

Review

A Review of Biomass-to-Bioenergy Supply Chain Research Using Bibliometric Analysis and Visualization

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Abstract: Based on current trends and policies aimed at decarbonizing energy systems, the conversion of biomass to bioenergy has the potential to grow rapidly, but such growth depends on the development of efficient, sustainable, and competitive biomass supply chains. As a result, the biomass supply chain has stimulated the interest of a diverse group of researchers across academia, government, and industry, and there is a need to synthesize and categorize the rapidly expanding literature in this field. We conducted a literature review using advanced bibliometric analysis and visualization of 1711 peer-reviewed articles published from January 1992 to August 2022 with the aim of promoting impactful research in both growing and neglected areas of investigation. The results show that there are potential research gaps and opportunities in six critical areas: globalization of supply chain research; incorporation of uncertainty, stochasticity, and risk into supply chain models; investigation of multi-feedstock supply systems; strengthening supply chain resilience; application of inventory control methods; and broader use of machine learning and artificial intelligence in this field. By providing a holistic examination of how biomass-to-bioenergy supply chain research has grown and evolved over this period, our results and subsequent framework and recommendations can aid researchers in developing future studies and can guide stakeholder strategies to identify, diagnose, and address modern challenges that face the bioenergy industry.

Keywords: biomass; supply chain management; bibliometric analysis; inventory control



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1. Introduction

Renewable energy has received a lot of attention from government, academic, and industrial experts looking to improve energy supply. Reducing the anthropogenic greenhouse gas emissions that lead to climate change is an explicit goal of renewable energy production, with additional social and economic development benefits that include better access to energy, improved energy security, and better human health outcomes [1]. Biomass is often considered as a renewable energy source to reduce fossil fuel emissions, especially in sectors of the economy that are hard to decarbonize, such as aviation. Broadly, solid biomass is defined as “any plant matter used directly as fuel or converted into other forms before combustion” [2]. As an alternative to fossil fuels, plant-based materials from forestry, agriculture, waste management (e.g., pulping byproducts), and other sources can be used as fuel for heat and power and as a feedstock in the production of liquid fuels. However, due to many factors, including high costs, policy changes, and uncertainties in supply chain reliability, bioenergy production faces various challenges that constrain biomass production and use [3]. Over the last decade, a growing body of research has confronted the challenges of bioenergy and biofuel supply chains across a wide range of feedstocks, products, processes, and system features using diverse methods and techniques [4,5].

The main sources of biomass for bioenergy include forest management, edible crops like corn, purpose-grown biomass crops such as willow and switchgrass, agricultural residues including nut hulls, corn stover, and rice straw, algae, and biomass from industrial, municipal and agricultural solid waste streams [6–10]. Effective supply chain management uses many approaches to integrate suppliers of these materials with producers, distributors, manufacturers, and retailers of energy products, so that intermediate and final products are produced and distributed in the right quantities to the right locations at the right time. Efficient supply chains minimize system costs while satisfying various demands at a competitive price [11–13].

Several previous reviews have been conducted that directly or indirectly span relevant aspects of biomass supply chain modeling, analysis, design, and management. For example, Mottaghi et al. [14] presented a taxonomic literature review based on scientific papers published between 2009 and 2021 on the topic of optimization and modeling of sustainable biomass energy supply chains. They evaluate economic, environmental, and social aspects of sustainability and the price of biomass raw materials on biogas production and energy supply and contributed to the advancement of biomass-to-biogas production. In another study [15], the authors reviewed published articles on the topic of design and modeling of biomass supply chains for biofuel production. Their objectives were to understand critical feedstock supply for renewable fuel production; identify appropriate commercial equipment for feedstock logistics; and consolidate information on feedstock cost, energy consumption, efficiency, feedstock storage, and transportation systems [15]. They gathered information necessary for the development and utilization of models that can be used in the identification of a feasible supply chain to produce renewable fuels commercially at a regional scale in the United States. In another review, Lo et al. [16] focus on feasibility evaluation of bio-based industries with an emphasis on technoeconomic methods and approaches and examine the effect of supply chain uncertainty on feasibility using a Malaysian case study.

In light of these and other previous reviews, a need remains for a more comprehensive, holistic evaluation of the biomass-to-bioenergy supply chain literature. Quantitative bibliometric methods have been developed in recent years that allow research on the development of science as an informational process. The advantages of these methods primarily revolve around the ability of advanced software to quickly analyze large volumes of bibliographic data and text to identify complex relationships, which is described in detail in the next section. The main aspects of bibliometric methods are novel, including ways of measuring research qualities and impact, understanding the process of citations, mapping scientific fields, and using quantitative indicators to inform research policy and management. To our knowledge, none of the previous reviews make use of quantitative bibliometric approaches to investigate the complex and multi-disciplinary character of this broad study area or describe how it has evolved over time. The objectives of this paper are to identify thematic patterns, landmark articles, emerging trends, and gaps in biomass-to-bioenergy supply chain research. The goal is to advance this field by promoting new and impactful research in both growing and neglected areas of investigation.

2. Methods

2.1. Background

Literature reviews are conducted for a variety of reasons, but most often to provide a synthesis of past research conducted on a particular topic that can be used to explore, evaluate, and distill existing research, examine specific research questions, and inform new research. As the scientific literature has grown and proliferated in the digital age, the methods used to conduct reviews have also evolved to span various needs. A full accounting of literature review methods is beyond the scope of this paper, but Snyder [17] provides examples of differentiated review methodologies that include structured review, review for model and framework development, meta-analysis, theoretical review, hybrid-future research, framework-based review, systematic review, and scientometrics.

As a field of study, scientometrics measures and analyzes scholarly literature using quantitative methods. The scientific literature itself becomes the subject of analysis. In general, scientometrics involves the cataloging of research, the assessment of the scientific contribution of authors, journals, and specific publications, as well as analysis of the dissemination process of scientific knowledge. In this context, science is seen as an informational process, and scientometrics is used to measure and characterize its development [18].

Within scientometrics, bibliometrics specifically applies statistical methods to bibliographic data to accomplish this goal [19,20]. The bibliometric design statistically analyzes and synthesizes the study topic to measure the evolution of a scientific domain, the impact of scholarly publications, patterns of authorship, and the process of scientific knowledge production. As a result, the use of the bibliometric techniques has the potential to produce different insights and perspectives on a research area than traditional literature review, especially when applied over large bodies of literature. Bibliometric analysis using advanced software tools also provides vivid graphical representations of the statistical interconnections among various topics, authors, and other characteristics embodied in research papers that can be difficult for readers to recognize without such tools.

Specific bibliometric methods include various ways of measuring research quality and impact, understanding the use and interaction of citations, mapping scientific fields, and using bibliometric indicators to better manage scientific policy and enterprise [21]. These methods are frequently used to conduct citation analysis, social network analysis, keyword analysis, and content analysis, as well as text-mining to achieve scientometric goals. Analysis of various types of keywords is an essential part of bibliometrics focused on the evolution of a specific field or topic [22–24].

In its modern application, bibliographic data from online databases are frequently the subject of bibliometric analysis. This allows for an objective review, because articles are not selected manually by the authors, and facilitates a comprehensive review because such databases are generally designed to include all relevant publications in a field that meet certain criteria for publication, such as being published in a peer-reviewed journal. Being able to analyze a large body of available research systematically also helps find existing research gaps efficiently [25]. Large commercial abstract and citation databases, such as Scopus (Elsevier) and Web of Science (Clarivate), contain all the information needed to produce representative bibliometric statistics and figures for an immense range of topic areas across many disciplines. As such online databases have increased access to bibliographic data and as software tools for analysis have become more widespread, the number of bibliometric reviews in different research areas has also increased [19].

However, it is important to recognize that the information provided by bibliometric reviews is different from other types of literature reviews in several significant ways. For example, this approach relies heavily on intensive computer-automated analytics that would be practically impossible to conduct without modern computer processing and software tools. These provide the power to quickly identify hidden relationships and gaps and visualize them in impressive ways, but the process is inherently sterile of the type of expert opinion and deep scholarship associated with specialists painstakingly conducting traditional literature reviews. Furthermore, bibliometric reviews are constrained to the information provided by bibliographic data contained in databases. In many cases, significant domain knowledge is needed to interpret and validate bibliometric outputs. Software tools, by themselves, are incapable of this and can produce “black box” results if the statistical processes underlying the analytics are unknown. Ideally, bibliometric analysis is conducted in parallel with manual review of key papers, informed by expert domain knowledge. Bibliometric reviews are best suited for identifying patterns and interconnections among authors, themes, and keywords and describing changes over time, but they are not necessarily suited for evaluating insights and theoretical contributions.

2.2. Data Collection

This study adopted a bibliometric science mapping workflow generally following the steps suggested by Zupic and Čater [20], with some variation. Bibliographic databases store metadata about scientific works and can be accessed to retrieve large volumes of bibliographic information. Many of these are available online, including Clarivate Analytics Web of Science (WoS at <http://www.webofknowledge.com>; accessed on 12 January 2023), Scopus (<http://www.scopus.com>; accessed on 12 January 2023), Google Scholar (<http://scholar.google.com>; accessed on 12 January 2023), and some others. In this study, we first used the Scopus database to census important documents concerning biomass-to-bioenergy supply chain research, then cross-referenced Scopus results with Web of Science (WoS) results for comparison. After careful comparison of search results from both databases, we did not find significant differences between documents identified from both sources, particularly in the peer-reviewed journal publication category. Following comparison, we chose to use the WoS dataset because Scopus bibliographic data were incompatible with some of the software used in this study and because WoS txt data were well-suited to use with all three of the primary software packages. Full institutional access to WoS by the lead author's institution also facilitated its use over Scopus, but Scopus can certainly be used for bibliometric analysis. Scopus was used to calculate the proportion of documents published in various study areas of the biomass supply chain domain.

As described in the Introduction, some previous reviews have used traditional approaches to examine the biomass supply chain literature or have used bibliometric methods applied to narrow topics in this field. Such reviews sometimes use search logic with a single critical keyword paired with one or more secondary keywords. For example, Toorajipour et al. [26] used search strings that included “artificial intelligence” and at least one of four companion keywords (using an AND operator), including “supply chain”, “production”, “marketing”, and “logistics”. Other papers use a dozen or more distinct keywords with more complex keyword search strings (e.g., [27]). We chose to use a small number of broad keyword terms, using variations of “biomass” with variations of “supply chain” (Figure 1). The benefit of this simple, “wide net” approach for a far-reaching review like this one is that it has a low risk of missing papers in this field. However, this approach would not be efficient or appropriate for reviews focused on narrower, specialized topics.

A preliminary search following the selection tree in Figure 1 produced 2218 documents in the topic area of biomass supply chain research. We further filtered the data to only include scientific articles published in peer-reviewed journals. It is widely understood and well-articulated by Kelly et al. [28] that a peer review process facilitates more reliable scientific communication, stimulates meaningful research questions, and provides accurate conclusions generally focused on primary research. This is an especially important distinction in supply chain management, where an extensive body of work is targeted at practitioner audiences in business through popular books, magazine articles, professional meeting proceedings, websites, and self-published white papers popularly known as “gray literature”. We further limited the search to only articles in English. Because the analysis aims to examine research trends from the early beginnings of this field, we truncated the search to 1992, which appeared to be the cutoff year that captured the earliest literature in this field according to our search criteria. Following the initial selection of 2218 documents, applying the two additional search criteria (the document type and language filters) reduced the count to 1711 peer-reviewed articles published in English from 1 January 1992 to 31 August 2022. Note that the year 2022 is not inclusive, omitting papers published after 31 August 2022.

WoS provided specific information for each of the 1711 articles. Bibliographic entries for the publications identified in WoS were downloaded in txt format. The dataset contains the metadata of published articles, including a list of authors, the title, the abstract, a set of author keywords and KeyWords Plus (discussed below), Digital Object Identifier (DOI), date of publication, the source, volume number, and set of references cited by the article. Given a DOI reference, we accessed the full text of the corresponding articles when possible. Thus, the bibliographic information stored by WoS for each publication allows us

to analyze the data to identify relationships among various attributes and, consequently, obtain systematic quantitative results and associated visualizations. It is worth mentioning that data frame columns are named using the standard Clarivate Analytics WoS field tag codes, with the primary field tags shown in Table 1.

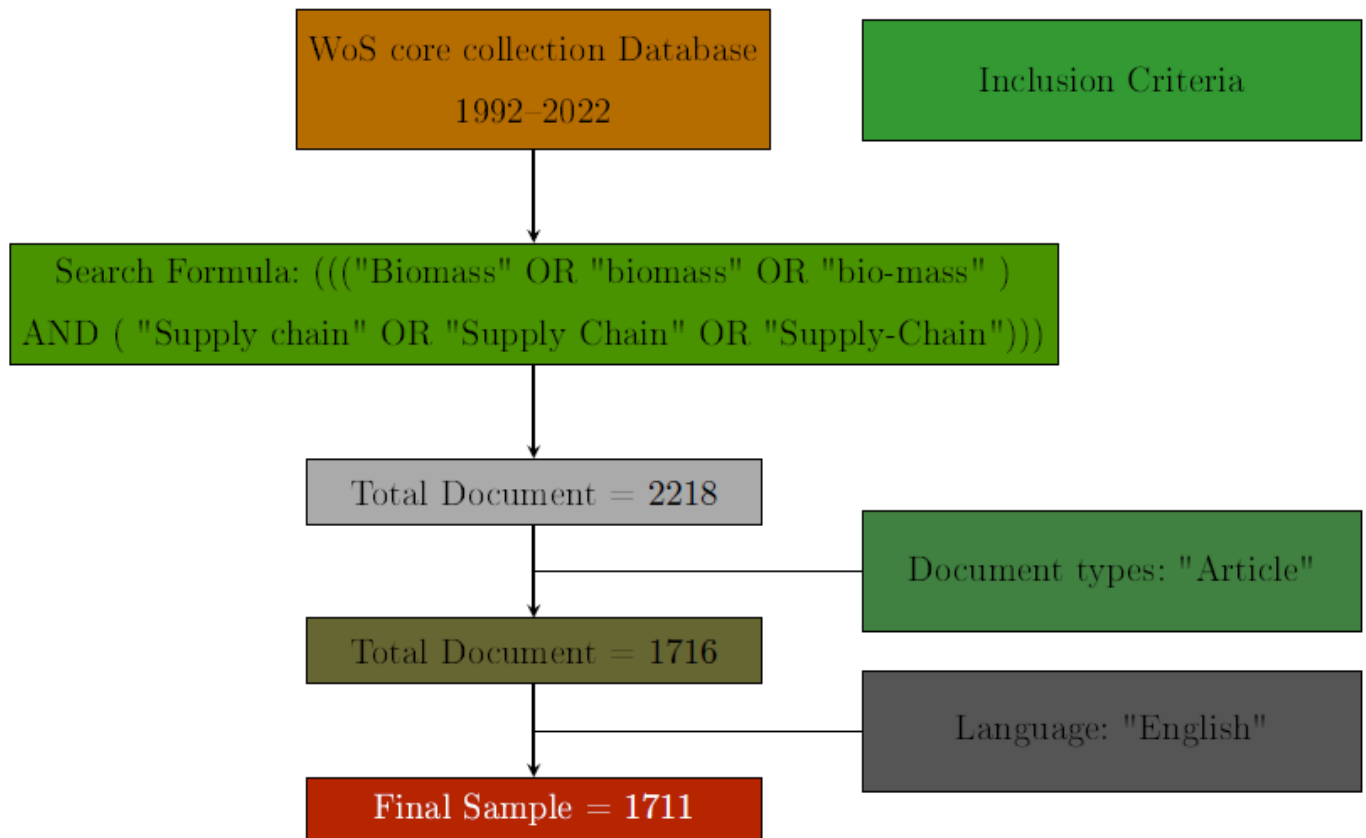


Figure 1. Search criteria and associated article counts used in this study.

Table 1. Primary WoS field tags. For a complete list of field tags see [29] (Clarivate Analytics 2018).

Field Tag	Description
AU	Authors
TI	Document Title
SO	Sources
DT	Document type
DE	Authors' keywords
ID	Database keywords
PY	Year
SC	Subject category

2.3. Analysis

For this study, bibliometrics facilitated performance indicator analysis and evaluating the impact of specific authors and publications, as well as characterizing subject evolution. To help visualize quantitative connections among journals, publications, and research themes, we also developed a variety of scientific maps using these methods. VOSviewer version 1.6.18.0 (Leiden University's Centre for Science and Technology Studies, Leiden, The Netherlands), Bibliometrix and Biblioshiny version 4.0.0 in R studio version 4.2.1 (K-Synth Srl, University of Naples, Naples, Italy), and CiteSpace version 6.1.3 (Chaomei Chen, Drexel University, Philadelphia, PA, USA) were used for this purpose. First, the journals' publications and their bibliographic information were extracted from the WoS

database as described and compiled and analyzed. Second, various diagrams and maps were developed using these software packages to visualize the statistical analysis. The one exception is a pie chart showing the proportion of documents published in predefined study areas, which was produced using Scopus. Below we describe briefly each software tool, its use, and general outputs. Due to the large number of different metrics generated as outputs and for the convenience of readers, brief descriptions of specific metrics are provided in the Section 3 alongside their presentation and interpretation rather than being cataloged sequentially in this section.

Bibliometrix is a comprehensive science mapping analysis tool with a companion Biblioshiny package based on R studio. It was used to build networks for co-citation, scientific collaboration, and co-word analysis. VOSviewer was used to display a graphical representation of bibliometric maps in a way that is easy to interpret. Science maps clearly visualize the evolution of a topic, delimiting research areas and their development, while capturing conceptual and cognitive structure. The construction of a map proceeds in three steps. First, a similarity matrix is calculated based on the co-occurrence matrix. In the second step, a map is constructed by applying the VOS mapping technique to the similarity matrix. Finally, to ensure that VOSviewer produces consistent results, it applies three transformations to the map (translation, rotation, and reflection), as described by van Eck and Waltman [30]. Translation centers the solution at the origin, rotation maximizes the variance on the horizontal dimension using principal component analysis, and reflection occurs across the vertical and horizontal axes depending on the sign of the median solution to improve visualization.

The information available in WoS facilitates the analysis of several performance indicators using Biblioshiny: productivity of authors in terms of publications and citations, journals, authors, and countries. This part of the analysis was complemented using the h-index, g-index, and m-index, which are described in more detail below. These indices allow measurement of both the authors' productivity and the impact of their publications, linking the number of publications and their citations.

CiteSpace is designed to synthesize and visualize a time series of individual networks extracted from each year's publications. It is an analytic system for visualizing emerging trends and critical changes in the literature. Emerging topics are identified by CiteSpace based on highly cited publications and by bursts (i.e., a surge in frequency) of citations and keywords over a specified period of time. Burst detection in CiteSpace is based on Kleinberg's algorithm. Algorithms developed in CiteSpace also measure the strength of links between citing and cited publications and are able to create clusters of papers or journals focusing on thematically distinct aspects of a particular research area, in this case the biomass-to-bioenergy supply chain. This allowed us to identify the most influential publications on the topic and the most pursued topics considered by the researchers publishing in different time frames.

Following the primary analysis, the main research themes within the biomass-to-bioenergy supply chain literature were further identified and displayed as a strategic map using VOSviewer and CiteSpace combined. We used a four-stage methodology, namely, the detection of research themes, visualization of research themes and their thematic networks, and discovery of thematic areas, followed by performance analysis. Thematic analysis is described well by López-Robles et al. [31]. In general, thematic networks are delineated based on the co-occurrence of keywords, with groupings determined by the method of simple centers. The simple center algorithm generates groupings that are tagged with the most central node in the group. Similarity is calculated from the co-occurrence analysis and a set of keyword groups, called themes, and their connections are visualized. Themes can be classified quantitatively into four categories according to Callon's centrality and density: (1) motor themes, (2) peripheral themes, (3) emerging or declining themes, and (4) basic and transversal themes [31].

Cobo et al. [32] provide a succinct description of centrality, density, and the four theme categories. Centrality measures the degree of interaction of a network with other networks,

while density measures the internal strength of the network. Motor themes have high density and high centrality and are considered both well-developed and important to the field. Peripheral themes have high density but low centrality and are of marginal importance within the core topic area. Cobo et al. [32] describe these as very specialized and peripheral areas of study. Themes with low centrality and low density can be either emerging or declining in the field, and the difference can be discovered using other metrics, such as keyword analysis. Lastly, themes with low density but high centrality are known as basic and transversal themes. These are of growing importance within a research field but are not yet well-developed. It is important to mention that the motor themes (high density and high centrality) and basic and transversal themes (high centrality but low density) are considered to be those that favor the development and consolidation of a field of knowledge (or a journal) due to their relative importance to the overall structure of a field.

In bibliometric analysis, themes in these four categories are visualized in the four quadrants of a plot of density and centrality known as a strategic diagram. Callon's centrality is on the x -axis, and Callon's density is on the y -axis. See [33–35] for more information on these techniques. Callon's centrality measures the degree of interaction among networks and can be defined by Equation (1), with k a keyword belonging to the theme and h a keyword belonging to other themes. The internal strength of the network can be measured by Callon's density, defined by Equation (2), with keywords i and j belonging to the theme and W being the keyword count in the theme.

$$C = 10 \times \sum e_{kh} \quad (1)$$

$$d = 100 \times \left(\sum \frac{e_{ij}}{w} \right) \quad (2)$$

Bibliographic information and associated indicators are used to classify thematic areas and elucidate the relationships between different research fields within different time frames. These analytics help identify areas of research that are both foundational (in need of continued attention) and emerging (in need of accelerated research) within a particular topic area, such as biomass-to-bioenergy supply chain research.

3. Results

3.1. Overview

Table 2 provides summary information on the 1711 articles published in biomass-to-bioenergy supply chain research between 1 January 1992 and 30 August 2022. Among the 1711 documents, the total number of authors is 4758, with only 53 documents that are single-authored. The average number of citations per document is 23.35. The collaboration index (CI) of this group of papers is 2.83, which is calculated as the total number of authors of multi-authored articles divided by the total number of multi-authored articles [36]. The statistics regarding authorship and author collaborations index of these documents appear to indicate that this research area is highly interdisciplinary and interconnected. A less integrated field would have fewer authors per document and a lower index.

With 4200 author keywords appearing in 1711 documents, the average number of author keywords used is 2.454 per document. However, KeyWords Plus, which are keywords identified by the database that frequently appear in article titles, total 2689, or 1.57 per document on average. The KeyWords Plus provide more significant descriptive trends as they help express research contents more succinctly than the author's keywords [37]. Keyword analysis is discussed in detail in Section 3.5.

Table 2. Summary information.

Description	Value
Timespan (years)	1992–2022
Sources (count)	365
Documents (count)	1711
Peer-reviewed articles (count)	1597
Average annual growth rate (annual % change)	17.4
Average citations (# per document in literature cited)	23.35
References (count)	60,281
“KeyWords Plus”, ID (count) ¹	2689
Author keywords, DE (count) ²	4200
Authors, total (count)	4758
Single-authored documents (count)	53
Authors of single-authored documents (count)	49
Co-Authors per doc	4.2
Collaboration index	2.83
International co-authorship (%) ³	29.81

¹ KeyWords Plus are words and phrases identified in the database which appear in the titles of references cited by the authors. KeyWords Plus are more descriptive than author-assigned keywords and thus can express the contents of the articles more succinctly and precisely [37]. ² Author keywords are chosen by the authors. ³ The international co-authorship rate was calculated for WoS data from the number of international collaborating publications therein.

Figure 2 depicts the proportion of articles published in predefined subject areas based on a journal’s disciplinary scope. It is important to note that a journal which is multi-disciplinary may be assigned to more than one category. There are obviously various reasons for the categorization, one of which is to help authors browse narrowly in a subject area they are interested in or to help in the selection of suitable journals in which to publish. Though journals (and articles) can clearly span multiple subject areas, in this analysis each article was identified with only one primary subject area. The subject area that received the most attention from researchers is Energy, which was included as a subject area for around 24 percent of the articles. The second highest subject area is Environmental Science, identified with approximately 22 percent of articles, and the combination of these two subject areas covers almost half of the documents published over the study period. The subsequent applied subject areas of interest are Engineering, Agriculture and Biological Sciences, and Chemical Engineering with 13.5, 9.1, and 8.4 percent, respectively. A variety of other areas are also included in Figure 2. Overall, it appears that biomass-to-bioenergy supply chain research cuts across a wide range of interrelated fields but is dominated by energy, the environment, and engineering.

3.2. Productivity

Over the last decade, the number of publications focused on biomass-to-bioenergy supply chain research has grown consistently. Figure 3 shows trends in publications and citations over the study period. The annual growth rate of scientific production in this research area is 17.4%. However, the rate of productivity in this domain began to accelerate after 2010. The annual scientific production has increased rapidly after the year 2013. In fact, 80% of the scientific papers in this field were produced after 2013. This rapid growth in scientific papers was connected to an increased number of citations such that 86.67% of the total citations were made after 2012. Though there was an apparent reduction in articles between 2014 and 2015, the overall trend is increasing annual productivity. As shown in Figure 3, out of a total of 1711 documents, the highest number of publications on an annual basis belongs to 2021 with 220 documents. Productivity in 2020 was close behind. Though data for 2022 are incomplete, only including publications up to 31 August 2022, the trend line and number of articles published in the first 8 months of 2022 (approximately 111 documents) indicate that production in 2022 will likely be higher than 2021.

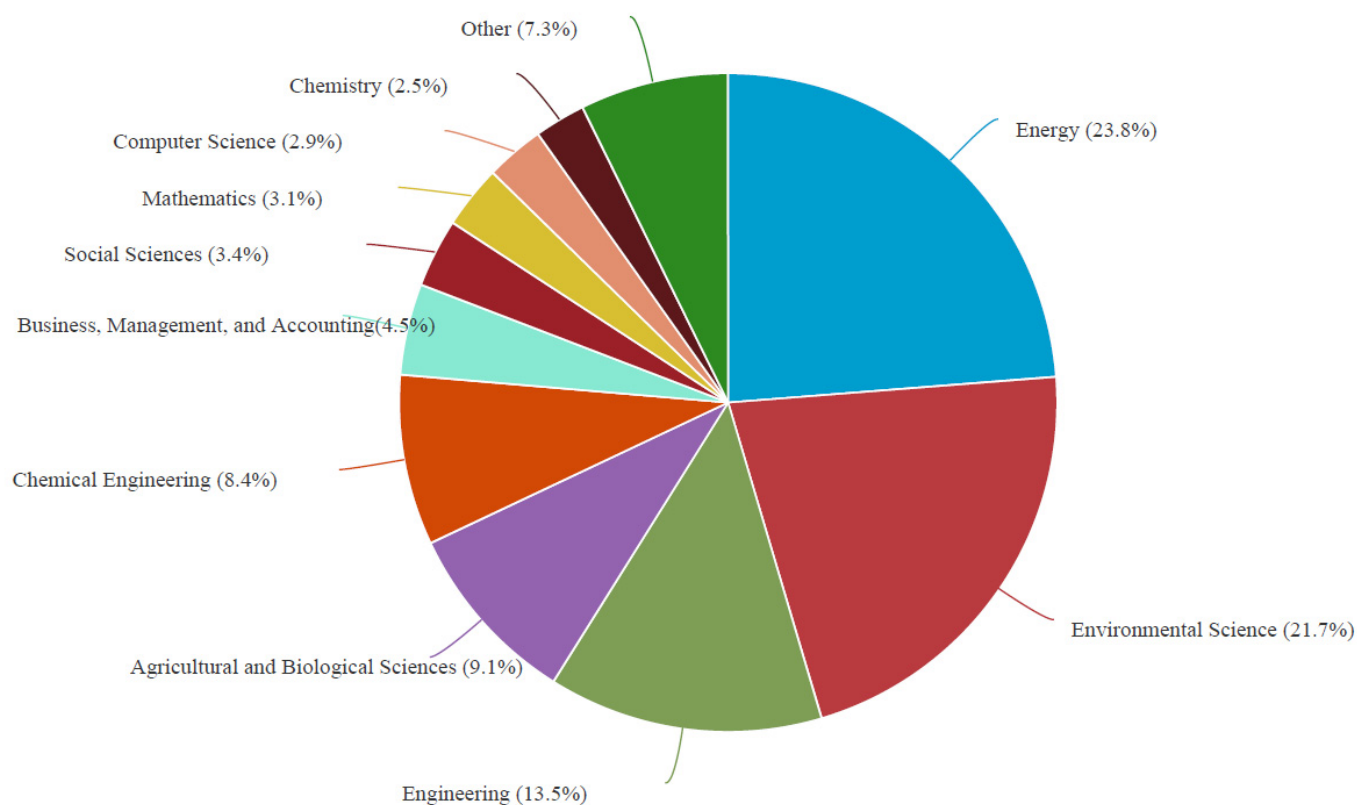


Figure 2. Proportion of documents published in various study areas of biomass supply chain according to Scopus.

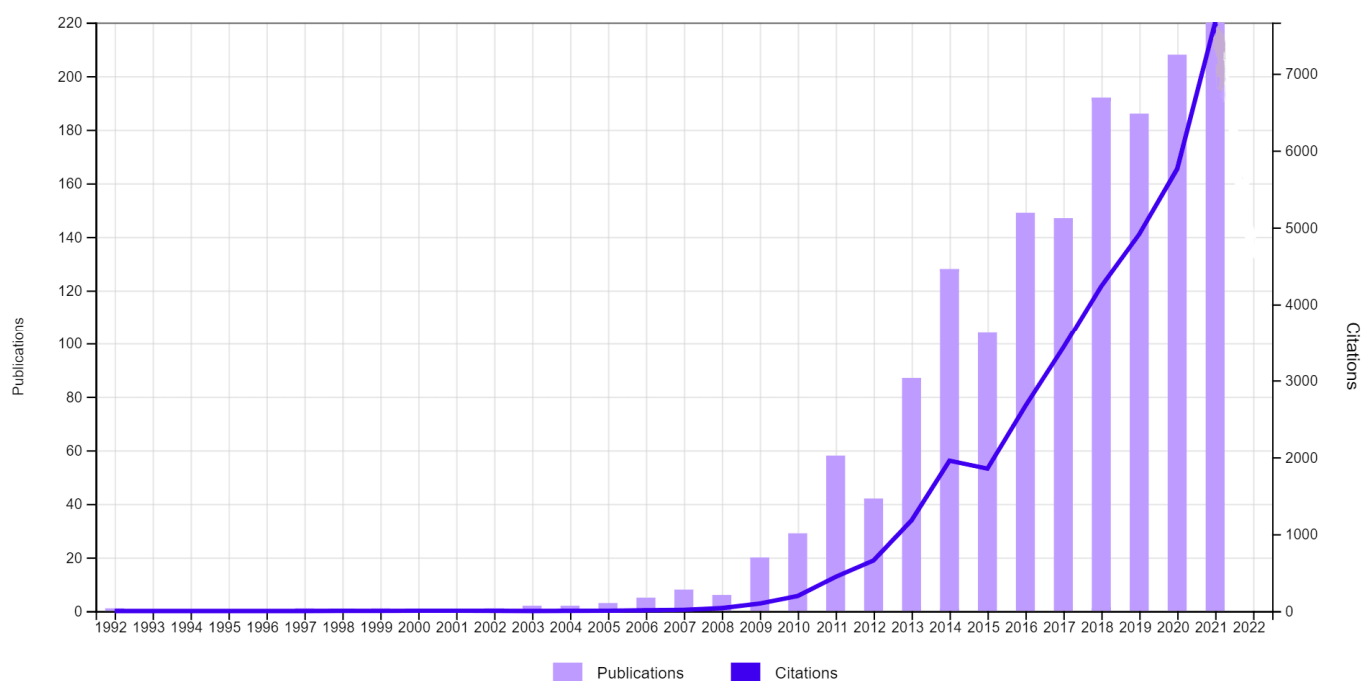


Figure 3. Annual peer-reviewed publication output and associated citations in biomass-to-bioenergy supply chain research. The year 2022 is not depicted because the analysis only included articles published up to 31 August 2022.

3.3. Impact of Source

Table 3 shows the 20 most influential journals in this field. We used three different measures of impact: h-index, g-index, and m-index. The h-index is the number of papers (n) on a list of publications ranked in descending order by the times cited that have n or more citations, the g-index is the top g articles that have together received g citations, and the m index is the h-index divided by the number of years that a scientist or journal has been publishing. According to the results, the five most impactful sources are Biomass and Bioenergy, Applied Energy, Journal of Cleaner Production, Energy, and Bioresources Technology. Considering all the bibliometric indicators (number of publications, total citations, growth, h-index, and g-index), the journal Applied Energy scored at the top. Four of the top five journals started publishing in the period between 2008 and 2011, which coincides with an upward and accelerating trend in publication, shown in Figure 3. In fact, 16 of the top 20 journals in this field began publication in the 4-year span between 2008 and 2012.

Table 3. Top 20 sources ordered by rank according to three indices, citation count, and paper count for biomass-to-bioenergy supply chain research published between 1992 and 2022.

Journal Title	h-Index ¹	g-Index ²	m-Index ³	Citations (Count)	Papers (Count)	First Year of Publication
Applied Energy	37	53	2.643	3488	106	2009
Biomass and Bioenergy	35	58	1.129	4322	133	1992
Journal of Cleaner Production	31	49	2.583	3287	128	2011
Energy	26	47	1.733	2341	69	2008
Bioresource Technology	21	29	1.750	1295	29	2011
Computers and Chemical Engineering	21	43	1.500	1924	52	2009
Renewable Energy	21	39	1.400	1574	46	2008
Biofuels, Bioproducts and Biorefining	19	34	1.357	1247	47	2009
Energy Policy	14	19	0.824	714	19	2006
Industrial and Engineering Chemistry Research	14	26	1.167	1095	26	2011
Energies	12	18	1.091	423	41	2012
Energy Conversion and Management	12	19	0.857	538	19	2009
GCB Bioenergy	12	19	1.000	392	19	2011
Renewable & Sustainable Energy Reviews	12	17	2.400	318	23	2018
Bioenergy Research	11	15	1.000	255	19	2012
Energy & Fuels	11	12	0.786	667	12	2009
ACS Sustainable Chemistry & Engineering	10	18	1.000	426	18	2013
Clean Technologies and Environmental Policy	10	15	0.769	349	15	2010
International Journal of Hydrogen Energy	9	9	0.818	270	9	2012
Sustainability	9	14	1.000	312	36	2014

¹ h-index: the number of papers (n) on a list of publications ranked in descending order by the times cited that have n or more citations. ² g-index: the top g articles that have together received g citations. ³ m-index: the h-index divided by the number of years that a scientist or journal has been publishing.

Figure 4 shows the top 10 journals based on the cumulative growth of articles. Between 2014 and 2021, there is a significant growth in the number of publications on the topic of biomass-to-bioenergy supply chains, following an increase in the number of journals in this field. One possible explanation of this trend is that it coincides with an increase in the implementation of public policy and publicly funded research in support of bioenergy and second-generation biofuels (i.e., advanced biofuels made from non-food biomass). For example, in the late 2000s in the United States, collaboration between the U.S. Department of Energy and the U.S. Department of Agriculture was directed by various laws, such as the Food, Conservation, and Energy Act of 2008, and the Biomass Research and Development (BR&D) Initiative [38] was founded to coordinate research and development investment focused on feedstock development, biofuel and bio-based product development, and biofuel development analysis. It is reasonable to assume such investment by the European Union, USA, and other countries helped spur, at least in part, an increase in primary bioenergy supply chain research that was published in these journals, perhaps with some time lag between policy implementation and publication. While the journal Biomass and Bioenergy, published since 1992, remains top-ranked in terms of the total number of publications, the Journal of Cleaner Production and Applied Energy show significant rapid growth into the number two

and three ranks, respectively, with the three journals accounting for a significant concentration of the total articles published (367 of 1711, or 21.4%).

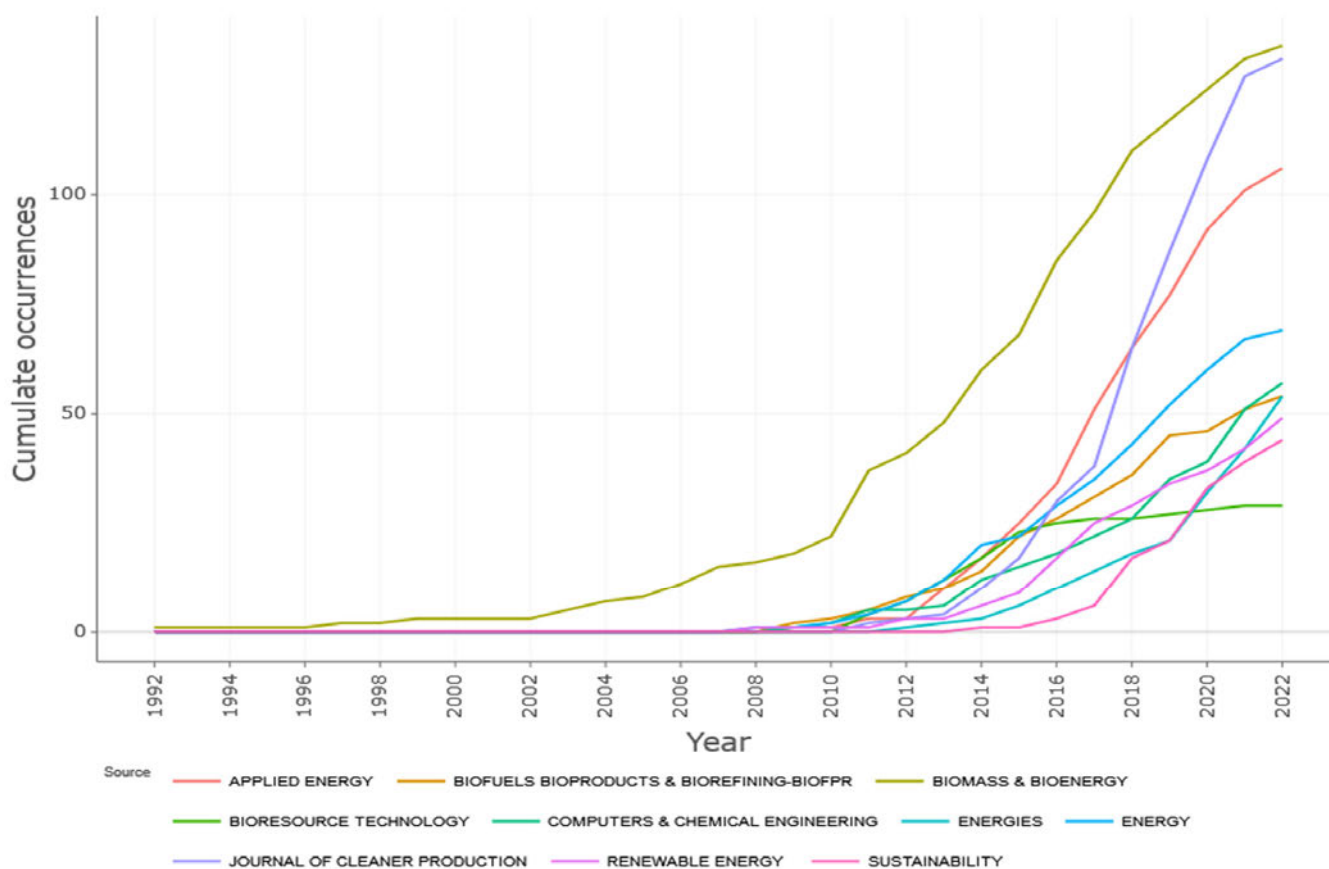


Figure 4. Cumulative growth of articles by source for the top 10 sources.

Figure 5 shows a bibliographic coupling network map of the top 25 sources in three clusters shown in red, blue, and green. In the bibliographic coupling approach, if two works refer to the common work(s), then the relation between two referring documents is called bibliographic coupling [39]. Bibliographic coupling is helpful in detecting the connections of research groups and is used to map a current research front [40,41]. Sources that have a minimum number of 10 documents and a minimum number of 100 citations are included. Out of 365 sources, 25 meet the threshold. For all 25 sources, the bibliographic coupling links, total strength of links, and number of publications are calculated.

The clusters in this visualization were developed using the association method. It reflects the interdependence and relevance between sources. Items shown as circles in the map represent the sources. The higher the weight of an item, the larger the circle of the item. A larger circle also represents a more productive source in this field. Lines between sources represent links between these items. Each link has a strength, represented by a positive numerical value. The higher this value, the stronger the link, with the total strength of an item calculated as the sum of the strength of all links.

From the analysis, it is clear that Biomass and Bioenergy is the most productive source, followed by Journal of Cleaner Production and Applied Energy. Applied Energy has the highest total link strength of 37,421 and 106 documents, followed by Journal of Cleaner Production with 128 documents and total link strength of 35,689. The third position is Biomass and Bioenergy, with a total link strength of 23,792 and 133 documents. Among the three clusters, the red cluster consists of nine items, mainly journals publishing biomass and bioenergy research related to forestry and resource conservation. The green cluster covers journals focusing on biochemical and energy technology research. The blue cluster

consist of journals publishing on sustainability and environmental policy perspectives on renewable energy research.

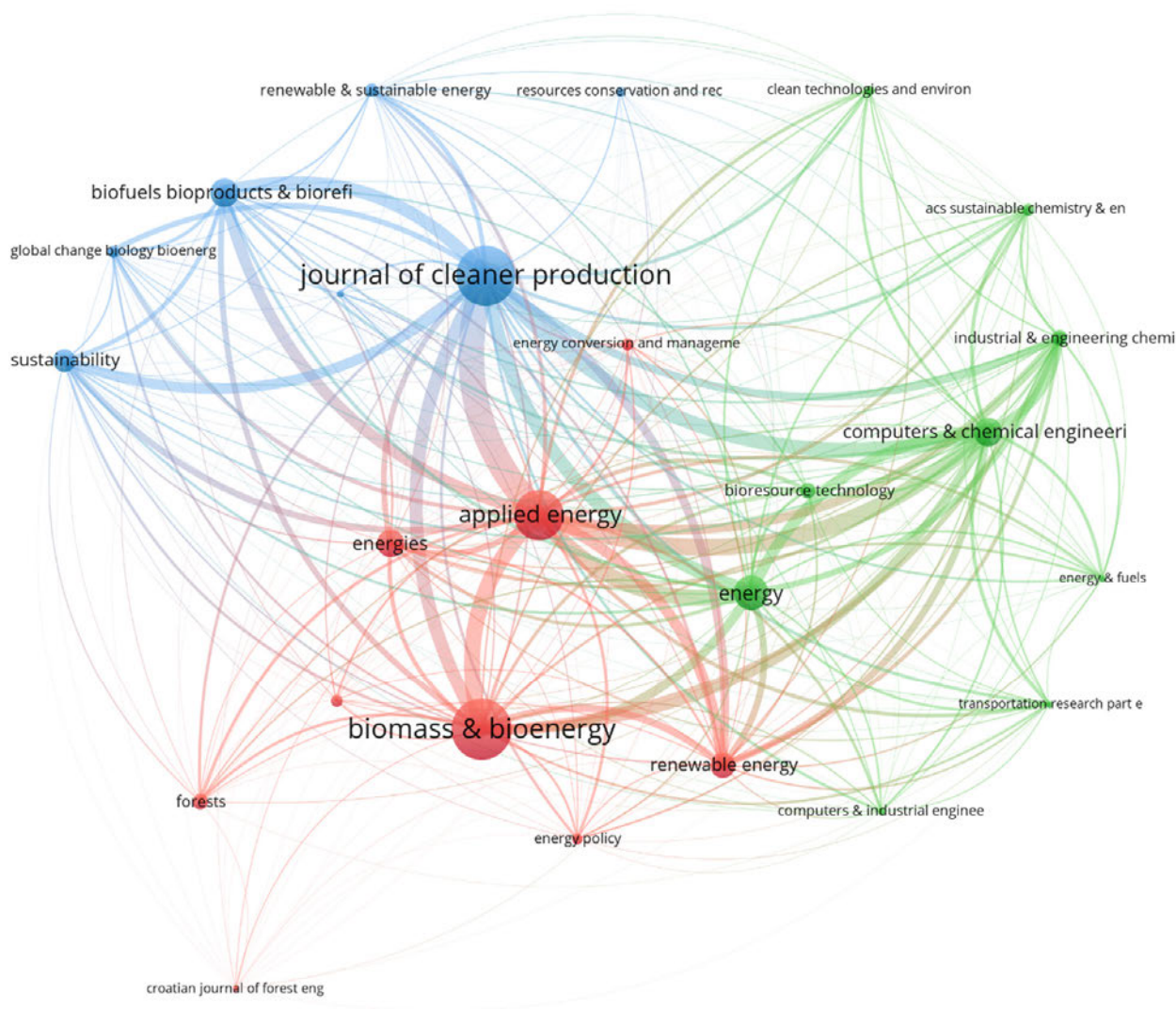


Figure 5. Structural network map of bibliographic coupling of source journals.

3.4. High-Impact Publications

The top ten most frequently cited articles are listed in Table 4. The article titled “Analyzing the design and management of bio-mass-to-biorefinery supply chain” [42] is the most frequently cited article in the field based on local citations, with 167 local citations and 292 global citations. “Optimal design of sustainable cellulosic biofuel supply chains: Multi-objective optimization coupled with life cycle assessment and input–output analysis” [43] is ranked second based on local citations, with 151 local citations and 471 global citations. Though no specific conclusions can be drawn from this ranking, many of the top-ranked papers appear to be broad in scope like [42] or integrate methods across multiple fields like [43]. A detailed analysis of the contributions and rankings of specific authors is beyond the scope of this study, but Appendix A provides detailed information on the most cited authors and analysis of paper co-citation. This information can help researchers and readers identify the most relevant research studies, but also understand the body of research that is considered or perceived to be most foundational in this field.

Table 4. The top 10 most frequently cited articles in this review with associated citation metrics.

Author	Title	DOI	Year	Local Citations ¹	Global Citations ²	Normalized Local Citations ³	Normalized Global Citations ³
[42] Ekşioğlu et al. (2009)	Analyzing the design and management of bio-mass-to-biorefinery supply chain	https://doi.org/10.1016/j.cie.2009.07.003	2009	167	292	6.49	3.97
[43] You et al. (2011)	Optimal design of sustainable cellulosic biofuel supply chains: Multi-objective optimization coupled with life cycle assessment and input–output analysis	https://doi.org/10.1002/aic.12637	2012	151	471	8.52	8.06
[3] Yue et al. (2014)	Biomass-to-bioenergy and biofuel supply chain optimization: Overview, key issues and challenges	https://doi.org/10.1016/j.compchemeng.2013.11.016	2014	139	423	14.94	12.06
[44] Kim et al. (2011)	Optimal design and global sensitivity analysis of biomass supply chain networks for biofuels under uncertainty	https://doi.org/10.1016/j.compchemeng.2011.02.008	2011	119	242	5.74	3.77
[45] Huang et al. (2010)	Multistage optimization of the supply chains of biofuels	https://doi.org/10.1016/j.tre.2010.03.002	2010	108	194	6.09	3.15
[46] You and Wang (2011)	Life cycle optimization of biomass-to-liquid supply chains with distributed–centralized processing networks	https://doi.org/10.1021/ie200850t	2011	102	248	4.92	3.87
[47] Sokhansanj (2006)	Development and implementation of integrated biomass supply analysis and logistics model (IBSAL)	https://doi.org/10.1016/j.biombioe.2006.04.004	2006	97	243	4.37	3.52
[48] Gold and Seuring (2011)	Supply chain and logistics issues of bio-energy production	https://doi.org/10.1016/j.jclepro.2010.08.009	2011	94	259	4.54	4.04
[49] Chen and Fan (2012)	Bioethanol supply chain system planning under supply and demand uncertainties	https://doi.org/10.1016/j.tre.2011.08.004	2012	83	157	4.69	2.69
[50] Kim J et al. (2011)	Design of biomass processing network for biofuel production using an MILP model	https://doi.org/10.1016/j.biombioe.2010.11.008	2011	82	160	3.96	2.49

¹ Local citations measure how many times an author or a document included in this collection have been cited by the documents also included in the collection. ² Global citations count the total number of citations that an article, included in your collection, has received from documents indexed on a bibliographic database (Scopus, WOS, etc.). ³ The Normalized Citation Score (NCS) of a document is calculated by dividing the actual count of citing items by the expected citation rate for documents with the same year of publication.

In addition to the frequency of citations, the dynamics of a field can be characterized in part by articles that have received the steepest increase in citations, that is, “citation bursts”, even if they are not ranked at the top in terms of total citations. A citation burst indicates the likelihood that the scientific community has paid or is paying special attention to the underlying contribution, often immediately following publication. A full visualization of the top 25 citation bursts is included in Appendix A. In our analysis, three papers stood out with the strongest citation bursts in the group of articles that started to burst at the same time, cutting across dynamic simulation, spatially explicit optimization, and incorporation of uncertainty in supply chain management. In [47], Sokhansanj et al. described the framework for the development of a dynamic integrated biomass supply analysis and logistics model (IBSAL) to simulate agricultural biomass logistics to a biorefinery. The model consists of time-dependent events that combine production rates of equipment supplying storage facilities with known capacity.

In Zamboni et al. [51], developed a spatially explicit mixed-integer linear programming (MILP) model for the design of first-generation and hybrid-generation ethanol supply chains under economic and environmental performance optimization (i.e., optimization for greenhouse gas emissions). The economics were assessed using supply chain analysis techniques with a focus on biomass cultivation sites, ethanol production capacity and facility location, and transportation optimization.

Using a combination of techniques, including probabilities tied to specific scenarios, fuzzy numbers for biomass yields, and interval uncertainty for gasoline demand, Bairamzadeh et al. [52] integrated detailed treatment of uncertainty into various segments of the supply chain. The proposed hybrid robust optimization model is an MILP model to determine the strategic and tactical-level decisions of the lignocellulosic bioethanol supply chain subject to different sources and types of uncertainty.

3.5. Keyword Analysis

Keywords are commonly used to identify primary research themes and topics in a publication; thus, the analysis of keywords is an essential part of understanding research trends. Keywords of research papers are intended to describe the topic of a paper in a succinct way, suitable for indexing and search functions, so they can be used to highlight important research areas and explore the interconnections of different themes and topics. WoS provides two types of keywords. Author keywords are provided by the authors and are typically included alongside the title and abstract on the first page of an article. Keywords designated “KeyWords Plus” are extracted from the titles of the articles by databases like WoS and Scopus. KeyWords Plus are automatically generated by a computer algorithm after publication, not by a human author or editor prior to publication, and are not explicitly identified within a published article. Though there is obviously overlap in many cases, independent analysis of the two types of keywords can illustrate different relationships in the bibliometric data, and that is the case for this dataset.

Keywords bursts, similar to citation bursts, are an important metric to identify and understand the most active areas of research at a particular time and indicate the degree of attention from the scientific community to a specific topic. Figure 6 shows the top 25 keywords with the strongest bursts in their appearances over the study period. The red bars represent periods of frequent use, based on Kleinberg’s algorithm, and the green bars represent periods of less frequent use. The strongest keyword bursts include “energy crop” and “mixed integer linear programming”. The most recent burst of keywords are “circular economy”, “life cycle assessment”, and “environmental impact”. The keyword “energy crop”, which emerged from 2008, showed the strongest citation burst (2.21).

In bibliometrics, keyword co-occurrence analysis demonstrates the conceptual structure of connected research themes within a topic area [53,54]. The author keyword co-occurrence visualization in Figure 7 was produced using VOSviewer and represents the most closely connected author keywords in biomass-to-bioenergy supply chain research. The keywords of an article can represent its main content, and the frequency of occurrence and co-occurrence can reflect themes that focus on a special field to some extent. In this visualization, the minimum co-occurrence of an author keyword is set to 20. Across 1711 documents with 4200 listed author keywords, only 37 keywords meet the threshold minimum co-occurrence of 20. Five clusters are identified in Figure 7, with each cluster indicating a specific theme. The color of the nodes indicates different keyword clusters, which were formed using association strength methods. The size of the label and the node of a keyword is determined by the number of occurrences of that keyword. The larger a circle, the more a keyword has been co-selected in biomass-to-bioenergy supply chain publications. Lines between the nodes represent the relationships between the keywords, where the distance between two nodes and thickness of the line indicate the strength of association between the keywords as determined by co-occurrence. Thus, the closer the two nodes are and the thicker the line between them, the greater their co-occurrence relationship.

The link and total link strength information of the top 10 co-occurrence keywords are listed in Table 5.

Table 5. The link and total link strength of the top 10 co-occurrence keywords.

Keyword	Cluster #	Links	Total Link Strength	Occurrences
Biomass	2	31	285	222
Supply chain	2	31	308	222
Bioenergy	2	31	199	154
Optimization	4	31	221	120
Sustainability	1	28	109	94
Life cycle assessment	1	26	67	77
Biofuel	3	30	144	91
Biorefinery	3	21	69	52
Logistics	2	24	107	57
Renewable energy	5	16	59	51

As one would expect given the search criteria for this review, the author keywords “biomass” and “supply chain” show the highest strength. The distance between the two keywords demonstrates relative strength and topic similarity. Clusters are indicated by circle color, with circles of the same color statistically grouped in the same cluster. This indicates a stronger relationship among author keyword use. Each cluster represents a subfield of a field of research in this domain. Appropriate labels of the five main clusters were allocated to each of them by analyzing their main node circles. Specifically, as is shown in the red cluster (Figure 7, cluster 1, upper left, 10 items), keywords such as “sustainability”, “life cycle assessment”, “techno-economic analysis”, “circular economy”, “biofuels”, and “bioethanol” are apparently strongly related to the topic of “sustainable development” of biomass-to-bioenergy production systems.

In the green cluster (Figure 7, cluster 2, right, nine items), keywords such as “biomass”, “supply chain”, “forest biomass”, “transportation”, “storage”, and “logistics” focused on the main domain of “biomass supply chain”. Next, in the yellow cluster (Figure 7, cluster 4, bottom left, seven items), keywords like “optimization”, “uncertainty”, “stochastic programming”, “supply chain design”, and “biodiesel” were concentrated on the aspect of “uncertainty” in the system design related to biomass supply chain systems. In the blue cluster (Figure 7, cluster 3, middle, seven items), keywords like “MILP”, “optimization”, “GIS”, and “biofuel” were also associated with “science technology topics” to optimize the system design for biomass-to-bioenergy supply chain. Another central cluster in purple (Figure 7, cluster 5, four items) comprised keywords including “biogas”, “bioenergy”, “renewable energy”, and “supply chain management”, which are more concerned with the supply chain system for “renewable energy”.

As the figure shows, all the clusters are interconnected, and there are strong relationships between the clusters. This indicates high interdependence of different areas of biomass-to-bioenergy supply chain research. A more independent association would show more distinct, disparate clusters, with weaker interconnections. However, it must be pointed out that clustering analysis has some degree of variability depending on the methods used, and the algorithms obviously have no inherent understanding of the meaning behind the keywords. Based on domain expertise, most of the clusters appear to make sense, but a few are not intuitive. For example, it is not conceptually obvious why “multi-objective optimization” appears in the red cluster instead of the yellow cluster or why “supply chain management” is buried under a few, small purple nodes rather than being featured more prominently. Even so, this visualization is useful in parsing out relationships among keywords and generating a relatively intuitive understanding of the keyword relationships.

In Table 5, a link indicates a co-occurrence connection between two keywords. Each link has a strength, represented by a positive numerical value [55]. The higher this value, the stronger the link. The total link strength indicates the number of publications in

which two keywords occur together. The research hotspots, as measured by co-occurrence, are mainly concentrated on the “biomass”, “supply chain”, “bioenergy”, “optimization”, “sustainability”, and “lifecycle assessment” keywords (Table 5). Figure 8 illustrates more recent trends in keywords from 2015 to 2022. “Switchgrass”, “ethanol”, and “GIS” (shown in purple) are supplanted in strength by “techno-economic analysis”, “bioeconomy”, and “circular economy” in more recent years (shown in green and yellow).

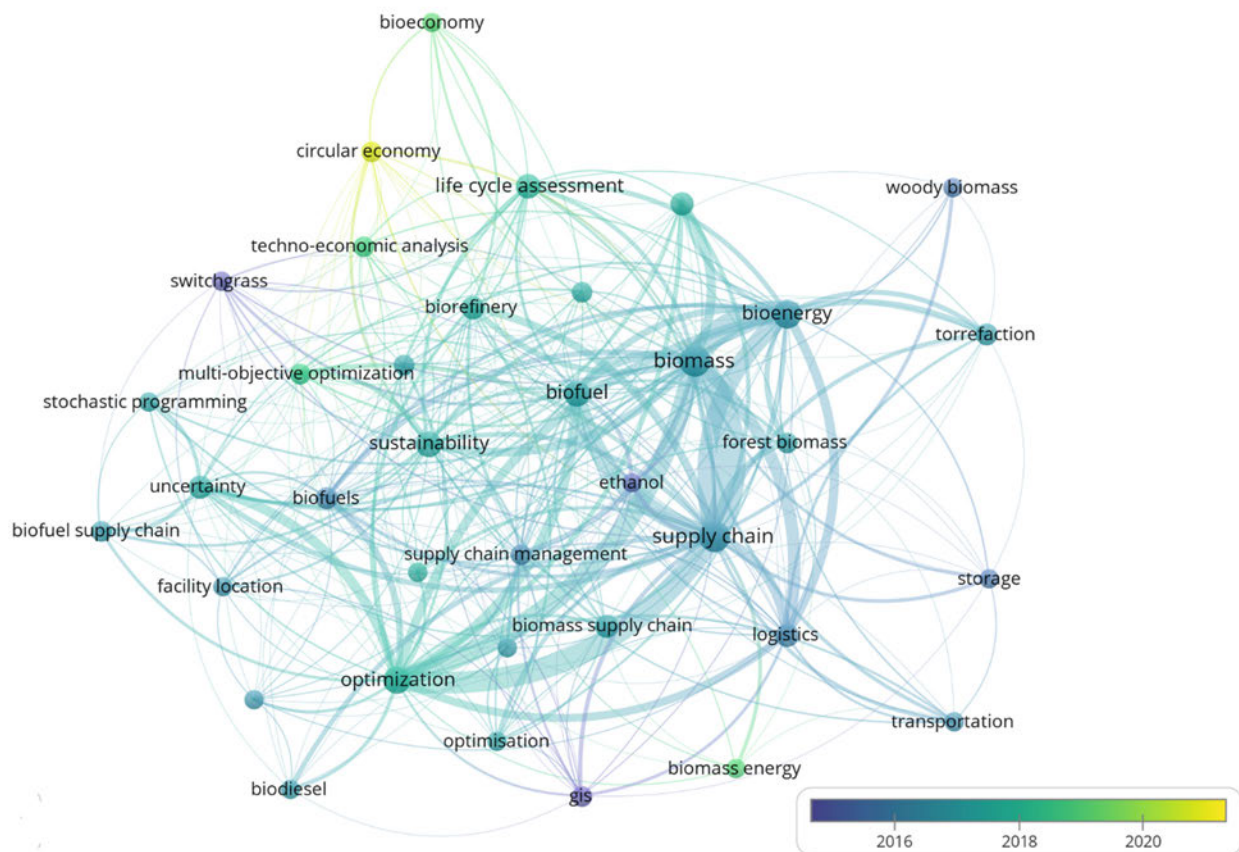


Figure 8. An overlay map showing keyword occurrence strength and relationships between 2015 and 2022.

Figure 9 illustrates the co-occurrence network for KeyWords Plus. The most frequent keywords were divided into four clusters with four different colors. Out of 2689, 116 keywords meet the threshold of minimum co-occurrence of 20. The most prominent keywords in Figure 9 are “biomass”, “optimization”, “supply chain”, “energy”, and “bioenergy”, which were placed in different clusters by the algorithm. It is clear that “greenhouse gas emissions”, “emissions”, and “model”, and “programming approach” are prominent in the KeyWords Plus network, but authors used these much less frequently as their keywords.

The author keyword network (Figure 7) and KeyWords Plus network (Figure 9) are quite different. It may be that author keywords show the actual concentration of all the papers in broader topic areas, while the KeyWords Plus network represents a more precise breakdown of the subjects commonly discussed in the biomass supply chain field, as reflected in the titles of these papers. An interesting example is greenhouse gas emissions. It appears in the Keywords Plus network, but not in the author keyword network. This may mean that greenhouse gas emissions are the topic of many papers, but not commonly listed by authors as a keyword. Alternatively, perhaps it is regularly used in the title or introduction to frame the problem but is not the topic of research. This may be linked to the breadth or specificity of journals and to guidance provided to authors by the journals

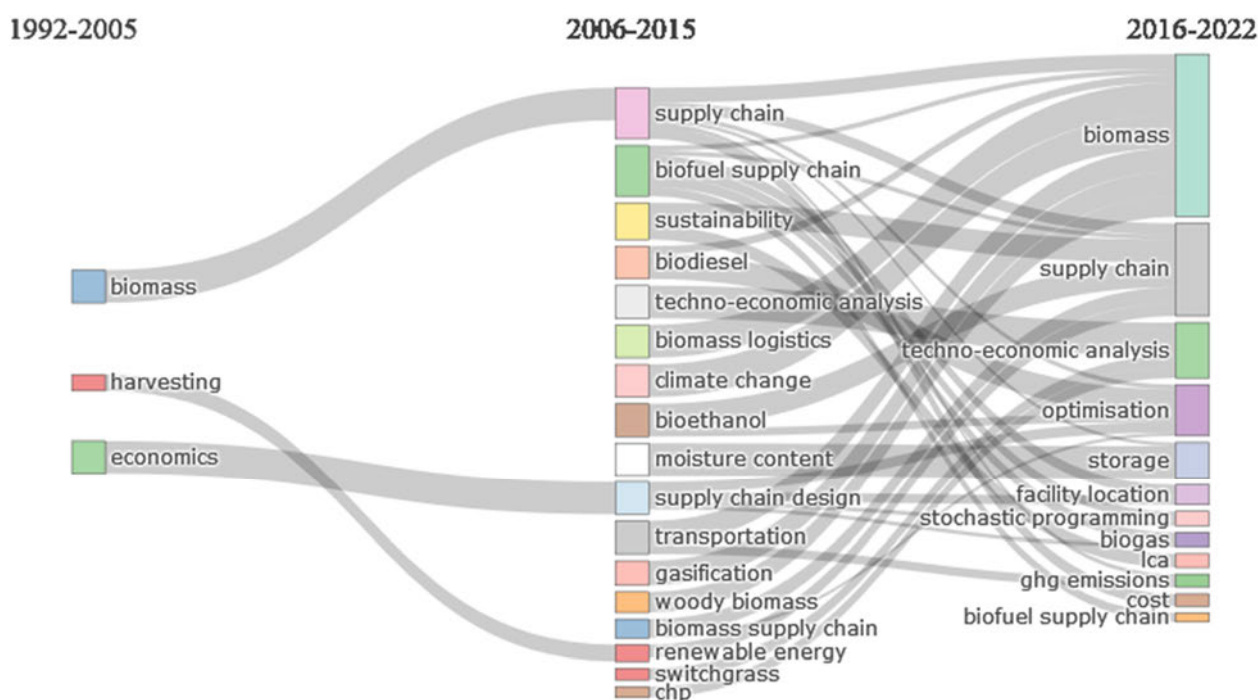


Figure 10. An illustration of the thematic evolution of author keywords.

The thematic evolution of author keywords in biomass-to-bioenergy supply chain research shows a clear change and refinement during the last 30 years from a few broad categories to many specialized categories. Generally, as the field advances, popular keywords trend to more narrow technical fields, but some terms cut across the full 30-year time frame. The keyword “biomass” is important in all three time periods, with multiple variants appearing in the center column, whereas “harvesting” appears in the first stage but is less popular in the most recent period. A large portion of the research in this early stage relates to agricultural biomass harvesting and related economics from agricultural systems, especially food crops grown to provide sugar, starch, and oils for first-generation biofuels. Stage one (1992–2005) has little overlap with stage two (2006–2015), as there is only one common keyword between these two stages. In addition, stage two (2006–2015) and stage three (2016–2022) have more common keywords as compared to the broad terms used in the first period.

The second period illustrates a refinement of some relevant topical areas including the emergence of terms associated with environmental impacts, such as “sustainability”, “renewable energy”, and “climate change”. Building on topics like supply chain optimization, we see an emergence of additional methods-driven keywords such as “life cycle assessment” (“lca” on Figure 10) and “stochastic programming”, as well as some growth in “techno-economic analysis”. The analysis shows that recent studies have shifted toward sustainable supply chain management, techno-economic analysis, and optimization of system design for biomass supply chain management. It is also evident that there are topics that have many links with each other belonging to several different areas of research.

3.7. Global Impact and Collaboration

Research collaboration among authors residing in different countries is linked to the globalization and internationalization of research. Collaborating with professional colleagues in other countries offers a potentially useful strategy for expanding and improving the work in a specific field. The authors of these 1711 articles come from the many countries, depicted in Figure 11. However, the figure is not inclusive of all countries represented in the literature. To keep the figure readable in this format, the bibliometric map of co-authorship

by country includes only countries that have published at least 10 papers and produced a minimum of 100 citations; hence, only 40 countries are shown in the figure.

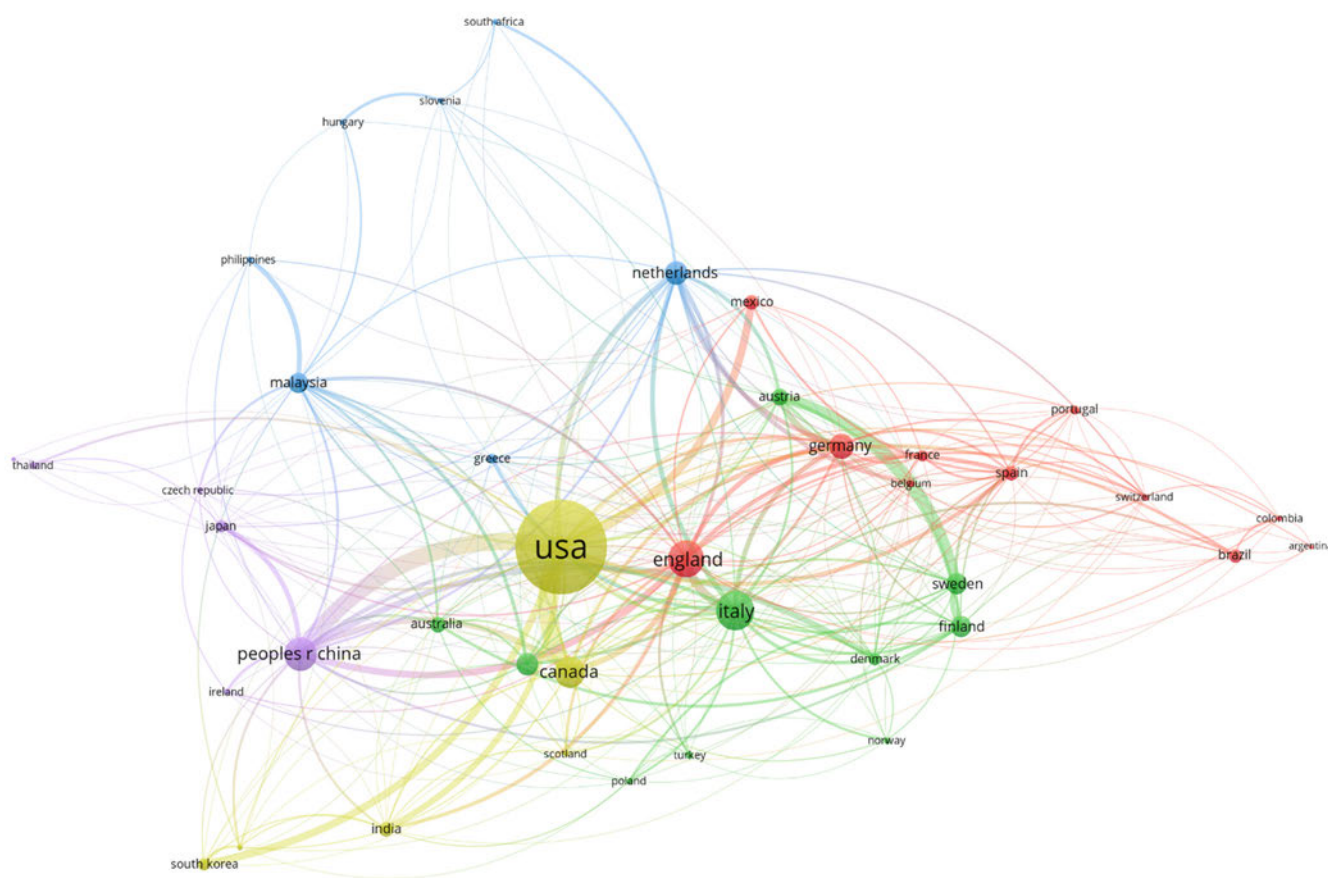


Figure 11. Network of co-authorship by country for the biomass-to-bioenergy supply chain literature.

The network of author collaboration is crucial in understanding both existing collaboration and opportunities for expanding collaboration. This information can be used to spur the formation of academic hubs that boost international partnership and the growth and future expansion of the study topic. The co-author network in Figure 11 illustrates the intellectual connections between researchers on a country basis. The size of each circle shows the number of English-language peer-reviewed papers in biomass-to-bioenergy supply chain research by authors residing in the country at the time of authorship as indicated by bibliographic information. A co-authorship relation among countries corresponds to a link, and the width of links reflects the number of co-authorships between countries. In the field of biomass-to-bioenergy supply chain research, the USA and UK, Canada, Italy, and China have the most collaboration with each other as well as with authors across the world. It is worth mentioning that authors based in the USA are most internally connected in terms of co-authorship among these countries. To establish that, USA-based authors have produced 486 documents in the biomass supply chain area with 33 links and a total link strength of 173. On the other hand, England-based authors have produced 149 documents with 31 links and a total link strength of 119. This indicates a higher level of internationalization for England. China has produced 133 documents with 24 links and 117 total link strength. However, to some degree, this analysis also shows that the topic area is not localized or regionalized but rather has broad appeal to researchers working across the globe, even when limited by the English language parameter on publications used in this study (Figure 1).

3.8. Keyword Mapping

The TreeMap in Figure 12 highlights the combination of possible keywords in this topic area. We analyzed author keywords, and the top 16 relevant keywords are shown in Figure 12. In our statistics, the keywords “biomass” and “supply chain” are the most frequent occurrences (as one might expect given the search criteria), followed by “bioenergy”, “optimization”, and “sustainability”. In addition, other keywords such as “life cycle assessment”, “biofuel”, and “uncertainty” present the main applications of biomass-to-bioenergy supply chain research over this period. On the other hand, some keywords such as “circular economy”, “stochastic modeling”, “climate change”, and “greenhouse gas emission” are relatively low in occurrence among the top keywords and are seen as emerging topics in an evolving field. This was also shown by other keyword metrics.

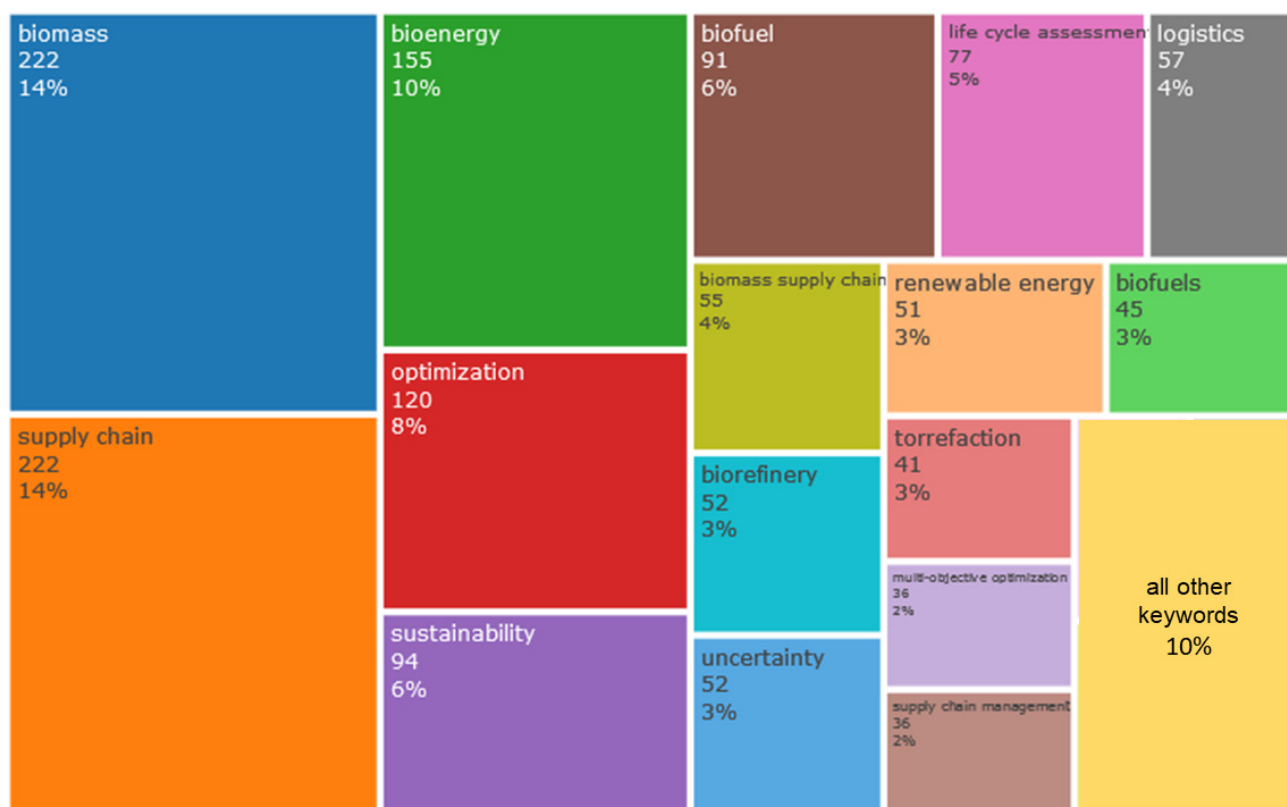


Figure 12. TreeMap of the 16 most popular keywords, which account for 90% of total key word use. All other key words account for the remaining 10% (shown in yellow).

3.9. Strategic Diagram

We can further analyze keywords into themes presented in a strategic diagram (Figure 13) to visualize the importance and development of research themes [41,56]. As described previously, metrics of centrality and density can be used to map research themes into a two-dimensional strategic diagram with four quadrants. The size of the thematic map circle is related to the factors that come under the theme. Themes that appear on the lower left quadrant are generally emerging or declining themes. Here we see “biomass logistics”, “facility location”, “MILP”, “biomass energy”, “GHG emissions”, and “supply chain analysis” in this quadrant. These are new themes that can emerge later to be important or declining themes that may drop from the research area altogether. The nature of these is discussed in more detail in a moment.

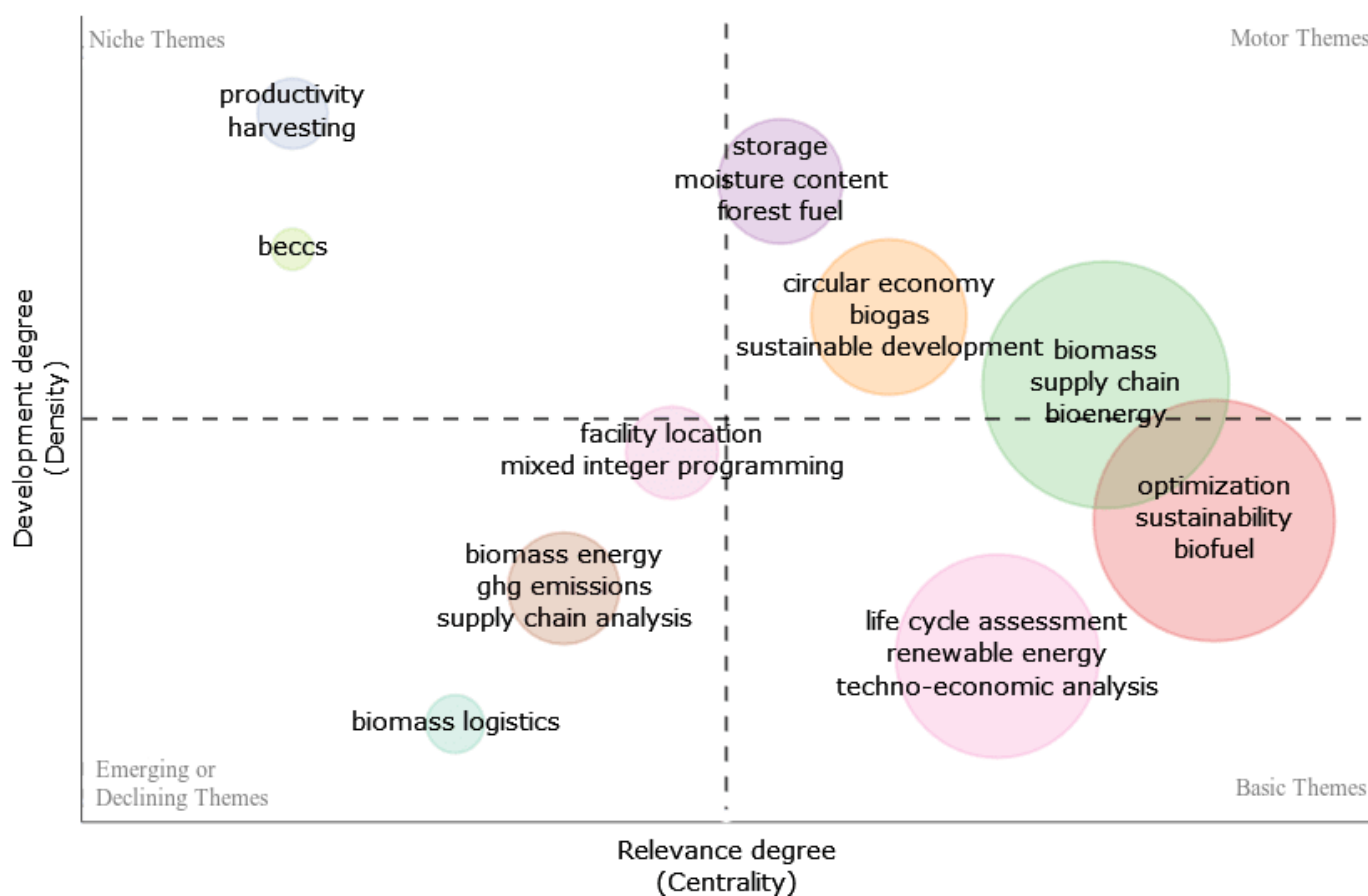


Figure 13. Thematic map using co-word analysis.

Themes that fall in the lower right quadrant of the thematic map are the primary or transversal themes, which are represented by a high degree of relevance and a low degree of development (i.e., low density but high centrality). Much research needs to be done on these themes. Things like “optimization”, “sustainability”, “techno-economic analysis”, “life cycle assessment”, and “renewable energy” fall into this quadrant using this approach.

The upper left quadrant represents high density but low centrality. These themes are highly developed but marginally related to the topic area. In this case, “productivity”, “harvesting”, and “bioenergy with carbon capture and storage” (BECCS) appear in this quadrant. The upper right quadrant represents high density and high centrality. The themes in this zone are developed and essential. However, they tend to move to basic themes over time. Nine different themes appear in this quadrant, including most generally “biomass”, “supply chain”, and “bioenergy”.

Emerging or declining themes have low centrality and low density, meaning that they are weakly developed and marginal. The interpretation of which trend (emerging or declining) applies to a specific theme can be qualitatively gleaned from a review of the development of keywords over time and the history of the specific theme. However, longitudinal analysis provides a quantitative approach to thematic evolution [41]. Splitting the timespan into different time slices allows us to identify the trajectory of a theme, whereby a direction toward the top of the map over time identifies an emerging trend, while a direction toward the lower left quadrant identifies a declining trend. All of the topics shown in this quadrant are among the earliest topics to emerge in this body of literature, indicating that they may be declining or transitioning to different types of research under more narrow specifications and new terminology, such as “techno-economic analysis”.

3.10. Limitations of This Study

Bibliometric analysis is a powerful tool. Nonetheless, some limitations are still inevitable. First, important research many have been excluded from this study. Although a large number of new research papers are added to bibliographic databases like WoS every day, some publications are outside of the indexed core databases and are not included in this analysis. In addition, the search strategy might not have found all of the pertinent studies in this research area, including the so-called “grey literature”—publications that were not published in indexed journals [57]. Furthermore, non-English-language articles were not included, which obviously excludes important research published in other languages. An analysis of non-English documents, if possible, would potentially yield new or different insights. Furthermore, the current growth trends predict a large increase in the number of global publications on biomass-to-bioenergy supply chain research, which leads to a fairly large number of papers that were published in the preprint version online in a database like ArXiv. These were not included in our study. This points to the need to replicate bibliometric studies like this one periodically to stay on top of research trends.

Another limitation is that bibliometric analysis, in relying on classification and statistical models, is good at identify significant trends and patterns but will not be accurate in identifying all patterns. These visualizations are useful but cannot be considered the only definitive representation of this diverse body of work. Similarly, it is possible that bibliographic data collected from different databases can produce slightly different results [58]. This is also why manual review and domain knowledge are important. More broadly, bibliometric methods cannot accomplish some objectives that are a core component of traditional literature reviews applied to narrower slices of the literature. Because these methods are based on quantitative analysis, important qualitative aspects are not considered [58]. However, this approach is well-suited to extracting insights from hundreds or even thousands of papers simultaneously. In this case, given the breadth, richness, and abundance of supply chain research, we believe that the bibliometric analysis was valuable in illuminating trends and patterns in this field, despite its limitations. Ultimately, the use of bibliometrics is a suitable jumping off point for deeper scholarship into narrower topics and domains.

4. Discussion: Constraints, Gaps, and Future Research

We conducted a bibliometric analysis in parallel with manual review of key papers using a modified version of the workflow suggested by Zupic and Čater [20]. Using bibliographic data contained within the WoS database, this analysis presents a holistic historical summary of the literature on biomass-to-bioenergy supply chain research that has developed over the last 30 years. Our manual review of key papers also led to some interesting complementary discoveries, which are articulated in this section along with a discussion of the bibliometric results. This analysis offers a broad view of bibliometric variables of biomass-to-bioenergy supply chain research that can contribute to achieving scientific and technical progress in this field. In addition, the study also highlights unexplored and underdeveloped topics that can be studied further by researchers. We offer six recommendations linked to both growing and neglected areas of investigation. These recommendations were developed from the results of this study in light of domain knowledge and current trends in supply chain research. Our findings have a number of theoretical and practical implications.

First, a relatively small number countries of the world are contributing to the research in this field (Figure 11) compared to the potential for biomass conversion to bioenergy across the globe. Geographical differences could greatly influence the biomass supply chain and impact the likelihood of commercial success of bioenergy around the world. Research developed in advanced economies, especially those with robust agricultural and forestry sectors, might not be well-suited to emerging and developing economies. Thus, the authors believe that global collaboration in this field is highly important to understanding many more dimensions, applications, and perspectives of this research, especially with regards

to expanding the bioeconomy globally. In addition, researchers could benefit from the integration of multidisciplinary fields.

Second, supply chain complexity is affected by parameter uncertainties such as demand, capacity, cost, and others [59]. Based on the growing challenges of such complexity, there appears to be a need to more fully integrate uncertainty and sustainability in the optimization of large-scale systems. Explicit incorporation of uncertainty, risk, and stochasticity would be facilitated by a systems approach to supply chain research, especially in modeling and design [60], and also by scenario planning [61]. Based on the importance of sustainability and uncertainty as keywords and other evidence, this is a trending and important topic.

Third, most of the studies we examined focus on a single biomass type or one actor or one objective function in a particular conversion pathway or scenario. Considering multiple sources of biomass in the supply chain can reduce supply chain risk and is an important future research direction. In terms of methods, game theory or graph theory and agent-based modeling are potentially useful to tackle the challenges in integration and collaboration in multi-feedstock biomass-to-bioenergy supply chain research.

Fourth, because supply chains are becoming more interconnected and interdependent, supply chain disruptions can become a big risk to establishing bioenergy and expanding the broader bioeconomy. Only a few studies in our review directly incorporate supply chain resilience in the optimization models of biomass-to-bioenergy production [62–64]. To deal with future challenges, more studies on the biomass-to-biofuel pathway specifically should consider incorporating resilience in their supply chain models.

Fifth, a resilient supply chain involves many interconnected yet independent parts working together to ensure continuous supply, reduce costs, and increase revenue. In the business world, the bioenergy supply chain is subject to many exogenous forces that are beyond the control of the firm, including shifting market demand and new competition, that can result in supply chain disruptions. Within supply chain management, “inventory control” is often considered the first step in ensuring an efficient supply chain [65–67]. Even with advances in modern supply chain management, global supply chains add several layers of complexity to inventory control. In our analysis, despite the potential direct and favorable influence of inventory control on supply chain efficiency and the fact that these methods are already widely used in other industries, inventory management and inventory control methods were only lightly investigated in the biomass-to-bioenergy domain. Interested readers are referred to [68–74] to learn more about inventory control methods and industrial inventory control policy. Considering the uncertainty and sensitivity of demand and supply, biomass production yield, and profitability, these methods can help entrepreneurs create more reliable, robust designs by assessing points of uncertainty in the supply chain structure, especially with regards to biomass storage. The authors suggest that researchers in this field consider modern inventory control techniques and policies for investigation.

Finally, artificial intelligence (AI) and machine learning (ML) have recently become buzzwords across a wide range of disciplines, including supply chain management. These tools have already helped supply chain managers quantify and reduce uncertainties to increase efficiency and productivity, which is a priority of supply chain management across all industries. Mounting expectations of rapid fulfillment and efficiencies between suppliers and business partners of all types further underscore the need for the industry to leverage the value AI and ML in supply chains. Discovering new patterns in supply chain data has the potential to revolutionize any business. However, only a few previous studies [75–77] have focused on using these techniques applied to the biomass supply chain, and these were mostly focused on sustainability or a single element of the larger supply chain (e.g., biomass conversion technology). The “Mathematics” and “Computer Science” subject areas evaluated in this study (Figure 2) represent a relatively small number of the papers in this study, but thanks to an explosion of research and tools in AI and ML techniques in computing [78], this area is currently receiving keen attention from researchers in the biomass-to-bioenergy field.

That attention should translate to a higher proportion of the literature being published in the mathematics and computer science subject areas moving forward.

Exploring the potential use of AI in supporting sustainable development of biomass systems from a systems perspective can be a promising future research direction to handle the significant uncertainties faced in biomass supply chain management. AI and ML techniques clearly have strong promise to improve the modeling and optimization of biomass supply chains in ways that can improve efficiency and sustainability and help meet the ambitious economic and public policy goals in this sector.

5. Conclusions

Supply chain research is mainly focused on improving the different activities along the supply chain from biomass cultivation, production, logistics, storage, conversion, and distribution of end products to final markets for end use. As a mantra, effective supply chains coordinate producers, distributors, manufacturers, and retailers so that intermediate and final products are produced and distributed in the right quantities to the right locations at the right time for the right price. In this context, it is also a major goal of supply chain research to improve the competitiveness of bioenergy and the bioeconomy more broadly. Improving the environmental, economic, and social sustainability of these supply chains has also become critically important. Driven by the need to reduce fossil fuel emissions contributing to climate change, bioenergy is experiencing a steep increase in supply-chain-related research in both academia and industry; thus, more and more academic papers have been published in this research area over the past 30 years. It is particularly important to evaluate the characteristics and interactions of such a great number of research papers and obtain valuable information to determine potential future research, including both emerging topic areas and potential gaps in our current research portfolio.

The novel aspect of this study is that the bibliometric approach has not been used in this context before. Though bibliometric methods have some limitations related to the nature of citation databases and the need to interpret results in light of domain knowledge, our findings appear to indicate the potential usefulness of bibliometric studies in uncovering a research field's topical structure and evolution. This helps identify and describe new branches of inquiry early in their development and also predict topics that are waning in a particular field and are no longer on the leading edge of research, sometimes because they are no longer relevant and sometimes because they have been fully operationalized in practice.

This bibliometric analysis provides a quantitative perspective of bibliographic data and citation analysis of journals, authors, and papers, including a description of research trends, which may be useful to both academics and practitioners. We have identified the latest research trends in this field and offer guidance to future studies in this field. Our six recommendations are to: enhance global collaboration and impact; more explicitly incorporate quantitative treatment of uncertainty, risk, and stochasticity using a systems approach; adopt multi-source, multi-type biomass supply models; explore and enhance supply chain resilience; expand the use of inventory control models and methods; and leverage the emerging power of artificial intelligence and machine learning to advance this field.

Author Contributions: Initial conceptualization, M.A.H.; concept improvement, M.A.H., N.A., Y.W. and M.T.; approach, M.A.H.; methodology, M.A.H., N.A., Y.W. and M.T.; software, M.A.H.; data analysis, M.A.H.; interpretation of results, M.A.H., N.A., Y.W. and M.T.; subsequent investigation and review, M.A.H., N.A., Y.W. and M.T.; data curation, M.A.H.; writing—original draft preparation, M.A.H. and N.A.; writing—new text, review, and editing, M.A.H., N.A., Y.W. and M.T.; visualization, M.A.H.; project administration, N.A. and Y.W.; funding acquisition, N.A., Y.W. and M.T. All authors have read and agreed to the published version of the manuscript.

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in this study are those of the author(s) and do not necessarily represent any official USDA or U.S. government position, determination, or policy.

Data Availability Statement: This study can be replicated as described in the Section 2 using bibliographic data provided by citation and abstract databases, but no additional publicly available data were generated by this study.

Disclaimer: The use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Additional Authorship Analysis

Appendix A.1. Impactful Authors and Citation Bursts

Figure A1 shows author productivity since 2006 for the top 15 authors. In addition, Table A1 lists the top 13 impactful authors with their h-index, m-index, and g-index, number of papers included in this analysis, and number of citations. Figure A2 shows the timing of citation bursts for the top 25 citation bursts.

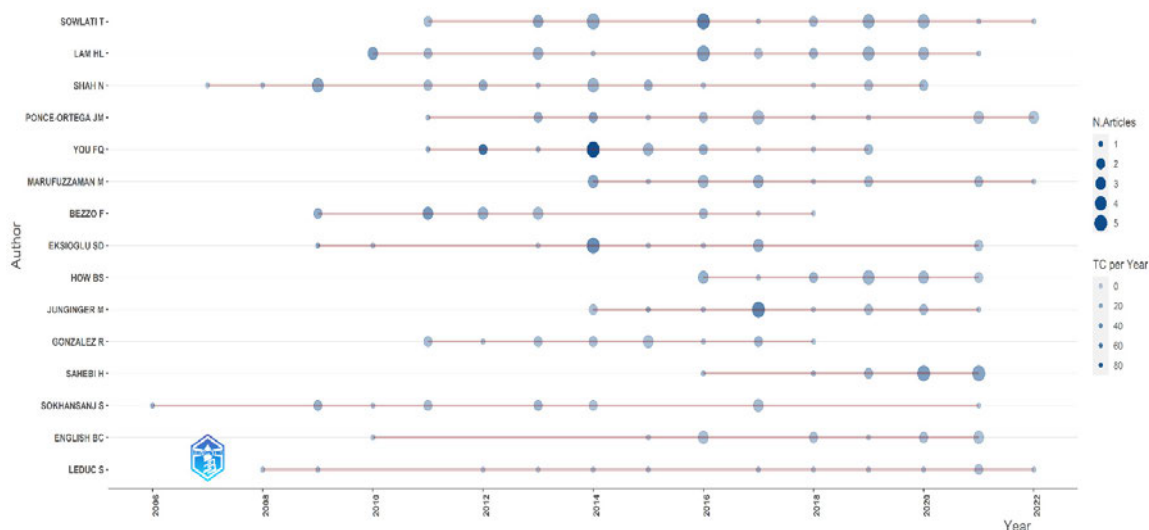


Figure A1. Top 15 authors in biomass-to-bioenergy supply chain research.

Table A1. Most impactful authors in biomass-to-bioenergy supply chain research. The indices are defined as: h-index is the number of papers (n) on a list of publications ranked in descending order by the times cited that have n or more citations; g-index is the top g articles that have together received g citations; and m-index is the h-index divided by the number of years that a scientist or journal has been publishing.

Name	h-Index	g-Index	m-Index	Citations (Count)	Papers (Count)	First Year of Publication
Lam HL	18	26	1.385	1003	26	2010
Shah N	18	23	1.125	1167	23	2007
Sowlati T	16	27	1.333	958	27	2011
You F	15	18	1.250	2085	18	2011
Bezzo F	13	15	0.929	993	15	2009
Eksioğlu SD	12	15	0.857	841	15	2009
Marufuzzaman M	12	15	1.333	469	15	2014
Ponce-Ortega JM	12	18	1.000	671	18	2011
Gonzalez R	11	14	0.917	420	14	2011
Sokhansanj S	11	14	0.647	798	14	2006
How BS	10	14	1.429	272	14	2016
Leduc S	10	13	0.667	467	13	2008
Giarola S	9	11	0.7750	632	11	2011

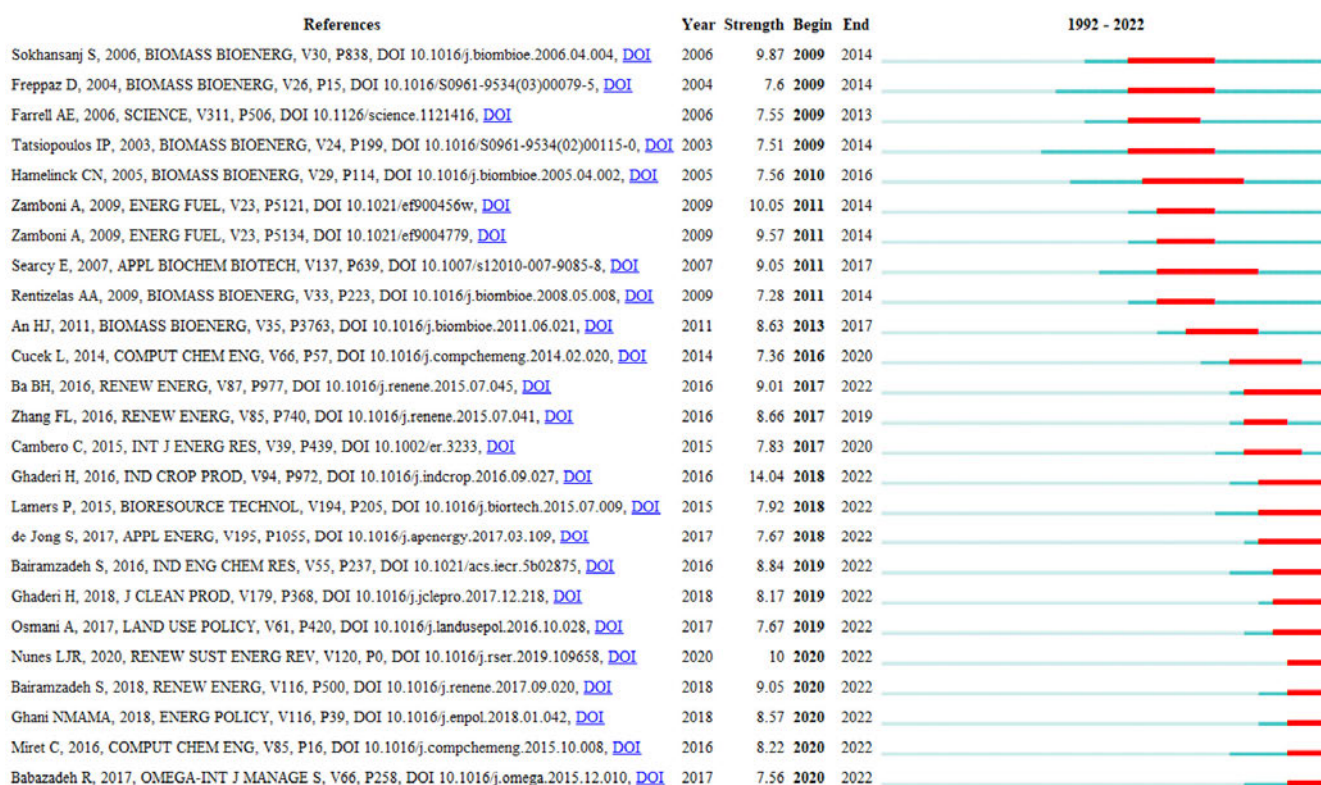


Figure A2. Top 25 citation bursts among the 1711 papers reviewed. The red bars represent periods of high citation of the paper (i.e., “bursts”), based on Kleinberg’s algorithm, and the green bars represent periods of less frequent citation for the paper. Citations for these papers from top to bottom on this list are [47,51,52,79–100].

Appendix A.2. Bibliographic Coupling between Documents

Two publications are bibliographically coupled if there is a third publication that is cited by both publications. In other words, bibliographic coupling is about the overlap in the reference lists of publications. The larger the number of references two publications have in common, the stronger the bibliographic coupling relation between the two publications. Compared with co-citation and bibliographic coupling, direct citations, sometimes referred to as cross citations, offer a more direct indication of the relatedness of publications.

Figure A3 shows the bibliographic coupling of documents with a condition that the minimum number of citations of a document is 150; thus, only 20 documents met this threshold. Overall, twenty documents, four clusters, and one hundred forty-eight links are shown in Figure A3. The size of the circle represents the citation occurrence of the document, and the link represents the citation strength. In general, the closer two references are located to each other in the visualization, the more strongly they are related to each other based on bibliographic coupling. In other words, documents that are located close to each other tend to cite the same publications, while documents that are located far away from each other usually do not cite the same publications.

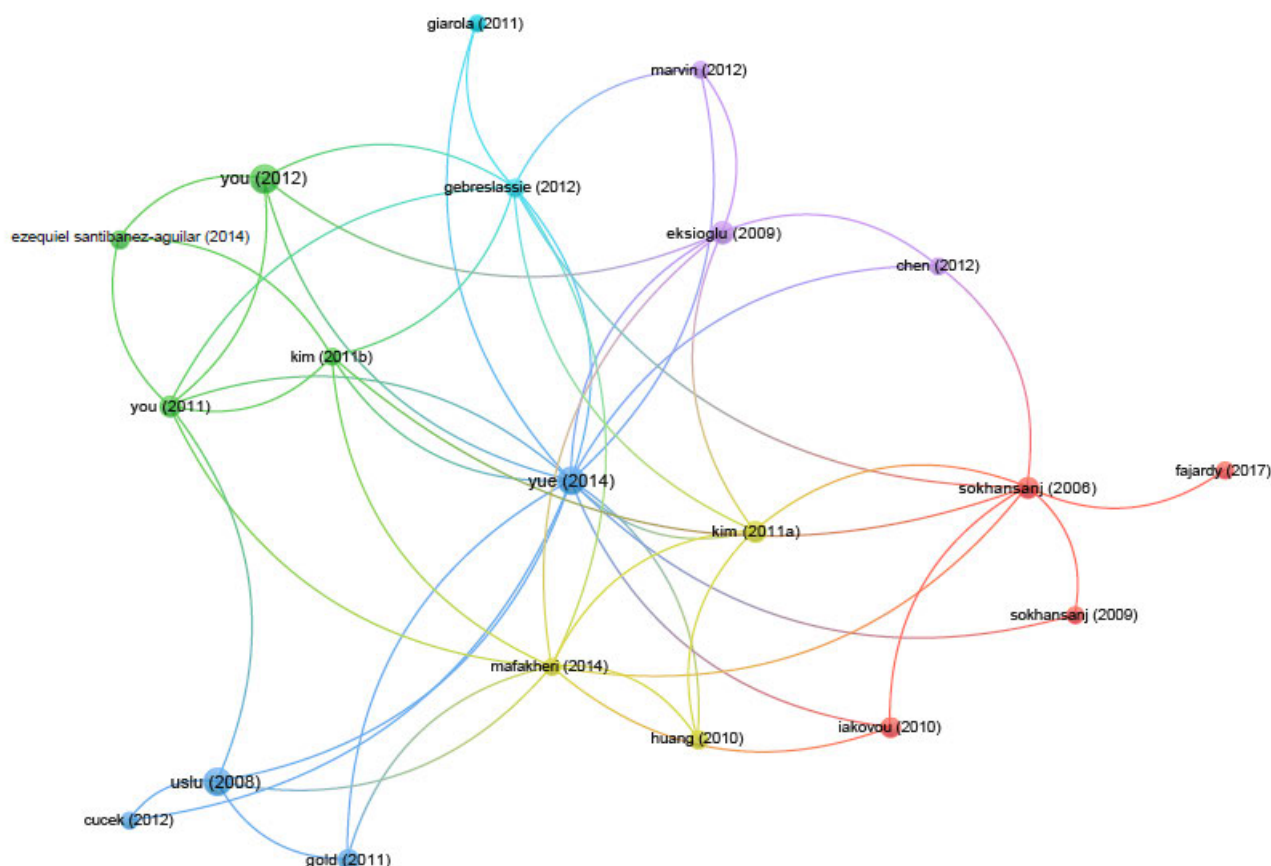


Figure A3. Bibliographic coupling between the top 20 most co-cited articles. Citations for these papers from top to bottom on this list are [42–44,101–110].

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