under hydrogen (H_2) atmosphere at elevated temperatures, achieving over 90% delignification of the lignin content. This process resulted in a lignin oil containing more than 50% of phenolic monomers (mainly 4-n-propylguaiacol and 4-n-propylsyringol) and around 20% of phenolic dimers, alongside a carbohydrate pulp that retained approximately 92% of the original polysaccharides, including nearly all cellulose. The research highlighted several key parameters influencing product yield, such as temperature, reaction time, wood particle size, and catalyst reusability. The lignin oil’s structural features were characterized using techniques like GC/MS, GPC, and 2D HSQC NMR, indicating potential applications in the polymer and resin industries. Notably, the process proved to be techno-economically feasible, with the carbohydrate pulp capable of being converted into valuable sugar polyols, while the inclusion of methyl acetate as a solvent enhanced the overall safety and efficiency of the process. The study concluded that the proposed biorefinery approach effectively valorizes both lignin and polysaccharide components, yielding multiple high-value products. Further research into cheaper catalysts and continuous flow designs is also suggested to enhance economic viability, particularly pursuing a nickel-based biorefinery aligned with the “lignin-first” concept [48].

The study titled “Lignin valorization through integrated biological funneling and chemical catalysis”, authored by Linger, J. G., has received 658 citations and was published in “Proceedings of the National Academy of Sciences” in 2014 [29]. This research explored the potential of lignin, an energy-dense and heterogeneous biopolymer, as a valuable feedstock for renewable fuels and chemicals. Despite its abundance, lignin is often underutilized and mainly burned for heat due to its complex structure, which complicates selective valorization. However, certain organisms have evolved to metabolize lignin-derived aromatic compounds, enabling their conversion into useful products. The study utilized (*Pseudomonas putida*) KT2440, which can catabolize aromatic compounds derived from lignin, converting them into medium-chain-length polyhydroxyalkanoates (mcl-PHAs). These bioplastics exhibited similar properties to conventional mcl-PHAs derived from carbohydrates. Furthermore, the produced mcl-PHAs were catalytically converted into chemical precursors and fuel-range hydrocarbons. The research introduced a comprehensive method for utilizing lignin, showcasing its conversion into renewable fuels, chemicals, and materials, thus addressing the challenges of lignin heterogeneity. The authors emphasized that this integrated approach allows for the full valorization of biomass, aligning with sustainable energy goals. The study involved alkaline pretreatment of corn stover to obtain a lignin-rich stream, which was then characterized and used to cultivate **Pseudomonas putida** for mcl-PHA production. The mcl-PHAs were extracted, characterized, and demonstrated potential for further upgrading into hydrocarbons through thermal depolymerization and catalytic conversion [29].

The study titled “Combined biomass valorization and hydrogen production in a photoelectrochemical cell”, authored by Cha, H. G., has received 658 citations and was published in “Nature chemistry” in 2015 [25]. This study developed a novel approach for combining biomass valorization with hydrogen production in a photoelectrochemical cell (PEC). In a typical PEC, hydrogen is generated through water reduction at the cathode, while water oxidation at the anode produces oxygen; however, the anode reaction often presents kinetic challenges. This study explores the oxidation of 5-hydroxymethylfurfural (HMF), a significant intermediate in biomass conversion, into 2,5-furandicarboxylic acid (FDCA), a valuable monomer for various polymers, at the anode of the PEC. By employing 2,2,6,6-tetramethylpiperidine-1-oxyl as a mediator, the researchers achieved near-quantitative yields and 100% Faradaic efficiency under ambient conditions, eliminating the need for precious-metal catalysts. Importantly, this oxidation reaction proved to be both thermodynamically and kinetically more favorable than traditional water oxidation. The findings indicate that solar-driven biomass conversion can serve as an effective anode reaction, enhancing the efficiency and applicability of PECs for solar fuel production [25].

The study titled "Valorization of biomass waste to engineered activated biochar by microwave pyrolysis: Progress, challenges, and future directions", authored by Foong, S.Y., has received 581 citations and was published in "Chemical Engineering Journal" in 2020 [27]. This study explored the potential of transforming biomass waste into engineered activated biochar through microwave pyrolysis, presenting a promising alternative to fossil fuels for energy recovery and the production of value-added products. Pyrolysis, a thermochemical conversion technique, is particularly attractive due to its low pollutant emissions and the diverse range of products it can produce. The study reviews various pyrolysis methods, including conventional pyrolysis, vacuum pyrolysis, solar pyrolysis, and innovative microwave pyrolysis. Unlike conventional methods that face challenges like poor heat transfer, microwave pyrolysis achieves efficient heating by generating energy directly within the biomass through interactions with microwaves. The mechanisms involved in this process include dipole polarization, ionic conduction, and interfacial polarization. However, the study identifies the lack of advanced reactor designs as a significant barrier to the commercial implementation of microwave pyrolysis in biomass recycling. The authors note that microwave pyrolysis primarily yields solid biochar, which could be further upgraded into engineered activated biochar. This upgraded biochar possesses desirable properties for various applications, including pollution control, catalysis, and energy storage. The review emphasizes the importance of producing engineered activated biochar from microwave pyrolysis and discusses its applications, aiming to bridge the existing research gap. The authors highlight key implications for future development, suggesting that addressing reactor design challenges and optimizing production processes could enhance the viability of this technology in biomass valorization and biofuel production [27].

The study titled "Adipic acid production from lignin", authored by Vardon, D. R., has received 506 citations and was published in "Energy & Environmental Science" in 2015 [49]. This study investigated the potential of converting lignin, a complex alkyl-aromatic polymer found in plant cell walls, into adipic acid, a widely produced dicarboxylic acid. While lignin has significant energy content, it is often discarded in modern biorefineries, where cellulose and hemicellulose are prioritized for conversion into renewable fuels and chemicals. The study emphasizes the importance of valorizing lignin to enhance the sustainability and viability of third-generation biorefineries. To achieve this, the researchers employed metabolic engineering, separation techniques, and catalysis. They engineered **Pseudomonas putida** KT2440 to convert lignin-derived aromatic compounds into cis, cis-muconic acid, which can then be hydrogenated to produce adipic acid. The engineered strain demonstrated a notable production of 13.5 g L^{-1} of cis, cis-muconate within 78.5 h, achieving high purity and yield through activated carbon treatment and crystallization. For the hydrogenation step, palladium on carbon (Pd/C) was identified as an effective catalyst, achieving over 97% conversion and selectivity for adipic acid under optimal conditions. The study reported a turnover frequency of 23–30 s^{-1}, indicating efficient catalysis. By successfully producing cis, cis-muconic acid from a lignin-enriched biomass stream, this research showcases an integrated approach to lignin valorization, aligning with biofuel production goals. The findings highlight the potential for lignin not only to serve as an energy source, but also to be transformed into valuable chemical commodities, thereby enhancing the overall sustainability of biomass utilization [49].

The study titled "Solar energy-driven lignin-first approach to full utilization of lignocellulosic biomass under mild conditions", authored by Wu, X., has received 473 citations and was published in "Nature catalysis" in 2018 [50]. This study explored a solar energy-driven, lignin-first approach to fully utilize lignocellulosic biomass at mild conditions, addressing the limitations of traditional high-temperature hydrogenolysis methods. These conventional strategies often result in low-functionalized products and complications in separating metal catalysts from cellulose and hemicellulose. The researchers introduced a novel method for fractionating and valorizing lignocellulose using cadmium sulfide quantum dots, which effectively catalyze the cleavage of β-O-4 bonds in lignin models at room temperature and under visible light. This process converts native lignin within the biomass into functionalized aromatic compounds while leaving cellulose and hemicellulose largely intact. Moreover, the colloidal nature of the quantum dots allows for easy separation and recycling through a reversible aggregation-colloidization strategy. The cleavage of the β-O-4 bond occurs via an electron-hole coupled photoredox mechanism involving a $C\alpha$ radical intermediate, where both photogenerated electrons and holes contribute to the reaction. This study highlights the potential of a lignin-first strategy coupled with solar energy to improve the efficiency of biomass utilization, paving the way for more sustainable approaches in biorefinery processes [50].

The study titled "Visible-light-driven valorization of biomass intermediates integrated with H2 production catalyzed by ultrathin Ni/CdS nanosheets", authored by Han, G., has received 430 citations and was published in "Journal of the American Chemical Society" in 2017 [51]. This research investigated the photocatalytic upgrading of biomass-derived intermediates, specifically furfural alcohol and 5-hydroxymethylfurfural (HMF), using ultrathin nickel-decorated cadmium sulfide (Ni/CdS) nanosheets under visible light. This innovative approach not only transformed these intermediates into valuable products like aldehydes and acids, but also facilitated simultaneous hydrogen production at ambient conditions. The study revealed that the transformation rates of furfural alcohol and HMF differed significantly when subjected to visible light in neutral water. Theoretical computations indicated that the stronger binding affinity of the aldehyde group in HMF to the Ni/CdS catalyst resulted in a lower conversion rate of HMF to 2,5-diformylfuran compared to the conversion of furfural alcohol to furfural. Furthermore, when the photocatalytic oxidation process was conducted under alkaline conditions, both furfural alcohol and HMF were completely converted into their respective carboxylates, accompanied by the production of hydrogen gas. This research demonstrates a promising strategy for biomass valorization that integrates chemical upgrading with renewable hydrogen production, contributing to more sustainable energy solutions [51].

The study titled "Efficient electrochemical production of glucaric acid and H2 via glucose electrolysis", authored by Liu, W.J., has received 404 citations and was published in " Nature communications " in 2020 [30]. This research explored the electrochemical production of glucaric acid and hydrogen (H_2) through glucose electrolysis, presenting a promising method for generating value-added chemicals and renewable energy from biomass-derived feedstocks. The study utilized nanostructured NiFe oxide (NiFeOx) and nitride (NiFeNx) catalysts, synthesized from NiFe-layered double hydroxide nanosheet arrays on three-dimensional nickel foams, which exhibited high activity and selectivity for anodic glucose oxidation. The assembled electrolytic cell demonstrated impressive performance, delivering a current density of 100 mA cm^{-2} at a voltage of 1.39 V. The process achieved a Faradaic efficiency of 87% and a glucaric acid yield of 83%, with the reaction proceeding via a guluronic acid pathway, as confirmed by in situ infrared spectroscopy.

Moreover, a comprehensive techno-economic analysis revealed that the electrochemical reduction in glucose can produce glucaric acid at a cost 54% lower than conventional chemical methods. This research highlights glucose electrolysis as a cost-effective and energy-efficient strategy for biomass valorization and hydrogen production, paving the way for more sustainable chemical synthesis processes [30].

The study titled "Synthesis and applications of alkyl levulinates", authored by Démolis, A., has received 404 citations and was published in "ACS Sustainable Chemistry & Engineering" in 2020 [52]. This research explored the synthesis and applications of alkyl levulinates, highlighting their significant potential as bio-based alternatives to petrochemical products. The study notes a marked increase in related literature over the past five years, indicating a growing interest in this field. Alkyl levulinates can be synthesized with high yields and selectivity from biomass-derived products such as levulinic acid or furfuryl alcohol. They can also be produced directly from lignocellulosic resources, though typically with lower yields. These transformations generally require catalysts, and current research focuses on developing efficient and recyclable catalyst systems. These compounds find diverse applications such as solvents, additives, and intermediates in chemical synthesis. Advances in preparation methods and the expanding applications of alkyl levulinates are critical for promoting greener and more sustainable chemical processes, supporting efforts to reduce reliance on fossil fuels and enhance the use of renewable resources [52].

3.6. Key Research Topics in Biomass Valorization and Biofuel Production Research

Biberci [38] emphasized the importance of co-occurrence analysis in identifying research topics and assessing the dynamics of research fronts within a specific field. In our study, we analyzed data from Scopus, applying a minimum occurrence threshold of 20 for keywords. This methodology enabled us to extract 40 keyword strings from a total of 3618 author keywords.

Table 8 presents the keywords that met or exceeded this threshold. It is important to highlight that our analysis focused on authors' keywords rather than indexed keywords. The top 40 keywords are ranked in descending order based on their total link strength (TLS). To establish this ranking, we conducted a comprehensive scientific analysis that considered factors such as cumulative link strength, the number of connections associated with each keyword, and their frequency of occurrence.

Table 8. Top 40 keywords from the studies published on biomass valorization and biofuel production research.

Keywords	Cluster	TLS	Occurrence	%Occurrence
Biomass	3	229	200	10.23
Biomass Valorization	1	176	176	9.00
Lignin	1	154	113	5.78
Heterogeneous Catalysis	1	132	97	4.96
Furfural	3	113	80	4.09
Biorefinery	3	94	69	3.53
Catalysis	1	85	57	2.92
Pyrolysis	2	82	56	2.86
Biomass Conversion	1	76	65	3.32
Biodiesel	2	73	60	3.07
5-Hydroxymethylfurfural	3	70	49	2.51
Hydrogenation	3	69	47	2.40
Waste Valorization	2	69	61	3.12
Levulinic Acid	3	56	50	2.56

Table 8. *Cont.*

Keywords	Cluster	TLS	Occurrence	%Occurrence
Green Chemistry	1	51	32	1.64
Photocatalysis	1	50	43	2.20
Bio-Oil	2	47	41	2.10
Hydrogenolysis	4	46	37	1.89
Valorization	2	46	42	2.15
γ-Valerolactone	3	45	30	1.53
Biofuel	2	44	33	1.69
Biofuels	1	43	30	1.53
Waste-to-energy	2	43	20	1.02
Cellulose	3	41	34	1.74
Lignocellulosic Biomass	1	41	39	2.00
Catalyst	2	40	39	2.00
Hydrodeoxygenation	1	40	32	1.64
Oxidation	1	39	25	1.28
Biochar	2	37	35	1.79
Furfuryl alcohol	3	37	22	1.13
Transesterification	2	36	23	1.18
Glycerol	4	35	34	1.74
Circular Economy	2	32	23	1.18
Heterogeneous Catalyst	4	32	22	1.13
Enzymatic Hydrolysis	3	29	21	1.07
Hydrogen	2	28	29	1.48
Biocatalysis	1	26	21	1.07
Glucose	3	23	24	1.23
Lignin Valorization	1	20	24	1.23
Biomass Valorisation	1	12	20	1.02

Table 8 presents the top 40 keywords from the Scopus database, which are integral to the study of biomass valorization and biofuel production. Central to this analysis are terms such as "biomass", "biomass valorization", and "biofuels", which indicate the essential role of biomass as a renewable resource for sustainable energy solutions. The inclusion of keywords like "lignin", "cellulose", and "lignocellulosic biomass" highlights the significance of different biomass components in the valorization process, emphasizing their potential for conversion into valuable fuels and chemicals.

The keywords "heterogeneous catalysis", "catalysis", and "biocatalysis" underscore the technological advancements in converting biomass into biofuels, indicating that effective catalytic processes are critical for enhancing reaction efficiencies [29]. For instance, terms such as "pyrolysis" and "hydrogenation" represent key thermochemical methods for biomass conversion [1,58], while "transesterification" is specifically related to biodiesel production from lipids [59].

Additionally, the mentions of "5-hydroxymethylfurfural", "furfural", and "levulinic acid" point to important intermediates in the biorefinery context, showcasing their roles in the production of biofuels and other value-added chemicals [60–62]. The keyword "green chemistry" reflects the sustainable and environmentally friendly approaches employed in the conversion processes, which aim to minimize waste and energy consumption [62].

The concept of "waste valorization" indicates the potential for converting agricultural and industrial waste into energy or useful products, reinforcing the idea of a circular economy [63]. Terms such as "biochar" and "waste-to-energy" highlight the multifaceted benefits of biomass utilization, including carbon sequestration and energy recovery [27].

Moreover, "hydrodeoxygenation", "oxidation", and "glycerol" point to specific chemical reactions and by-products involved in biofuel production, indicating a comprehensive understanding of the processes required for effective biomass conversion [27,28,64]. The mention of "photocatalysis" suggests innovative approaches to biomass valorization, utilizing light-driven reactions to enhance chemical transformations [65].

In summary, the keywords collectively illustrate the interconnectedness of various aspects of biomass valorization and biofuel production. They emphasize the need for advanced catalytic technologies, sustainable practices, and the utilization of diverse biomass resources to achieve efficient energy conversion. This holistic perspective underscores the urgency for continued research and development in the field to maximize the potential of biomass as a key player in the transition to renewable energy. In this context, Figure 7 presents a network diagram that illustrates the co-occurrences of keywords found in research articles on biomass valorization and biofuel production.

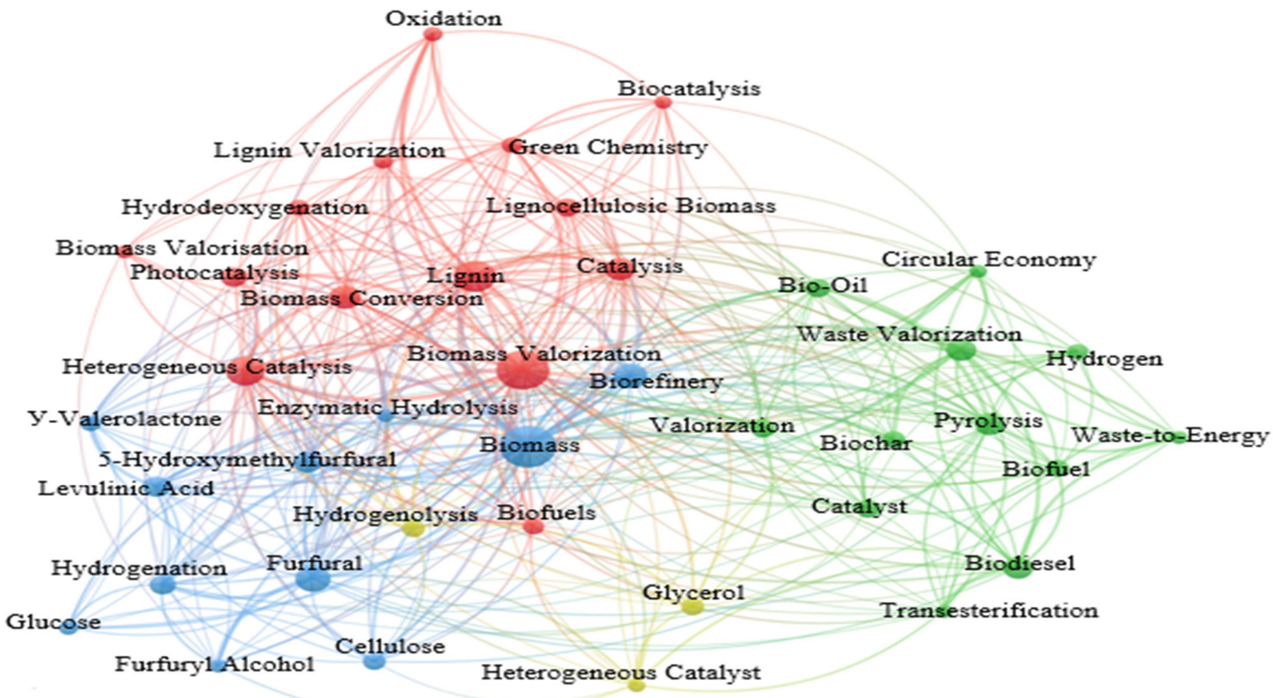
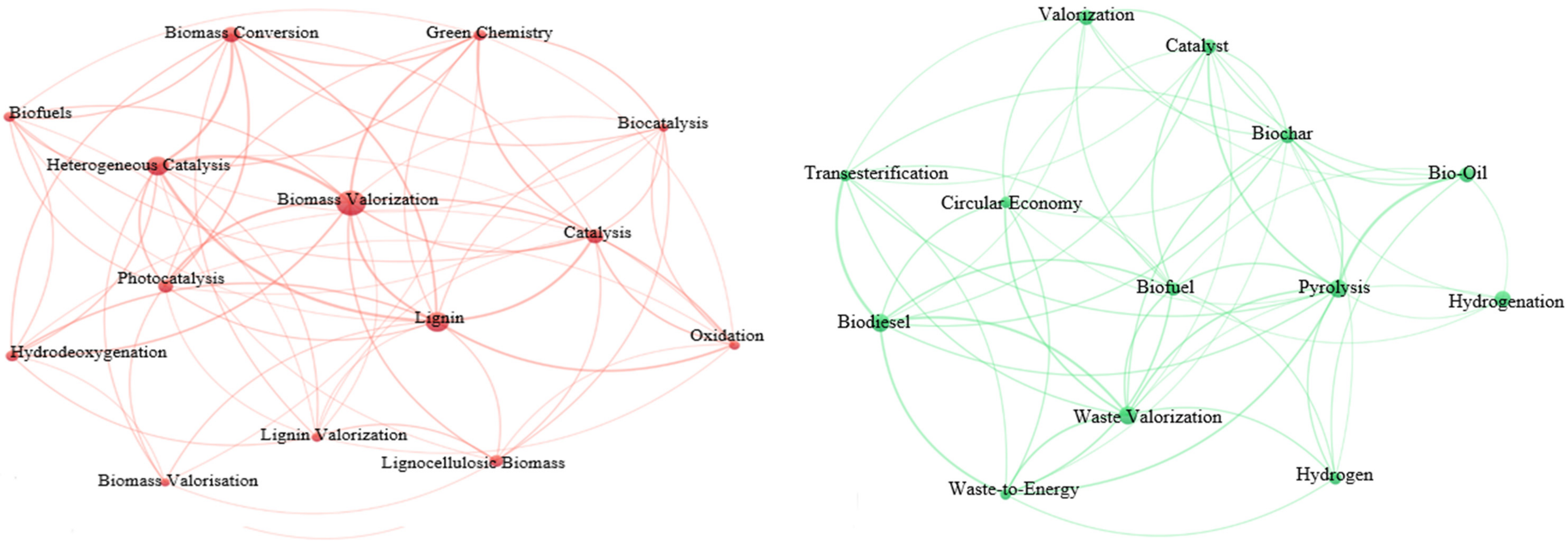


Figure 7. Co-occurrence clustering of author keyword in a network visualization.

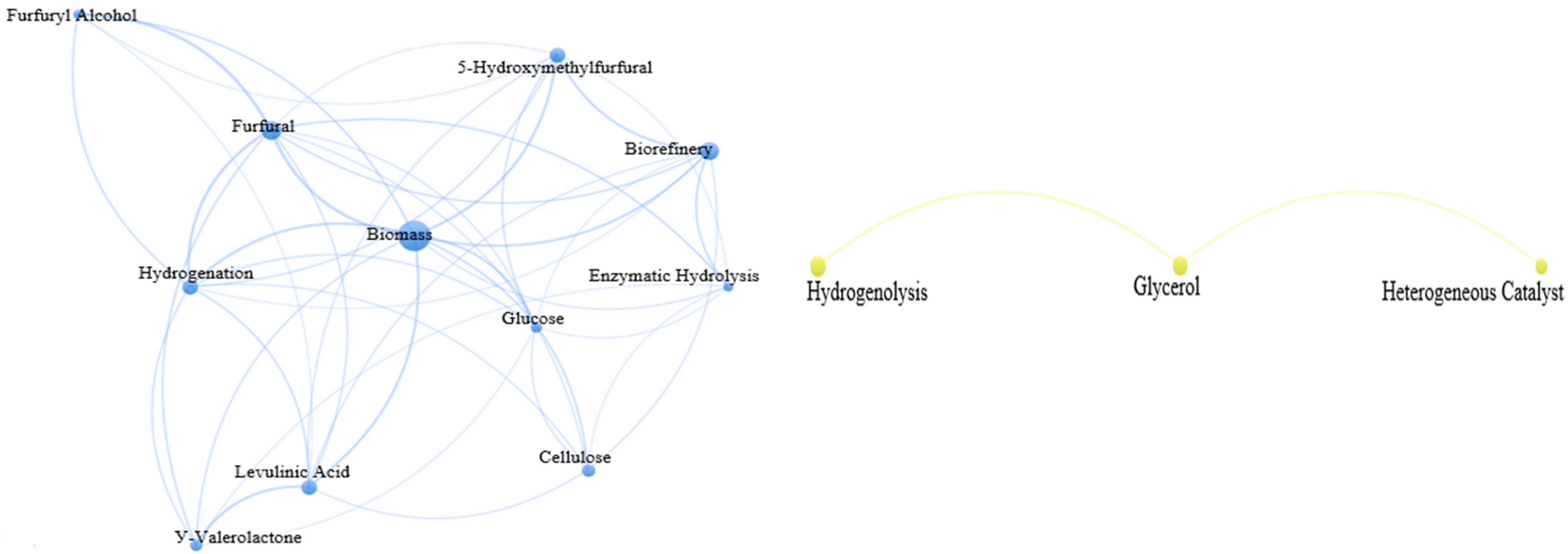
In the diagram shown in Figure 7, the nodes represent different elements, with their shapes and positions indicating the likelihood of co-occurrence among these elements. Analyzing the keyword co-occurrence network reveals four distinct clusters, each represented by different colors, corresponding to various topics within the field of biomass valorization and biofuel production research. The colored nodes signify these clusters, with each focusing on a specific discipline related to biomass valorization and biofuel production. The size of the nodes indicates their frequency of occurrence, while the thickness of the connections between nodes reflects the strength of their relationships.

Furthermore, Figure 8 provides a detailed illustration of each cluster, showcasing the network of shared keywords and the primary keyword groups identified in publications related to biomass valorization and biofuel production.



(**a**) Cluster I (**b**) Cluster II

Figure 8. *Cont*.



(**c**) Cluster III (**d**) Cluster IV

Figure 8. Cluster of the keywords in biomass valorization and biofuel production.

The network map presented in this study, illustrated in Figure 8, reveals four prominent clusters. Cluster I, highlighted in red, comprises 14 keywords that are closely associated with biomass valorization and biofuel production. Each keyword plays a significant role in understanding the multifaceted impacts of these processes. Central to this cluster is the term "Biomass Valorization", which encapsulates the transformation of biomass into valuable products, including biofuels and chemicals [31]. The inclusion of "Lignin" and "Lignin Valorization" emphasizes the importance of this complex polymer in the biomass matrix, highlighting its potential for conversion into high-value products through various catalytic processes [50]. "Heterogeneous Catalysis" and "Catalysis" reflect the significance of catalytic methods in enhancing biomass conversion efficiency, particularly in the context of green chemistry principles that aim to minimize environmental impact [50,55]. The keywords "Biomass Conversion" and "Lignocellulosic Biomass" indicate the focus on converting raw biomass materials into usable energy forms [11], while "Hydrodeoxygenation" and "Oxidation" represent key chemical reactions involved in refining these biomass feedstocks [26,28]. "Photocatalysis" adds another dimension by showcasing innovative methods that utilize light to drive chemical transformations, further supporting sustainable practices [65]. Lastly, the inclusion of "Biofuels" and "Hydrogen" underscores the ultimate goal of these processes: to produce renewable energy sources that can replace fossil fuels [1]. Together, these keywords form a comprehensive framework for understanding the various aspects of biomass valorization and biofuel production, pointing to the critical interplay between chemistry, technology, and sustainability in advancing these fields.

Cluster II, highlighted in green, encompasses 13 keywords that are vital for understanding biomass valorization and biofuel production. The term "Pyrolysis" serves as a foundational concept in this cluster, representing a thermochemical process that converts organic material into bio-oil, gas, and char, offering a pathway for effective waste valorization [4]. The inclusion of "Biodiesel" and "Biofuel" illustrates the primary products derived from biomass, emphasizing their role as renewable energy sources [38]. "Waste Valorization" and "Waste-to-Energy" highlight the importance of converting waste materials into valuable energy forms, promoting sustainability and resource efficiency [27]. Keywords such as "Transesterification" point to the specific chemical processes used in the production of biodiesel from oils and fats [59], while "Catalyst" signifies the need for effective catalytic agents to enhance reaction efficiencies [28]. The term "Bio-Oil" indicates one of the key outputs from pyrolysis, which can be further processed into various fuels and chemicals [1]. "Biochar" represents another by-product of pyrolysis, which is valuable for soil enhancement and carbon sequestration [27]. Finally, the concept of a "Circular Economy" underscores the overarching goal of these processes: to create sustainable systems that minimize waste and maximize resource recovery [11]. The inclusion of "Hydrogen" reflects the potential for producing clean energy from biomass-derived materials, further supporting the transition to renewable energy sources [47]. Together, these keywords form a comprehensive framework for understanding the essential aspects of waste valorization and biofuel production, highlighting the critical connections between waste management, energy production, and sustainability.

Cluster III, highlighted in blue, comprises 11 key terms that are essential for understanding biomass valorization and biofuel production. The term "Biomass" stands at the center of this cluster, representing the renewable organic material that serves as the primary feedstock for various conversion processes. The inclusion of "Biorefinery" indicates a holistic approach to biomass utilization, where multiple products, including biofuels and chemicals, are produced from biomass through integrated processes [22]. Keywords like "Furfural" and "5-Hydroxymethylfurfural" highlight important chemical intermediates derived from biomass, which can be further transformed into valuable products such as biofuels and biochemicals [61]. "Hydrogenation" represents a key reaction involved in converting these intermediates into more saturated and stable compounds, enhancing their usability in fuel applications [58]. "Levulinic Acid" and "γ-Valerolactone" are notable platform chemicals that can be derived from biomass and serve as building blocks for various applications, including biofuels and specialty chemicals [62]. The term "Cellulose" emphasizes the significance of this abundant polysaccharide in biomass, which can be broken down through processes such as "Enzymatic Hydrolysis" to release fermentable sugars for biofuel production [50]. Additionally, "Furfuryl Alcohol" is another derived compound that can be utilized in the production of bio-based materials and chemicals [66]. Together, these keywords form a comprehensive framework for understanding the critical components and reactions involved in biomass conversion, highlighting the potential of biomass as a versatile resource for sustainable energy and chemical production.

Cluster IV, highlighted in yellow, contains three keywords that are crucial for understanding advanced biomass conversion processes. The term "Hydrogenolysis" refers to a chemical reaction that involves the breaking of bonds in a molecule through the addition of hydrogen, often used to convert biomass-derived compounds into more valuable products [67]. The inclusion of "Glycerol" emphasizes its significance as a by-product of biodiesel production and as a potential feedstock for various chemical processes. Glycerol can be transformed through hydrogenolysis into products such as propylene glycol and other valuable chemicals, showcasing its versatility [64]. Lastly, "Heterogeneous Catalyst" signifies the use of solid catalysts that facilitate the hydrogenolysis reaction, improving efficiency and selectivity in biomass conversion processes [65]. This highlights the importance of catalytic technologies in enhancing the economic viability and sustainability of biomass-derived fuel and chemical production. Together, these keywords provide insights into advanced methods for converting biomass into high-value products, underscoring the role of innovative chemical processes and catalysts in the field of biomass valorization.

The analysis of biomass valorization and biofuel production reveals a multifaceted landscape driven by innovative chemical processes and environmental sustainability. The four clusters identified—ranging from fundamental concepts like biomass conversion and catalytic processes to advanced techniques such as hydrogenolysis—highlight the interconnected nature of this field. Cluster I emphasizes the importance of lignin and heterogeneous catalysis in enhancing biomass conversion efficiency, while Cluster II showcases the potential of pyrolysis and waste valorization in transforming waste materials into valuable biofuels. Cluster III introduces key chemical intermediates that can be derived from biomass, underscoring the role of biorefineries in maximizing resource utilization. Finally, Cluster IV focuses on advanced reactions such as hydrogenolysis, which can convert glycerol into more valuable products through the use of heterogeneous catalysts.

4. Key Trends in Biofuel Catalysis and Biomass Valorization

- Shift Toward Heterogeneous Catalysis
    - The study highlights the increasing dominance of heterogeneous catalysts in biomass conversion. These catalysts, particularly metal-organic frameworks (MOFs), nanocatalysts, and bio-derived catalysts, have gained attention due to their recyclability, efficiency, and ability to operate under milder reaction conditions.
    - The transition from homogeneous to heterogeneous catalysis is a crucial advancement that improves process sustainability by reducing catalyst loss and contamination.
- Pyrolysis and Waste Valorization as Key Technologies

    - The study identifies pyrolysis and hydrothermal liquefaction as essential pathways for biomass-to-fuel conversion, particularly in waste valorization strategies.
    - Microwave-assisted pyrolysis has gained attention due to its energy efficiency and rapid processing capability.
- Integration of Biomass Valorization with Circular Economy Principles
    - The growing trend of waste-to-energy and biorefinery approaches aligns with global efforts to establish a circular economy. Biomass valorization not only contributes to renewable fuel production but also minimizes environmental waste.
    - The emergence of biorefinery models, which integrate multiple conversion pathways, allows for high-value co-products (biochar, platform chemicals, hydrogen) alongside fuel production.

Future research in this area should prioritize the development of integrated systems that combine these diverse approaches, aiming for a more circular economy that minimizes waste and maximizes resource recovery. Investigating innovative catalytic materials, optimizing reaction conditions, and exploring new biomass feedstocks will be essential for enhancing the efficiency and sustainability of biofuel production. Additionally, the exploration of new bioprocessing techniques, such as enzymatic hydrolysis and advanced pyrolysis methods, could further unlock the potential of biomass as a renewable resource. Addressing these challenges with a holistic perspective will be critical for advancing the field of biomass valorization and contributing to a sustainable energy future.

5. Conclusions

The study was conducted through a comprehensive bibliometric analysis of research related to biomass valorization and biofuel production, utilizing a dataset of 1657 publications sourced from the Scopus database, covering the period from 2010 to December 2024. The objective of this analysis was to identify current trends, assess the contributions of various authors and institutions, and evaluate the overall progress within this field of study.

The results reveal that China is the dominant contributor, with 550 publications and a remarkable 17,577 citations, illustrating its significant role in advancing research on biomass utilization. The United States follows with 160 publications and 9359 citations, indicating a strong presence in the field. Other notable contributors include Hong Kong, which has 75 publications, and Republic of Korea, with 107 publications, highlighting a robust global engagement with biomass research. Key journals play a pivotal role in disseminating impactful research. Influential publications such as "ACS Sustainable Chemistry and Engineering" and "Chemsuschem" have been vital, with the former publishing 95 articles that accumulated 3721 citations. The peak year for publications was 2020, which saw 163 articles generating 7302 citations, reflecting a surge in interest and research activity in biomass valorization and biofuel production. Prominent institutions have also made significant contributions to this field. The Department of Environmental and Energy at Sejong University in Republic of Korea and the Department of Civil and Environmental Engineering at The Hong Kong Polytechnic University are among those emphasizing the critical role of academic engagement in addressing environmental challenges and advancing sustainable practices.

Innovative methods for biomass conversion have been highlighted in previous studies. Catalytic valorization of lignin, for instance, is crucial for transforming biomass into high-value products. Techniques such as oxidative biomass upgrading combined with hydrogen production have shown promise in enhancing energy conversion efficiency while minimizing harmful by-products. Additionally, advanced methods like microwave pyrolysis for converting biomass waste into engineered activated biochar and solar energy-driven approaches utilizing innovative catalytic systems have been identified. Looking ahead, future research should focus on developing integrated systems that promote a circular economy, optimizing catalytic processes, and exploring novel biomass feedstocks. Advancements in bioprocessing techniques, such as enzymatic hydrolysis, should also be prioritized to unlock further potential in biomass as a renewable resource.

The key trends of this study can be summarized in shifting toward heterogeneous catalysis, pyrolysis and waste valorization as key technologies, and integration of biomass valorization with circular economy principles.

In conclusion, this comprehensive bibliometric analysis not only illustrates the growing body of research in biomass valorization and biofuel production but also underscores the importance of collaborative efforts across institutions and countries. By addressing the identified challenges and exploring innovative methodologies, the field can significantly enhance the efficiency and sustainability of biofuel production, contributing to the transition toward renewable energy solutions and long-term environmental goals.

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