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Comparative assessment of the scientific structure of biomass-based hydrogen from a cross-domain perspective

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Abstract
Biomass-based hydrogen production is an innovative approach for realizing carbon-neutral energy solutions. Despite their promise, both structures differ in terms of the biomass energy domain, which is at the entry point of the technology, and the hydrogen energy domain, which is at the exit point of the technology. In this study, we conducted structural and predictive analyses via cross-domain bibliometric analysis to clarify the differences in the structures and perspectives of researchers across domains and to suggest ways to strengthen collaboration to promote innovation. Our study revealed that the hydrogen energy domain has a balanced impact on realizing a hydrogen society using biomass-based hydrogen production technology, while the biomass energy domain has a strong interest in the process of processing biomass. The results reveal that different communities have different ideas about research, resulting in a divide in the areas to be achieved. This comparative analysis reveals the importance of synergistic progress through interdisciplinary efforts. By filling these gaps, our findings can lead to the development of a roadmap for future research and policy development in renewable energy and highlight the importance of a unified approach to sustainable hydrogen production. The contribution of this study is to provide evidence for the importance of cross-disciplinary cooperation for R&D directors and policy makers.

Keywords Biomass-based hydrogen, Scientific structure, Multi perspective analysis, Emerging prediction

Introduction

Hydrogen production technology using renewable energy as primary energy is essential for a green energy society (Hassan et al. 2023; Sarker et al. 2023; Li et al. 2023). Renewable energy with large output fluctuations requires a combination of electrolysis, photocatalysis, and biomass. Li and Li (2024) argued for the importance of a model that comprehensively considers the interaction between multiple energy forms. The U.S. Department of Energy has provided $34 million to 19 industries for projects aimed at advancing clean hydrogen technology (Department of Energy 2023a). These include the development of innovative gas upgrade solutions, hydrogen production from organic waste, and cost-effective methods for producing biomass-based hydrogen (Department of Energy 2023a). Biomass is characterized by high storability and stability during the energy conversion process. Biomass-based hydrogen also consumes renewable resources, so CO_2 emissions can be significantly lower without combustion than can gray hydrogen, which is generated from fossil fuels. Biomass-based hydrogen has a lower environmental impact because it can react at room temperature and pressure (Dari et al. 2024). Biomass-based hydrogen has an advantage among green hydrogen derived from renewable energy sources in terms of the stability of raw material procurement, unlike solar and wind power, which have large output fluctuations (Hassan et al. 2024). These abundant sources and their stable storage potential provide an effective means of solving the problem of renewable energy output fluctuations. The US Department of Energy has high expectations for hydrogen generation as a potential source of biomass, which is equivalent to approximately 13 trillion ~ 14 trillion Btu/year in 2030 (Department of Energy 2023b). The EU has focused on several biomass-based hydrogen production processes in its Horizon2020 projects. The BIG-H2 project is focused on improving the efficiency and purity of hydrogen production from biomass gasification to address technical challenges to help the UK achieve its net zero target (Department for Energy Security & Net Zero, 2024). Biomass will play an important role in meeting Colombia's projected massive demand for hydrogen by 2050 (Rodríguez-Fontalvo et al. 2024).

There are various products from biomass processing other than hydrogen. FT synthetic oil, which is produced by the catalytic reaction of CO and hydrogen to produce long-chain carbon hydrogen, can be used as an e-fuel. The esterification of fats and oils derived from biomass can provide a substitute for diesel fuel. In other words, there are various possibilities for accessing biomass, and its utilization is not limited to hydrogen production. Similarly, there are various means of producing hydrogen, not limited to biomass. These include electrolysis of water, thermochemical water splitting, photocatalysis, and production from natural gas using steam reforming, partial oxidation of methane (POX), and autothermal reforming for hydrogen (ATR). In other words, "generation of biomass-based hydrogen" can be seen as one of the utilizations of biomass from the viewpoint of biomass researchers and as one of the many means of hydrogen production from the viewpoint of hydrogen-related researchers. This means that different perspectives can be observed from the biomass energy sector, which is the entry point, and the hydrogen energy sector, which is the exit point. The purpose of this study is to clarify the knowledge gap between the biomass energy domain, which is the entry point of the technology, and the hydrogen energy domain, which is the exit point of the technology, on the evaluation and trend of biomass-based hydrogen production technology.

link R&D to innovation, it is effective to utilize knowledge outside the community (Cohen and Levinthal 1990; Laursen and Salter 2006; Powell et al. 1996). Open innovation through collaboration between different fields brings benefits such as avoiding duplicated research, early identification and resolution of technical issues, and creation of innovative ideas. This perspective has recently attracted attention in several energy fields (Greco et al. 2017; Dall-Orsoletta et al. 2022). Lacerda and Bergh (2020) showed that knowledge procurement strategies affect renewable energy innovation for solar and wind power (Lacerda and Bergh 2020). Biomass-based hydrogen production technology can be said to be a technology that realizes carbon-neutral hydrogen production as a fusion of biomass energy and hydrogen energy fields. In such a fusion field, if the research communities of biomass energy and hydrogen energy fields integrate knowledge based on mutual understanding, it will be possible to realize a more effective green hydrogen society. Strengthening knowledge collaboration will promote the formation of networks among all stakeholders, including researchers, engineers, and companies. If human resources with expertise in both fields are developed, a foundation that supports the long-term development of "biomass-based hydrogen production" technology will be established. As a result, economic, social, and policy barriers can be analyzed from various angles, and comprehensive social implementation strategies can be formulated. In other words, by evaluating knowledge on "biomass-based hydrogen production" from various angles based on expertise in the two fields, the R&D process will be more efficient, and innovation utilizing the strengths of each field can be promoted.

Bibliometric analysis is a method for quantitatively analyzing unstructured document data such as academic papers and patent publications. In recent years, many review articles have utilized bibliometric analysis (Bibri et al. 2023; David et al. 2024). The Delphi method has conventionally been used to investigate a bird's-eye view of technology and trends. However, in reality, it is impossible to objectively evaluate complex knowledge that increases day by day, and results depend only on specific experts. In addition, bibliographic information analysis is effective for the possibility of time series analysis and objective comparison between different fields. Additionally, several studies have shown that machine learning can be used to perform trend analysis to predict future citations with high accuracy (Sasaki et al. 2016, 2020). Many studies have systematically summarized biomass-based hydrogen production technologies using bibliometric information analysis (Vuppaladadiyam et al. 2022; Buffi et al. 2022). Ubando et al. (2022) demonstrated the utility of these technologies in a circular economy based on a review of 4096 papers on biomass-based hydrogen production (Ubando et al. 2022). Vuppaladadiyam, A.K. (2022) and colleagues highlighted the advantages and disadvantages of several production approaches based on a literature review (Vuppaladadiyam et al. 2022). Buffi et al. (2022) examined the literature on pathways for biomass-based hydrogen production and showed that some production pathways are at a sufficient technology readiness level (Buffi et al. 2022). All these previous studies focused directly on and analyzed datasets in one technical domain, "biomass-based hydrogen production". In other words, "biomass-based hydrogen production" has not been discussed from two perspectives: the hydrogen energy domain and the biomass energy domain. This means that conventional studies based on bibliometric information analysis discuss a specific technical domain from one perspective, and at the same time, the two energy domains are not discussed from different perspectives. In other words, for the mutual communities that constitute "biomass-based hydrogen production" to make effective use of each other's knowledge and lead to innovation, it is essential to make a multifaceted and relative evaluation of how "biomass-based hydrogen" is evaluated from each energy academic domain in the biomass energy domain and the hydrogen energy domain.

This study is based on the following hypotheses. "The evaluation of biomass-based hydrogen production technology may differ between the entrance and exit of the technology. There may be differences in research focus and trends between the two domain". In order to verify these hypotheses, this study conducts bibliographic information analysis using a large-scale database of academic papers. Specifically, we propose cross-domain bibliographic analysis as a multilateral approach that combines (1) clustering analysis based on citation network, (2) qualitative analysis based on central papers in the citation network of the cluster, and (3) prediction of highly cited papers using machine learning. The novelty of this method is that, unlike conventional bibliographic analysis, which analyzes a single technology domain from a single perspective, it analyzes the same technology from multiple perspectives from different research domains (the hydrogen energy domain and the biomass energy domain in this study). This approach makes it possible to clarify differences in the positioning of the technology in each research domain and knowledge gaps between domains. Cross-domain bibliographic analysis is especially effective for interdisciplinary research domain and evaluation of technologies that span multiple disciplines. It can identify differences in perceptions between different research communities and potential opportunities for collaboration, which are often overlooked in conventional single-domain analysis. This method is applicable not only to biomass-based hydrogen production technologies but also to other interdisciplinary research domains. It is expected to contribute to a comprehensive understanding of research trends and design of future research strategies.

Through this verification, we compare the evaluation and trends of communities in the domain and contribute to the understanding of "biomass-based hydrogen" technology from multiple perspectives. Specifically, by conducting structural analysis and trend prediction analysis based on the bibliometric information of scientific papers on "biomass-based hydrogen" in the hydrogen energy domain where the technology is located at its entrance, we clarify how researchers in the hydrogen energy domain are focusing on "biomass-based hydrogen" and in which direction they are going. Similarly, by conducting structural analysis and trend prediction analysis based on the bibliometric information of scientific papers on "biomass-based hydrogen" in the biomass energy domain where the technology is located at its exit, we can clarify how researchers in the biomass domain are focusing on "biomass-based hydrogen" and in which direction they are going.

Through this study, we can obtain guidelines for new technology development by integrating the knowledge of both domains, and this study is expected to contribute to the development of biomass-based hydrogen production technology. This paper has the following structure. The "Introduction" section describes the subject, ideal, current status and issues, structure of issues, idea, and purpose of this study. The "Methods" section describes the paper dataset used, the clustering analysis method, the labeling method, the high citation prediction analysis method, and the evaluation index of prediction. The "Results" section shows the results of both the hydrogen energy domain and biomass energy domain for clustering analysis and high citation prediction analysis, respectively. In the discussion, the comparison between the hydrogen energy domain and biomass energy domain is discussed based on the obtained results. Finally, as a summary, the background, purpose, results, and significance of this research are summarized again, and the subjects of this research are mentioned.

Methods

Overview

The flow of analysis in this study is shown in Fig. 1. The dataset of the hydrogen energy domain and the dataset of the biomass energy domain are extracted through bibliographic databases. For each data, duplicate documents and incomplete data are

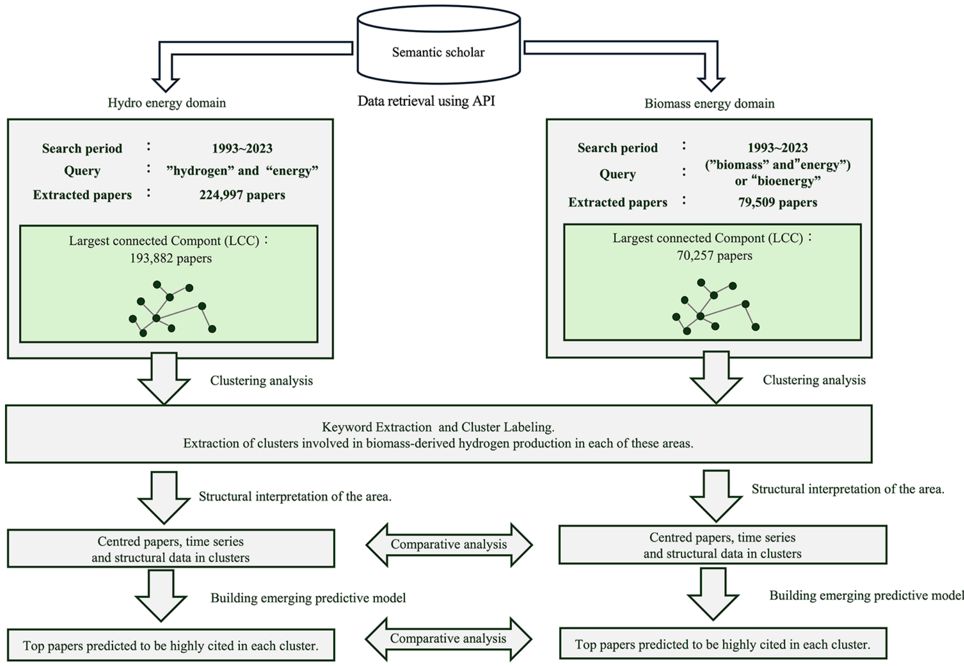

Fig. 1 Overview of analysis

removed, and the citation network is directly constructed. Based on the obtained network, clustering targeting only the largest connected component is performed. Gaps in research trends of both data sets are compared by assigning labels expressing each cluster and time series analysis. In addition, using machine learning, a model is constructed to predict papers with the possibility of obtaining many citations in the future. Gaps in research policies of both data sets are compared based on the prediction results. Details of each process are described below.

Data retrieval

In this study, we discuss the differences between biomass-based hydrogen production technologies in the hydrogen energy and biomass fields based on bibliometric information analysis of academic papers. The hydrogen energy domain data were selected from papers with "hydrogen" and "energy" in the title, abstract, and author keywords. The biomass domain data were selected from papers with "biomass" and "energy" or "bioenergy" in the same fields. All academic papers published between 1993 and 2023 were extracted using the Semantic Scholar API[1]. Direct citation-based networks were constructed from the extracted groups of papers. In each domain, the largest connected component (LCC) was extracted based on the direct citation network between papers.

[1] In addition to Semantic scholar API, Web of Science (WoS), Scopus and pubmed are known as databases for research utilizing bibliographic information analysis. However, WoS and Scopus require considerable funds and contracts to secure the data needed for this research. Pubmed is a database mainly for medicine and pharmacy, so it is not appropriate for the purpose of this research. Semantic scholar API is a database that can obtain bibliographic information through API free of charge, and is used in many bibliographic information analyses. We utilized Semantic scholar API from the overall viewpoint of availability, openness, and reproducibility. In addition, the viewpoints of the differences among databases are quite diverse, and a detailed comparison of them can be found in another study that compared 28 databases in the past (Gusenbauer et al., 2020).

Cluster analysis

Bibliometric information is able to clarify related fields by citation relationships. Using this property, clustering by direct citation network analysis is known to provide an appropriate overview of the releted fields. Modularity clustering by Newman method is used in many fields for large-scale citation networks due to its high computational efficiency and natural extraction of data specific structures without the need to determine the number of clusters in advance. The networks were divided into several clusters using a topological clustering method (Newman and Girvan 2004; Newman 2006). Topological clustering is a method based on the graph structure of the network, and modularity maximization is used here. Here, a cluster is a module in a citation network, and a group of papers is densely aggregated by dividing citation relationships using the modularity (Q -value) maximization method (Newman 2006). The modularity maximization method evaluates the network division such that the clusters are dense and sparse. The modularity maximization method extracts the partition pattern that maximizes modularity using a greedy algorithm and determines the optimal partition pattern. Q is an evaluation function of the coupling degree between clusters and within clusters and is given as follows.

$$Q = \sum_{i} \left(e_{ii} - a_i^2\right)$$

e_{ii} represents the ratio of links existing inside cluster i to the links in the entire network. a_i^2 is the expected value of links existing inside cluster i calculated from the number of links included in the entire network.

2.4 Keyword Extraction and Cluster Labeling.

The general term frequency-inverse document frequency (TFIDF) was used for the extraction of characteristic keywords in documents. In this study, the term frequency-inverse cluster frequency (TFICF) was calculated for keyword extraction on a cluster basis.

$$TFICF = tf_{i,j} \cdot \ icf_i = tf_{i,j} \cdot \ log(N/cf_i)$$

$tf_{i,j}$ represents the frequency of occurrence of the word to all words in the cluster. icf_i represents the total number of clusters, and cf_i represents the number of clusters containing the word. Since direct citation network clusters are formed by papers discussing similar themes, it is known that a certain validity can be obtained by checking the bibliographic information of multiple central papers. In this study, the titles and abstracts of the top 20 or so central papers in each cluster were comprehensively labeled. Then, they were revised through discussions with experts. In the cluster analysis, the average of the number of years since the publication year is expressed as the average age. The average age can be regarded as the period during which the discussion of each cluster is active and can be regarded as an index of the maturity of technological trends.

Emerging prediction analysis

In this paper, we defined the top 5% of all papers published in the same year in the dataset with citation growth three years after publication" as emerging papers based on previous studies (Sasaki et al. 2016, 2020).

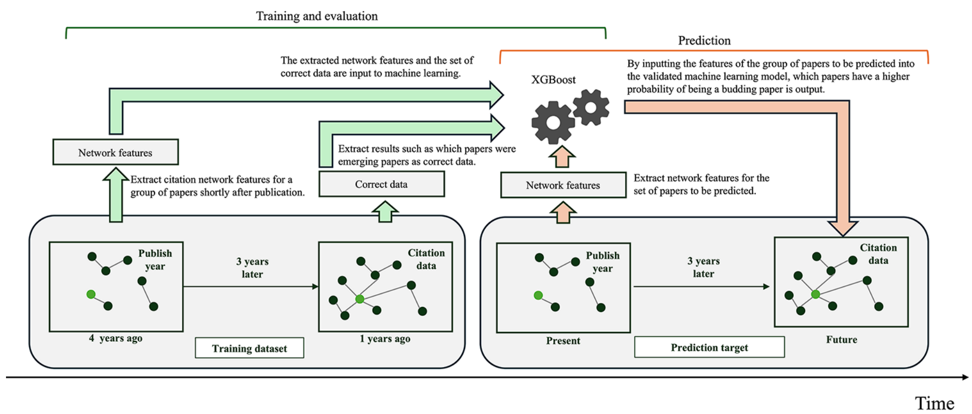

Fig. 2 Overview of the emerging prediction model

First, a prediction model was built based on historical data for which supervised data are already available as training data. Here, papers published in 2019 were used as training data. The teacher labels were based on how many citations this group of papers would have in 2022, three years later. As mentioned above, papers with times cited in the top 5% were considered positive examples, while those with times cited below 50% were considered negative examples. The performance of the model was validated by 5-fold cross-validation. 5-fold cross-validation is a method to accurately verify the generalization performance of a prediction model. It is a validation method in which the training dataset is divided into five subsets, training is performed on four subsets, and validation is performed on the remaining subset for all combinations. The performance of the model was obtained by taking the average of the five validation results, and robustness is ensured in this respect.

By applying the validated model to a set of papers published in 2022, an attempt was made to predict the number of emerging papers published three years later, in 2025. Figure 2 shows the relationship between the learning target period and the prediction target period.

The feature values used in the prediction model are classified into four classes: citation network values, graph embedding values, reference values, and others. Degree centrality, which is classified into citation network values, means the number of links each node has (Freeman 1978). Eigenvector centrality is an index that considers a node connected to a central node to be central (Bonacich 1972). The clustering coefficient represents the degree of network clustering (Watts and Strogatz 1998). PageRank is an index based on the idea that "papers cited from highly cited papers are of high importance." (Brin and Page 1998). The Hub/Authority score is based on the Hypertext Induced Topic Selection (HITS) algorithm (Guimerà and Amaral 2005). The hub score is an index indicating the degree of linkage to a good authority. The authority score is an index indicating the degree of linkage from a good hub. The hub score and authority score are cross-referenced.

Graph embedding values are distributed representations of networks. The DeepWalk norm is a distributed representation based on the skip-gram model in which a random walk is performed at each node as a starting point and the obtained node sequence is used as an input (Perozzi et al. 2014). The Node2vec norm is not a random walk but rather obtains a distributed representation by sampling that prioritizes neighboring

Table 1 Feature values of the emerging prediction

Category of Feature values	Feature values	Description	References
Citation network values	Degree centrality	The number of links each node has. Higher values mean that the node is more central.	(Freeman 1978)
	Eigenvector centrality	An index that considers a node connected to a central node to be central. It assigns relative scores to all nodes in the network, based on the concept that connections to high-scoring nodes contribute more to the score of the node in question than equal connections to low-scoring nodes.	(Bonacich 1972)
	Clustering coefficient	The degree of network clustering. An index how close its neighbours are to being a clique (complete graph).	(Watts and Strogatz 1998)
	PageRank	An index based on the idea that "papers cited from highly cited papers are of high importance."	(Brin and Page 1998)
	Hub/Authority score	The Hub/Authority score is based on the Hypertext Induced Topic Selection (HITS) algorithm. The hub score is an index indicating the degree of linkage to a good authority. The authority score is an index indicating the degree of linkage from a good hub. The hub score and authority score are cross-referenced.	(Guimerà and Amaral 2005)
Graph embedding values	DeepWalk norm	A distributed representation based on the skip-gram model in which a random walk is performed at each node as a starting point and the obtained node sequence is used as an input	(Perozzi et al. 2014)
	node2vec norm	A distributed representation by sampling that prioritizes neighboring nodes and distant nodes based on a fixed transition probability.	(Grover and Leskovec,2016)
	LINE norm	A distributed representation based on the first-order proximity in which nodes are connected and the second-order proximity in which nodes share the same node	(Tang, 2015)

nodes and distant nodes based on a fixed transition probability (A. Grover and J. Leskovec 2016). The LINE norm is a distributed representation based on the first-order proximity in which nodes are connected and the second-order proximity in which nodes share the same node. Compared with the DeepWalk norm, the LINE norm assumes similarity only in neighboring nodes (Tang, 2015). Bibliometric values are calculated by calculating the above-mentioned values for the references cited by the paper concerned, and then a statistically representative value is calculated. The feature values shown in Table 1 were used (Sasaki, 2020). In addition to the features in Table 1, further features were calculated for all the references of each article, for which the features in Table 1 were calculated and the statistical representative values (Max, Min, Sum, Average) of the article in question were calculated. These features are calculated for all the papers included in the largest connected component and used as explanatory variables. As a result, it is possible to predict whether a certain paper will receive a high number of citations. XGBoost (eXtreem Gradient Boost) is used as a predictor, and the probability for each paper is output as the prediction result. It is effective in the following points: the risk of over-learning can be reduced because it includes a regularization term; the transparency of the model is high because the importance of the feature quantity can be evaluated; and the results can be obtained with relatively high accuracy and efficient computing resources.

Evaluation of the prediction model

In this study, 'emerging papers' was defined as a paper that is in the top 5% of citations three years after publication. A paper that is predicted to be highly cited by the model and actually becomes highly cited is counted as a true positive, a paper that is predicted to be highly cited but actually does not become highly cited is counted as a false positive, and a paper that is predicted not to be highly cited but actually becomes highly cited is counted as a false negative.

We also used $F1_{measure}$, which is defined as $Precision$, $Recall$ and their harmonic mean. $Precision$ is the ratio of the number of papers that actually appeared to the number of papers that were predicted to appear. $Recall$ is the ratio of the number of papers predicted to appear to the number of papers actually appearing. Since $Precision$ and $Recall$ are mutual trade-offs, we calculate $F1_{measure}$, which is the harmonic mean. We chose these measures because both accurately identifying important research (Precision) and not missing important research (Recall) are important in predicting future research trends in biomass-based hydrogen production technology. F1_measure provides a balance between these two measures, making it suitable for evaluating the overall performance of a model. Accuracy is available to assess the predictive models for the two classifications. This indicator shows how accurately a forecast is made and is the ratio of the sum of true positives and true negatives in all forecast results. However, Accuracy alone cannot adequately assess the proportion of false positives and false negatives. The definitions are as follows.

Precision is the fraction of positive data that are actually positive.

$$Precision = \frac{True\ Positive}{(True\ Positive + False\ Positive)}$$

Recall is the fraction of predicted positive data that are actually positive.

$$Recall = \frac{True\ Positive}{(True\ Positive + False\ Negative)}$$

The F1_measure is the harmonic mean of the precision and recall.

$$F1_{measure} = \frac{2Precision \cdot\ Recall}{(Precision +\ Recall)}$$

Results

Cluster analysis results

Hydrogen energy domain

As a dataset on the hydrogen energy domain, 224,997 academic papers were extracted. These papers were clustered by citation network analysis, and 121,436 academic papers were extracted, excluding clusters that were not related to hydrogen energy, such as intermolecular bonds. The list of the top 10 clusters of these extracted papers is shown in Table 2. 'Average age' represents the number of years elapsed between the average publication year of the papers in each cluster and 2023.

The cluster labels in Table 2 are named for each cluster based on the extracted keywords and the papers that are at the center of the citation networks of each cluster. The correspondence of each cluster with the extracted keywords is shown. Clusters 1, 2, and 6 are related to hydrogen generation technology by photocatalysis and water electrolysis and to catalysts such as water electrolysis. Keywords related to catalysts, such as "photocatalytic," "electrocatalyst," "pt," and "catalyst", were extracted. Cluster 3 is a cluster

Table 2 Top 10 clusters in the Hydrogen Energy Domain

No.	Cluster label	Number of papers	Number of papers Ratio (%)	Average age	Keywords
1	Photocatalyst	18,759	15.4	4.80	photocatalytic, photocatalyst, water, light, tio2, splitting, solar, evolution, visible, production
2	Water electrolysis	17,234	14.2	3.31	evolution, electrocatalyst, reaction, catalyst, metal, water, oer, splitting, efficient, activity
3	Power to gas	16,442	13.5	5.22	fuel, cell, power, storage, production, membrane, renewable, based, vehicle, cost
4	Thermochemical conversion and reforming of biomass	12,760	10.5	6.71	catalyst, reforming, production, gasification, steam, biomass, methane, co2, process, fuel
5	High-Capacity hydrogen storage materials	8834	7.3	8.24	adsorption, graphene, storage, h2, carbon, metal, atom, surface, molecule, nanotube
6	Catalytic reactions	8230	6.8	7.88	surface, pt, reaction, catalyst, adsorption, pd, co2, metal, reduction, electrochemical
7	Microbial decomposition of biomass	8179	6.7	7.03	production, microbial, h2, biohydrogen, anaerobic, fermentation, cell, hydrogenase, methane, waste
8	Hydrogen adsorption alloys /Metal borohydrides	7520	6.2	8.40	storage, mgh2, hydride, mg, alloy, metal, property, desorption, material, temperature
9	Internal combustion engine	5487	4.5	6.04	engine, combustion, fuel, flame, ignition, sensor, air, h2, emission, effect
10	Catalyst of Metal borohydrides/LOHC/formic acid	4695	3.9	6.27	catalyst, borane, dehydrogenation, reaction, catalytic, generation, ammonium, borohydride, nanoparticle, metal
	Total of all related clusters	121,436	100.0	5.97	

in which the economic efficiency of hydrogen generation and utilization by renewable energy is the main consideration. Keywords such as "fuel," "cell," "storage," "renewable," and "cost" were extracted. Cluster 4 is related to synthesis gas generation by thermochemical conversion and reforming of biomass. Keywords such as "reforming," "gasification," "steam," and "biomass" were extracted. Cluster 7 is related to hydrogen generation by decomposition and fermentation of biomass by the metabolic activity of microorganisms. Keywords such as "microbial", "biohydrogen", and "fermentation" were extracted. Clusters 5, 8, and 10 are related to hydrogen transportation and storage, such as hydrogen adsorption alloys. Keywords such as "storage," "adsorption," "mgh2," and "borane" were extracted. Cluster 9 is related to hydrogen engines using hydrogen for internal combustion engines. Keywords such as "engine" and "combustion" were extracted. Finally, looking at the whole cluster in the hydrogen energy domain, each cluster corresponds to one or more of three processes—hydrogen production, storage, transportation, and utilization—and the whole cluster represents the whole supply chain.

Next, clusters related to biological and thermochemical methods of producing hydrogen using biomass in the hydrogen energy domain are examined in detail. In the hydrogen energy domain, clusters 4 and 7 are biomass-based hydrogen production technology or its neighboring technology domain. Figure 3 shows the trend of the number of papers by year of publication related to cluster 4 (Thermochemical conversion and reforming of biomass). The number of papers started to increase from the early 2000s. Similarly, Fig. 4 shows the trend of the number of papers by year of publication related to cluster 7 (Microbial decomposition of biomass). The number of papers started to increase from

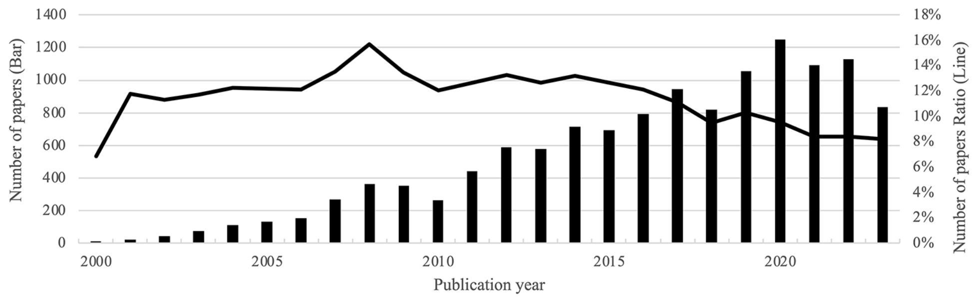

Fig. 3 Trends in the number of papers in Cluster 4 in the hydrogen energy domain and its share in domain

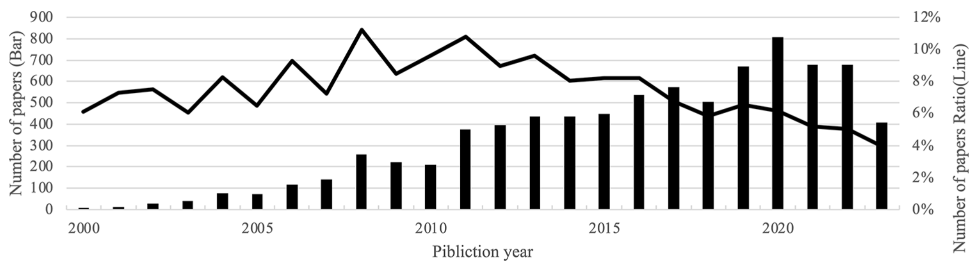

Fig. 4 Trends in the number of papers in Cluster 7 in the hydrogen energy domain and its share in domain

the early 2000s, and the increase began to fade from 2020. For both clusters, the percentage of the total number of papers in the hydrogen energy domain has been decreasing since the early 2010s.

Biomass energy domain

Next, 79,509 academic papers were extracted as a dataset on the biomass energy domain. These papers were clustered by citation network analysis, and 64,811 academic papers were extracted by excluding clusters that were not related to biomass energy, such as technological trends in cell metabolism. The list of the top 10 clusters of these extracted papers is shown in Table 3. 'Average age' represents the number of years elapsed between the average publication year of the papers in each cluster and 2023.

The cluster labels in Table 3 are named for each cluster based on the extracted keywords and the papers that are at the center of the citation networks of each cluster. The correspondence of each cluster with the extracted keywords is shown below. Cluster 1 is related to the fermentation process of biomass and its pretreatment technology. The keywords "pretreatment," "anaerobic," "digestion," and "fermentation" were extracted. Cluster 2 is related to the economics of the supply chain from the production of raw materials to the processing of biomass. The keywords "production," "fuel," "cost," and "supply" were extracted. Cluster 3 is a cluster related to biomass gasification technology by thermochemical conversion, such as synthesis gas production. The keywords "gasification," "hydrogen," "steam," and "gasifier" were extracted. Clusters 4 and 6 are related to biomass utilization using perennial grasses and microalgae. The keywords "switchgrass" and "microalgae" were extracted. Cluster 5 is related to the rapid pyrolysis process, which is a bio-oil production method. The keywords "kinetic" and "oil" were extracted. Clusters 7, 8, and 9 are related to biomass-derived fuels and materials produced from biomass. The keywords "torrefaction," "pellet," "carbon," "material," and "hmf" were extracted. Cluster

Table 3 Top 10 clusters in the Biomass Energy Domain

No.	Cluster label	Number of papers	Number of papers Ratio (%)	Average age	Keywords
1	Fermentation and pretreatment process of biomass	8430	13.0	5.47	production, pretreatment, waste, anaerobic, digestion, process, lignin, lignocellulosic, fermentation, methane
2	Biomass supply chain	8429	13.0	7.08	production, renewable, fuel, cost, forest, supply, economic, study, based, power
3	Thermochemical conversion of biomass	7176	11.1	5.79	gasification, hydrogen, production, fuel, steam, waste, process, power, catalyst, gasifier
4	Perennial grass biomass	7015	10.8	7.34	crop, soil, production, switchgrass, yield, land, plant, ha, potential, biofuel
5	Rapid pyrolysis	6301	9.7	5.14	kinetic, oil, bio, waste, temperature, product, combustion, reaction, fuel, coal
6	Microalgae	6205	9.6	5.28	microalgae, production, lipid, algal, microalgal, biodiesel, biofuel, algae, wastewater, oil
7	Solid fuels	5931	9.2	5.27	torrefaction, pellet, fuel, combustion, ash, waste, biochar, temperature, wood, process
8	Biomass-based carbon materials	5010	7.7	3.02	carbon, supercapacitor, material, electrode, derived, high, performance, doped, capacitance, electrochemical
9	HMF	2935	4.5	4.39	catalyst, reaction, acid, hmf, catalytic, production, conversion, chemical, hydrogen, furfural
10	Environmental impacts of aboveground biomass utilization	2585	4.0	6.16	forest, carbon, emission, climate, wood, change, co2, land, impact, use
	Total of all related clusters	64,811	100.0	5.71	

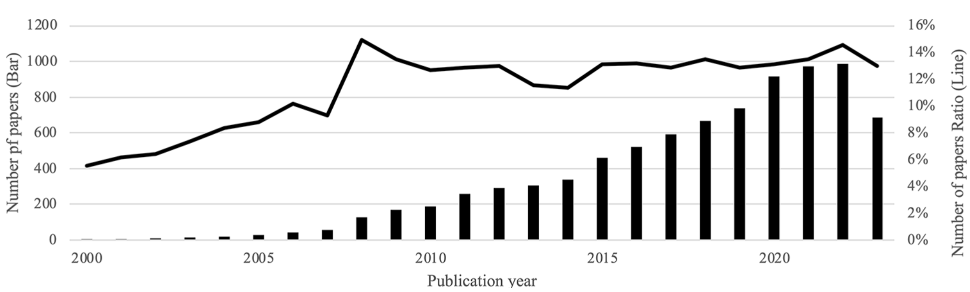

Fig. 5 Trends in the number of papers in Cluster 1 in the biomass energy domain and its share in domain

10 is related to the environmental impact of aboveground biomass utilization. The keywords “forest,” “climate,” “co2,” and “impact” were extracted. Each cluster corresponds to one or more biomass types, processing processes, or products obtained, and the whole cluster represents the entire supply chain of biomass.

Next, the clusters related to biological and thermochemical methods of producing hydrogen using biomass in the biomass energy domain are examined in detail. In the biomass energy domain, both clusters 1 and 3 are biomass-based hydrogen production technology or its neighboring technology domain. Figure 5 shows the trend of the number of papers for Cluster 1 (Fermentation and pretreatment process of biomass) by year of publication. The number of papers started to increase in the late 2000s and is still increasing. Similarly, Fig. 6 shows the trend of the number of papers for Cluster 3

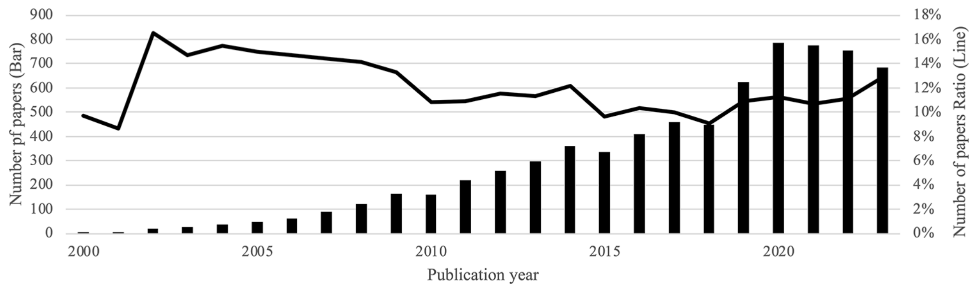

Fig. 6 Trends in the number of papers in Cluster 3 in the biomass energy domain and its share in domain

(Thermochemical conversion of biomass) by year of publication. The number of papers started to increase in the late 2000s and has maintained the number of papers since 2020. Both clusters have maintained their presence in recent years since 2018 as a percentage of the total number of papers in the biomass energy domain.

Results of the analysis of central papers in the citation network of the cluster

Next, check central papers in the citation network of the cluster. In the hydrogen energy domain, Clusters 4 and 7 are biomass-based hydrogen production technology or its neighboring technology domain. On the other hand, in the biomass energy domain, Clusters 1 and 3 are both biomass-based hydrogen production technology or its neighboring technology domain. In these clusters, the discussion content of the papers with high citation network centrality can be confirmed to identify the center of discussion in each cluster.

Hydrogen energy domain

In the hydrogen energy domain, the central papers in the citation network of Cluster 4 and Cluster 7 related to biomass-based hydrogen production technology or its neighboring technology domain were extracted. Table 4 shows the top 10 most common papers in the citation network of Cluster 4. The number of citations in the cluster in Table 4 can be regarded as the number of citations from papers that are more related to the relevant paper.

First, the central papers in the citation network of Cluster 4 (Table 4) are discussed as follows. Ni et al. (2007), ranking no. 1 in the cluster, introduced a method to produce hydrogen by reforming bioethanol (Ni et al. 2007). They described that a catalyst using rhodium and nickel is effective in steam reforming and that bioethanol reforming is promising for future fuel cell applications even though it is still in the early stage of research and development. Cortright et al. (2002), ranked no. 2 in the cluster, reported that glucose is converted to hydrogen and alkane, and ethylene glycol and methanol are converted to hydrogen and carbon dioxide by aqueous phase reforming (APR) of biomass-based sugars and alcohols using platinum-based catalysts (Cortright et al. 2002). Haryanto et al. (2005), ranked no. 3 in the cluster, compared hydrogen production by various catalysts in steam reforming of ethanol (Haryanto et al. 2005). In addition, Davda et al. (2005) ranked fourth in the cluster and discussed the effects of catalysts with high hydrogen yields, types of catalysts, and process conditions on hydrogen and alkane production selectivity in aqueous-phase reforming of biomass-based sugars and alcohols (Davda et al. 2005). Kruse (2008), who ranked no. 5 in the cluster, clarified the main reaction pathways and reaction conditions involved in the supercritical gasification

Table 4 Top 10 central papers of cluster 4 in the hydrogen energy domain

Rank	Title	Journals	Times cited in the Cluster	References
1	A review on reforming bioethanol for hydrogen production	International Journal of Hydrogen Energy	282	Ni et al. (2007)
2	Hydrogen from catalytic reforming of biomass-derived hydrocarbons in liquid water	Nature	274	Cortright et al. (2002)
3	Current status of hydrogen production techniques by steam reforming of ethanol : A review	Energy & Fuels	273	Haryanto et al. (2005)
4	A review of catalytic issues and process conditions for renewable hydrogen and alkanes by aqueous-phase reforming of oxygenated hydrocarbons over supported metal catalysts	Applied Catalysis B-environmental	173	Davda et al. (2005)
5	Supercritical water gasification	Biofuels	150	Kruse (2008)
6	Supercritical water gasification of biomass for hydrogen production	International Journal of Hydrogen Energy	150	Reddy et al. (2014)
7	Recent advances on membranes and membrane reactors for hydrogen production	Chemical Engineering Science	144	Gallucci et al. (2013)
8	Review of catalytic supercritical water gasification for hydrogen production from biomass	Renewable & Sustainable Energy Reviews	140	Guo et al. (2010a)
9	Biomass-based hydrogen production: A review and analysis	International Journal of Hydrogen Energy	140	Kalinci et al. (2009)
10	Hydrogen from biomass – Present scenario and future prospects	International Journal of Hydrogen Energy	137	Balat and Kırtay (2010)

of biomass on which they depend by using model compounds (Kruse 2008). Supercritical water gasification technology has the advantage that biomass does not need to be dried and can be gasified. Reddy et al. (2014), ranking no. 6 in the cluster, focused on biomass degradation pathways in supercritical water gasification using biomass rich in cellulose, hemicellulose, and lignin. The authors discussed reactor design and technical issues related to maximizing hydrogen production (Reddy et al. 2014). Although the paper is relatively young, it received a high number of citations in the cluster. Gallucci et al. (2013), ranked no. 7 in the cluster, reviewed recent progress in membrane and membrane reactors for selective hydrogen extraction from synthesis gas and discussed the application of membrane reactors with various raw materials (Gallucci et al. 2013). Guo et al. (2010a), ranked no. 8 in the cluster, reviewed recent research trends in supercritical gasification technologies and noted that hydrogen production by supercritical gasification of biomass is promising as an alternative to fossil fuels but that it is costly to meet high-temperature and high-pressure reaction conditions (Guo et al. 2010a). Kalinci et al. (2009), ranked no. 9 in the cluster, compared overall technologies for biomass conversion to hydrogen from an exergy point of view and evaluated the performance of hydrogen production by steam gasification using a downdraft gasifier as a case study (Kalinci et al. 2009). Balat and Kırtay (2010), ranked no. 10 in the cluster, mentioned that current hydrogen production methods are based on reforming and gasification with fossil fuels and argued that they are important for future hydrogen production in biomass-based sustainable energy systems (Balat and Kırtay 2010).

In the 2000s, the discussion focused on catalysts for steam reforming of alcohols and sugars (Ni et al. 2007; Cortright et al. 2002; Haryanto et al. 2005; Davda et al. 2005). In the late 2000s and early 2010s, the discussion focused on supercritical gasification technology (Kruse 2008; Guo et al. 2010; Reddy et al. 2014). As shown in Fig. 3, these

Table 5 Top 10 central papers of Cluster 7 in the hydrogen energy domain

Rank	Title	Journals	Times cited in the Cluster	References
1	Biohydrogen production from waste materials	Enzyme and Microbial Technology	476	Kapdan and Kargi (2006)
2	Biohydrogen production: prospects and limitations to practical application	International Journal of Hydrogen Energy	462	Levin et al. (2004)
3	FACTORS INFLUENCING FERMENTATIVE HYDROGEN PRODUCTION: A REVIEW	International Journal of Hydrogen Energy	296	Wang and Wan (2009)
4	Continuous dark fermentative hydrogen production by mesophilic microflora: principles and progress	International Journal of Hydrogen Energy	259	Hawkes et al. (2007)
5	Microbial electrolysis cells for high yield hydrogen gas production from organic matter.	Environmental science & technology	258	Logan et al. (2008)
6	Biological hydrogen production: effects of pH and intermediate products	International Journal of Hydrogen Energy	253	Khanal et al. (2004)
7	A review on dark fermentative biohydrogen production from organic biomass: Process parameters and use of byproducts	Applied Energy	253	Ghimire et al. (2015)
8	Hydrogen production from agricultural waste by dark fermentation: A review	International Journal of Hydrogen Energy	250	Guo et al. (2010b)
9	Electrochemically assisted microbial production of hydrogen from acetate.	Environmental science & technology	245	Liu et al. (2005)
10	Hydrogen production in a single chamber microbial electrolysis cell lacking a membrane.	Environmental science & technology	236	Call and Logan (2008)

researches were conducted during a period when the number of publications was increasing, which formed the direction of the discussion in Cluster 4.

The central papers in the citation network of Cluster 7 (Table 5) are as follows. Kapdan and Kargi (2006), ranked 1 in this cluster, provided an overview of the overall biological methods for producing hydrogen from waste and presented recent developments regarding the decomposition of water by algae and the dark fermentation and photofermentation of organic matter (Kapdan and Kargi 2006). Levin et al. (2004) ranked number 2 in this cluster and examined the efficiency of various methods for producing hydrogen through the biological conversion of biomass to operate proton exchange membrane fuel cells (Levin et al. 2004). Wang and Wan (2009) ranked 3rd in this cluster; described the major influences on hydrogen production by fermentation of biomass, such as microorganisms, bacteria, reactor type, temperature, and pH; and outlined recent research results about how each influences hydrogen production (Wang and Wan 2009). Hawkes et al. (2007), ranked 4th in this cluster, suggested the commercial potential of dark fermentation of biomass using specific microorganisms and proposed the usefulness of a two-step fermentation process (Hawkes et al. 2007). Logan et al. (2008), ranked 5th in this cluster, described the recent increase in the efficiency of hydrogen production by microbial electrolysis cells and suggested that microbial electrolysis cells may be useful as a method for sustainable renewable energy production and wastewater treatment (Logan et al. 2008). Khanal et al. (2004), ranked number 6 in this cluster, investigated the effects of pH and intermediate products on hydrogen production by fermentation of sucralose and starch (Khanal et al. 2004). Ghimire et al. (2015), ranked 7th in this cluster, reviewed recent research results focusing on dark fermentation as an important technology for hydrogen production from crop residues, livestock waste, and food waste. Although the paper is relatively young, it received a high number of citations

Table 6 Top 10 central papers of Cluster 1 in the biomass energy domain

Rank	Title	Journals	Times cited in the Cluster	References
1	Pretreatments to enhance the digestibility of lignocellulosic biomass.	Bioresource technology	434	Hendriks and Zeeman (2009)
2	Hydrolysis of lignocellulosic materials for ethanol production: a review.	Bioresource technology	433	Sun and Cheng (2002)
3	Biomass Recalcitrance: Engineering Plants and Enzymes for Biofuels Production	Science	337	Himmel et al. (2007)
4	Pretreatment of lignocellulosic biomass for enhanced biogas production.	Progress in Energy and Combustion Science	269	Zheng et al. (2014)
5	Biogas production: current state and perspectives	Applied Microbiology and Biotechnology	246	Weiland (2010)
6	Biomass pretreatment: fundamentals toward application.	Biotechnology advances	233	Agbor et al. (2011)
7	Review on research achievements of biogas from anaerobic digestion	Renewable and Sustainable Energy Reviews	165	Mao et al. (2015)
8	The biorefinery concept: Using biomass instead of oil for producing energy and chemicals	Energy Conversion and Management	158	Cherubini (2010)
9	Lignin Valorization: Improving Lignin Processing in the Biorefinery	Science	152	Ragauskas et al. (2014)
10	Production of first and second generation biofuels: A comprehensive review	Renewable and Sustainable Energy Reviews	146	Naik et al. (2010)

in the cluster (Ghimire et al. 2015). Liu et al. (2005), ranked 9th in this cluster, proposed a method for efficient hydrogen production through a combined system of conventional fermentation and hydrogen production using biomass-based acetic acid in a microbial electrolysis cell (Liu et al. 2005). Call and Logan (2008), ranked number 10 in this cluster, suggested the use of a simple design in a microbial electrolysis cell for hydrogen production, which can achieve a high hydrogen yield in a single-chamber microbial electrolysis cell without the previously required membrane between electrodes (Call and Logan 2008).

Hydrogen production from biomass such as waste by dark fermentation (I. Kapdan and F. Kargı 2006; Levin et al. 2004; Jianlong Wang and W. Wan 2009; Hawkes et al. 2007; Khanal et al. 2004; Ghimire et al. 2015) has been at the center of discussion since the 2000s, and hydrogen production by microbial electrolysis cells (Logan et al. 2008; Liu et al. (2005; Call and Logan (2008) has been at the center of discussion since the late 2000s. As shown in Fig. 4, these researches were conducted on during a period when the number of publications was increasing, which formed the direction of the discussion in Cluster 7.

Biomass energy domain

In the biomass energy domain, the central papers in the citation network of Cluster 1 and Cluster 3 related to biomass-based hydrogen production technology or its neighboring technology domain were extracted. Table 6 shows the top 10 most common papers in the citation network of Cluster 1. The number of citations in the cluster in Table 1 can be regarded as the number of citations from papers that are more related to the relevant paper.

First, the central papers in the citation network of Cluster 1 (Table 6) are discussed as follows. Hendriks and Zeeman (2009) ranked number 1 in this cluster and noted that lignocellulose is rarely used for biogas and ethanol production due to its structural characteristics and lignin content, and pretreatment before fermentation is important for improving digestibility (Hendriks and Zeeman 2009). The authors also compared the effects of various pretreatment technologies. Sun and Cheng (2002), ranked 2nd in this cluster, reviewed methods for efficiently producing ethanol from lignocellulose. Pretreatment with lignocellulose greatly increases the efficiency of cellulose hydrolysis, and simultaneous saccharification and fermentation can effectively increase the ethanol yield (Sun and Cheng 2002). Himmel et al. (2007), ranked 3rd in this cluster, mentioned that lignocellulose is difficult to decompose, which increases the cost of converting lignocellulose to biofuels and other fuels and highlights the challenges of overcoming the natural defenses of plants (Himmel et al. 2007). Zheng et al. (2014), ranked 4th in this cluster, systematically compared pretreatment methods for the anaerobic digestion of lignocellulose for biogas production and described the current status and future prospects of pretreatment technologies (Zheng et al. 2014). Weiland (2010) ranked number 5 in this cluster and reviewed the current status and prospects of biogas production, including biogas production methods and biogas utilization methods (engine-based power plants, gas turbines and fuel cells) (Weiland 2010). Agbor et al. (2011) ranked number 6 in this cluster, discussed the importance of pretreatment to breakdown the complex structure of biomass for the production of biofuels such as bioethanol and examined the advantages and disadvantages of various pretreatment technologies and their potential for industrial use (Agbor et al. 2011). Mao et al. (2015) ranked number 7 in this cluster, focused on anaerobic digestion technology for biogas production, and discussed the effects of biomass feedstock, temperature, and other factors on conversion efficiency, reaction accelerators, and reactors (Mao et al. 2015). They argue that the probability of practical theoretical and technical research based on pilot-scale experiments is important, and further stability and efficiency improvements are necessary for commercialization. Although this paper is relatively young, it has a high number of citations in the cluster. Cherubini (2010), ranked 8th in this cluster, emphasized the importance of biorefineries as alternative solutions to fossil fuel depletion and comprehensively discussed the current status of biofuel production, feedstocks, and conversion technologies (Cherubini 2010). Ragauskas et al. (2014), ranked 9th in this cluster, reviewed recent developments in the field focusing on the efficient use of lignin, which is separated and produced during the conversion of lignocellulose into biofuels and other products (Ragauskas et al. 2014). Their review ranged from genetic engineering approaches to tailoring lignin properties to chemical processing techniques to extract lignin in a biorefinery and convert it into high-performance plastics and chemicals. Naik et al. (2010), ranked number 10 in this cluster, reviewed cost-effective technologies and processes for processing second-generation biomass, noting that first-generation biomass-based biofuels are problematic because they compete with food (Naik et al. 2010).

From the 2000s to the first half of the 2010s, the discussion on lignocellulose properties and pretreatment technologies in the fermentation process continued to take a central position (Hendriks and Zeeman 2009; Sun and Cheng 2002; Himmel et al. 2007; Agbor et al. 2011; Naik et al. 2010; Zheng et al. 2014). There is also a discussion on anaerobic digestion for biogas production, which is relatively new among the top 10 in

Table 7 Top 10 central papers of cluster 3 in the biomass energy domain

Rank	Title	Journals	Times cited in the Cluster	References
1	Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials	Energy Conversion and Management	285	Zainal et al. (2001)
2	Review and analysis of biomass gasification models	Renewable & Sustainable Energy Reviews	244	Puig-Arnavat et al. (2010)
3	Energy production from biomass (Part 3): Gasification technologies.	Bioresource technology	236	McKendry (2002)
4	Process and technological aspects of municipal solid waste gasification. A review.	Waste management	208	Arena (2012)
5	Biomass gasification in a circulating fluidized bed	Biomass & Bioenergy	202	Li et al. (2004)
6	Hydrogen from catalytic reforming of biomass-derived hydrocarbons in liquid water	Nature	176	Cortright et al. (2002)
7	The study of reactions influencing the biomass steam gasification process	Fuel	174	Franco et al. (2003)
8	The reduction and control technology of tar during biomass gasification/pyrolysis: An overview	Renewable & Sustainable Energy Reviews	172	Han and Kim (2008)
9	Thermodynamic Equilibrium Model and Second Law Analysis of a Downdraft Waste Gasifier	Energy	172	Jarungthammachote and Dutta (2007)
10	Recent advances in the development of biomass gasification technology: A comprehensive review	Renewable & Sustainable Energy Reviews	166	Sansaniwal et al. (2017)

central papers in the citation network of the cluster (Weiland 2010; Mao et al. 2015). As shown in Fig. 5, the discussion on lignocellulose properties and pretreatment technologies in the fermentation process was seen from the early stage of the increasing number of papers, and has continued to be the focus of the discussion in Cluster 1.

The central papers in the citation network of Cluster 3 (Table 7) are discussed as follows. Zainal et al. (2001) ranked number 1 in this cluster and used equilibrium modeling to predict the gasification process of a biomass downdraft gasifier to investigate how the water content and temperature in the biomass affect the composition and energy content of the syngas (Zainal et al. 2001). Puig-Arnavat et al. (2010), ranked number 2 in this cluster, examined several modeling approaches (thermodynamic equilibrium models, kinetic models, and artificial neural network models) for the biomass gasification process and compared them, explaining their advantages and disadvantages (Puig-Arnavat et al. 2010). McKendry (2002), ranked 3rd in this cluster, argued for the usefulness of a technology for generating electricity with a gas engine fueled by biomass syngas (McKendry 2002). Arena (2012), ranked 4th in this cluster, evaluated the feasibility and environmental impact of gasifying municipal solid waste by examining the gasification process, gasifier, and plant configuration, suggesting that gasification is an effective means of waste disposal and a promising alternative to reduce landfill disposal (Arena 2012). Li et al. (2004), ranked 5th in this cluster, reported the experimental results of a pilot-scale circulating fluidized bed gasifier for biomass gasification and developed an equilibrium model for the gasifier (Li et al. 2004). Cortright et al. (2002), ranked number 6 in this cluster, reported that biomass-based saccharides and alcohols were converted from glucose to hydrogen and alkane and from ethylene glycol and methanol to hydrogen and carbon dioxide by aqueous-phase reforming using platinum-based catalysts. The same paper as the central paper in the citation network of Cluster 4 in the hydrogen energy domain is extracted (Cortright et al. 2002). Franco et al. (2003), ranked 7th in this cluster, investigated the effect of biomass type on the steam gasification process at various temperatures and weight ratios (Franco et al. 2003). Han and Kim (2008), ranked 8th in this cluster, mentioned the problem that the tar generated in the gas or furnace during gasification and pyrolysis of biomass hinders the utilization efficiency of biomass and introduced methods to reduce or remove tar (Han and Kim 2008). Jarungthammachote and Dutta (2007), ranked number 9 in this cluster, developed a thermodynamic equilibrium model of a downdraft gasifier for gasifying municipal solid waste and explained how the amount of water contained in municipal solid waste affects the type, quantity, and efficiency of synthesis gas (Jarungthammachote and Dutta 2007). Sansaniwal et al. (2017), ranked number 10 in this cluster, highlighted recent advances in biomass gasification technology and challenges in its spread and provided recommendations for policymakers to spread gasification technology (Sansaniwal et al. 2017). Although this paper is relatively young, it has a high number of citations in the cluster.

The gasification process of biomass and its modeling have been widely discussed in the 2000s (Zainal et al. 2001; Puig Arnavat et al. 2010; Li et al. 2004; Jarungthammachote and Dutta 2007; Franco et al. 2003). In addition, the environmental impact of gasification and its practicality have been discussed, and some of the new papers are among the top 10 papers in central papers in the citation network of the cluster (Arena 2012; Sansaniwal et al. 2017). As shown in Fig. 6, the discussion on the gasification process of biomass and its modeling has been seen from the initial stage of the increasing trend of the number of papers, and has continued to be the center of the discussion in Cluster 3.

Emerging prediction results

Emerging prediction in the hydrogen energy domain

First, we see the results of emerging predictions in the hydrogen energy domain. Table 8 shows the performance of the emerging prediction model in the hydrogen energy domain. A precision of 0.92 means that 92% of the papers were predicted to be emerging papers by the model. On the other hand, a recall of 0.78 means that the model was able to predict 78% of all possible emerging papers in the dataset. A model with higher precision than Recall was constructed, although the difference was small. This result can be said to be a cautious model in which a paper that is concluded to be emerging becomes an emerging paper with a high probability, although it allows for spillage. In the context of limited R & D resources, a cautious model like the one obtained in this study may contribute to decision making. On the other hand, a model with relatively high Recall may be more appropriate when individual researchers want to search widely based on their own interests and curiosities, and a model that recommends papers with even a slight possibility at random. Since this analysis aimed at the former, we think that we obtained good results.

The top three features contributed to the prediction model for the hydrogen energy domain were as follows: Sum of degree of references (0.215), Sum of eigenvector

Table 8 Performance of the emerging prediction model in the hydrogen energy domain

Precision	Recall	F1_measure
0.92	0.78	0.84

centrality of references (0.097) and Degree centrality (0.093). It can be seen that not only the total number of references cited, but also the fact that many of the references that should be cited are cited, contributes to the description becoming an emerging paper.

The number of emerging papers for each cluster in the hydrogen energy domain is shown in Table 9. The numbers of emerging papers in cluster 1 (photocatalysis) and cluster 2 (water electrolysis) are very large. Focusing on Clusters 4 (thermochemical conversion and reforming of biomass) and 7 (microbial decomposition of biomass) for technology trends in biomass-based hydrogen production technology or its neighboring technology domain, the numbers of emerging papers are smaller than those of the other Clusters (1 and 2) for hydrogen production technology.

Additionally, by checking the top 10 probabilities of the emerging papers in Cluster 4 (Table 10), we can see how the discussion of the emerging papers in Cluster 4 unfolds.

Table 9 The number of emerging papers in the hydrogen energy domain

No.	Cluster label	Number of emerging papers
1	Photocatalyst	486
2	Water electrolysis	1099
3	Power to gas	124
4	Thermochemical conversion and reforming of biomass	45
5	High-Capacity hydrogen storage materials	71
6	Catalytic reactions	171
7	Microbial decomposition of biomass	31
8	Hydrogen adsorption alloys/Metal borohydrides	56
9	Internal combustion engine	4
10	Catalyst of Metal borohydrides/LOHC/formic acid	89
	Total of all related clusters	2340

Table 10 Emerging papers in cluster 4 in the hydrogen energy domain (top 10)

Probability	Title	Journals	References
0.9998	Plasma pyrolysis for a sustainable hydrogen economy	Nature Reviews Materials	Chen et al. (2022)
0.9998	A tailored multifunctional catalyst for ultraefficient styrene production under a cyclic redox scheme	Nature Communications	Zhu et al. (2021)
0.9998	A two-step process for energy-efficient conversion of food waste via supercritical water gasification: Process design, products analysis, and electricity evaluation.	The Science of the total environment	Liu et al. (2021a
0.9998	An autonomous fuel cell: Methanol and dimethyl ether steam reforming direct fed to fuel cell	International Journal of Hydrogen Energy	Rodrigues et al. (2023)
0.9998	Effect of nickel on combustion synthesized copper/fumed-SiO2 catalyst for selective reduction of CO2 to CO	International Journal of Energy Research	Kumar et al. (2022)
0.9997	The function of porous working electrodes for hydrogen production from water splitting in nonthermal plasma reactor	Fuel	Li et al. (2022)
0.9997	Investigating influential effect of methanol-phenol-steam mixture on hydrogen production through thermodynamic analysis with experimental evaluation	International Journal of Energy Research	Tahir et al. (2022)
0.9997	Hydrogen generation in crushed rocks saturated by crude oil and water using microwave heating	International Journal of Hydrogen Energy	Yuan et al. (2022)
0.9997	Tunable Metal-Oxide Interaction with Balanced Ni0/Ni2 + Sites of NixMg1 – xO for Ethanol Steam Reforming	Applied Catalysis B-environmental	Tian et al. (2021)
0.9997	Tuning of active nickel species in MOF-derived nickel catalysts for the control on acetic acid steam reforming and hydrogen production	International Journal of Hydrogen Energy	Kumar et al. (2023)

Chen et al. (2022) reported that plasma pyrolysis (the technology used to produce useful gasses such as hydrogen by decomposing methane and biomass using high-temperature plasma) has recently attracted attention as a technology for large-scale production of hydrogen at low carbon emission and low economic cost, although it is not commercially mature (Chen et al. 2022). Zhu et al. (2021) reported the development of catalysts that enable efficient and low-carbon production of styrene from ethylbenzene by dehydrogenation (Zhu et al. 2021). Liu et al. (2021a) achieved high efficiency supercritical gasification for food wastes containing high organic matter content and moisture, which are difficult to gasify, by adding pretreatment before the heating process (Liu et al. 2021a). Rodrigues et al. (2023) modeled a fuel cell system using steam reforming of methanol and dimethyl ether for energy supply to remote areas and discovered the importance of low-temperature operation in optimizing the hydrogen production process in the system (Rodrigues et al. 2023). Kumar et al. (2022) reported the usefulness of nickel-added copper-based catalysts for the efficient methanation of carbon dioxide (Kumar et al. 2022). Li et al. (2022) investigated the effect of electrode type on the hydrogen yield in hydrogen production by water splitting steam using nonthermal plasma (Li et al. 2022). Tahir et al. (2022) conducted thermodynamic analysis and experiments in steam reforming of a mixture of methanol and phenol to determine the optimal temperature and atmospheric pressure/gas ratio for hydrogen production (Tahir et al. 2022). Yuan et al. (2022) suggested the feasibility of using microwave heating of unrecovered oil and gas left underground to produce hydrogen (Yuan et al. 2022). Tian et al. (2021) investigated the optimum catalyst for efficient hydrogen production by steam reforming biomass-based ethanol and suggested the importance of nickel metal and nickel oxide as catalysts (Tian et al. 2021). Kumar et al. (2023) investigated the characteristics of nickel catalysts for efficient hydrogen production by steam reforming acetic acid and determined the optimum nickel content (Kumar et al. 2023). Furthermore, they discussed the stability of the catalyst.

Next, by checking the top 10 probabilities of the emerging papers in Cluster 7 (Table 11), we can see how the discussion of the emerging papers in Cluster 7 unfolds. Ahmed et al. (2021) investigated the technical progress and economics of biohydrogen production by photosynthesis and fermentation of microalgae and noted that biohydrogen production is much more costly than that of gasoline, further suggesting the importance of biotechnological advances in improving microalgal metabolism (Ahmed et al. 2021). Kovalev (2021) proposed the efficient laboratory-scale production of gases containing hydrogen and methane using liquid organic wastes through stepwise dark fermentation (Kovalev 2021). Wang et al. (2021) investigated the effect of cofermentation of lignocellulosic biomass by a microbial consortium on hydrogen production efficiency (Wang et al. 2021). Wang et al. (2023) emphasized the need for a better understanding of algal metabolic processes to economically and sustainably produce biofuels in algae-based biorefineries (Wang et al. 2023). Kadier et al. (2022) conducted modeling and experiments using response surface methodology to determine the optimum conditions for hydrogen production from palm oil mill effluent using a microbial electrolysis cell (Kadier et al. 2022). Wu et al. (2022) simulated the effect of water electrolysis on hydrogen production efficiency using a mathematical model involving air-gap diffusion distillation (AGDD), which generates a potential difference due to the difference in concentration in an aqueous solution generated by thermal energy (Wu et al. 2022).

Table 11 Emerging papers in cluster 7 in the hydrogen energy domain (top 10)

Probability	Title	Journals	References
0.9999	Biohydrogen Production From Biomass Sources: Metabolic Pathways and Economic Analysis	Frontiers in Energy Research	Ahmed et al. (2021)
0.9998	Energy analysis of the system of two-stage anaerobic processing of liquid organic waste with production of hydrogen- and methane-containing biogases	International Journal of Hydrogen Energy	Kovalev (2021)
0.9998	A syntrophic co-fermentation model for biohydrogen production	Journal of Cleaner Production	Wang et al. (2021)
0.9998	A review on optimistic biorefinery products: Biofuel and bioproducts from algae biomass	Fuel	Wang et al. (2023)
0.9997	Performance optimization of microbial electrolysis cell (MEC) for palm oil mill effluent (POME) wastewater treatment and sustainable Bio-H2 production using response surface methodology (RSM)	International Journal of Hydrogen Energy	Kadier et al. (2022)
0.9997	Hydrogen production from water electrolysis driven by the membrane voltage of a closed-loop reverse electrodialysis system integrating air-gap diffusion distillation technology	Energy Conversion and Management	Wu et al. (2022)
0.9997	Biohydrogen production from the photocatalytic conversion of wastewater: Parametric analysis and data-driven modeling using nonlinear autoregressive with exogenous input and back-propagated multilayer perceptron neural networks	Fuel	Kanthasamy et al. (2023)
0.9997	Neo-Carbon Food concept: A pilot-scale hybrid biological–inorganic system with direct air capture of carbon dioxide	Journal of Cleaner Production	Ruuskanen et al. (2021)
0.9996	Review on Solar Hydrogen: Its Prospects and Limitations	Energy and Fuels	Abbasi and Abbasi (2011)
0.9996	An overview on light assisted techniques for waste-derived hydrogen fuel toward aviation industry	Fuel	Suresh et al. (2023)

Kanthasamy et al. (2023) modeled the process of hydrogen production by photocatalytic reforming of wastewater containing organic matter by using multilayer perceptron neural networks and nonlinear autoregressive neural networks and reported that the size of the photocatalyst has a large effect on hydrogen production (Kanthasamy et al. 2023). Ruuskanen et al. (2021) attempted to produce food substitutes such as biomass-based protein and fertilizer using hydrogen obtained by water electrolysis and carbon dioxide obtained by direct air capture (Ruuskanen et al. 2021). Abbasi and Abbasi (2011) introduced various hydrogen production methods using solar energy and reviewed water electrolysis using solar power, thermochemical conversion of biomass using solar energy, photofermentation, and photosynthesis from the viewpoint of economic efficiency (Abbasi and Abbasi 2011). Suresh et al. (2023) reviewed overall hydrogen production technologies using light, such as photocatalytic water electrolysis, organic matter reforming, and photofermentation of biomass, and suggested the importance of understanding the nanomaterial domain and waste utilization (Suresh et al. 2023).

Emerging prediction in the biomass energy domain

Next, we review the emerging prediction results for the biomass energy domain. Table 12 shows the performance of the emerging prediction model in the biomass energy domain. A precision of 0.94 means that 94% of the papers were predicted to be emerging papers by the model. On the other hand, a recall of 0.63 means that the model was able to predict 63% of all possible emerging papers in the dataset.

Table 12 Performance of the emerging prediction model in the biomass energy domain

Precision	Recall	F1_measure
0.9414	0.6337	0.752

The top three features that contributed to the prediction model for the biomass energy domain were as follows: Degree centrality (0.141), Eigenvector centrality (0.087), and Number of citations (0.0476). The most significant contribution of Degree was not only the number of references cited by oneself but also the number of citations acquired between publication and the end of the institution under analysis. Next, the fact that the higher the Eigenvector centrality of oneself, the more likely it is to be predicted as an emerging paper indicates that the paper cites the papers that should be cited. The number of citations indicates that the research is purely based on a large number of references. Review papers inevitably tend to have more references cited.

The number of emerging papers for each cluster in the biomass energy domain is shown in Table 13. The number of emerging papers in Cluster 5 (rapid pyrolysis), which is related to biomass processing, is the largest in the biomass energy domain overall. On the other hand, there were 124 and 142 emerging papers in Clusters 1 (fermentation and pretreatment process of biomass) and 3 (thermochemical conversion of biomass), respectively, related to biomass-based hydrogen production technology or its neighboring technology domain. Although these numbers are not as large as those of Cluster 5 (rapid pyrolysis), they hold a large weight in the domain.

Additionally, by checking the top 10 probabilities of the emerging papers in Cluster 1 (Table 14), we can see how the discussion of the emerging papers in Cluster 1 unfolds. Hu et al. (2021) proposed a two-step lignocellulosic fermentation process to produce hydrogen efficiently by eliminating the costly pretreatment process (Hu et al. 2021). Parvez et al. (2021) noted the potential utility of industrial hemp as an energy source for converting fossil fuels and argued that there is a need to address the challenges of growing industrial hemp in Canada and the lack of processing facilities (Parvez et al. 2021). Wang and Lee (2021) assessed the current research on the pretreatment process used to ferment lignocellulose to produce biogas and explained the economic and technical challenges (Wang and Lee 2021). Zhang et al. (2022a) used genetic algorithms to identify the conditions that maximize exergy efficiency in the process of producing biogas from corn stalks through pretreatment and anaerobic digestion (Zhang et al. 2022a).

Table 13 Number of emerging papers in the biomass energy domain

No.	Cluster label	Number of emerging papers
1	Fermentation and pretreatment process of biomass	124
2	Biomass supply chain	67
3	Thermochemical conversion of biomass	142
4	Perennial grass biomass	55
5	Rapid pyrolysis	248
6	Microalgae	132
7	Solid fuels	117
8	Biomass-based carbon materials	80
9	HMF	12
10	Environmental impacts of aboveground biomass utilization	20
	Total of all related clusters	1028

Table 14 Emerging papers in cluster 1 in the biomass energy domain (top 10)

Probability	Title	Journals	References
0.9990	Directly convert lignocellulosic biomass to H2 without pre-treatment and added cellulase by two-stage fermentation in semicontinuous modes	Renewable Energy	Hu et al. (2021)
0.9989	Potential of industrial hemp (*Cannabis sativa* L.) for bioenergy production in Canada: Status, challenges and outlook	Renewable and Sustainable Energy Reviews	Parvez et al. (2021)
0.9989	Lignocellulosic biomass pretreatment by deep eutectic solvents on lignin extraction and saccharification enhancement: A review.	Bioresource technology	Wang and Lee (2021)
0.9985	Exergy analysis and optimization of biomethane production from corn stalk pretreated by compound bacteria based on Genetic Algorithm.	Bioresource technology	Zhang et al. (2022a)
0.9984	Farmer's willingness to adopt private and collective biogas facilities: An agent-based modeling approach	Resources, Conservation and Recycling	Burg et al. (2021)
0.9982	Lignocellulosic Biomass Pretreatment for Enhanced Bioenergy Recovery: Effect of Lignocelluloses Recalcitrance and Enhancement Strategies	Frontiers in Energy Research	Banu et al. (2021)
0.9983	Biological treatment of plant biomass and factors affecting bioactivity	Journal of Cleaner Production	Singh (2021)
0.9983	Wastewater Based Microbial Biorefinery for Bioenergy Production	Sustainability	Bhatia et al. (2021)
0.9982	Influence of wet oxidation pretreatment with hydrogen peroxide and addition of clarified manure on anaerobic digestion of oil palm empty fruit bunches.	Bioresource technology	Lee et al. (2021)
0.9981	Hydrogen economy and storage by nanoporous microalgae diatom: Special emphasis on designing photobioreactors	International Journal of Hydrogen Energy	Rai et al. (2022)

Burg et al. (2021) investigated what factors incentivize farmers to produce biogas from livestock dung. Their results and simulations using an agent-based model revealed that profitability from biogas provides the strongest incentive (Burg et al. 2021). Banu et al. (2021) explored the challenges of converting lignocellulosic biomass to biomethane and discussed in detail the importance of pretreatment technologies for increasing efficiency and economics (Banu et al. 2021). Singh (2021) discussed the economics and technical challenges of plant biomass pretreatment, with a particular focus on biological treatments (Singh 2021). Bhatia (2021) reviewed the current status of microbial wastewater treatment technologies in biorefineries using bibliometric methods (Bhatia, 2021). Lee et al. (2021) researched the efficiency of wet oxidation (a kind of heat treatment) in the pretreatment process of anaerobic digestion of palm oil waste and reported that it was possible to significantly increase methane gas production by adding cattle compost (Lee et al. 2021). Rai et al. (2022) suggested that diatoms may be useful for hydrogen production in microbial fuel cells and photobioreactors to cultivate photosynthetic organisms (Rai et al. 2022).

Next, by checking the top 10 probabilities of the emerging papers in Cluster 3 (Table 15), we can see how the emerging papers in Cluster 3 are most likely to be related to each other. Liu et al. (2021b) reported that the copyrolysis of lignocellulosic biomass and plastic waste simultaneously has a synergistic effect on increasing the yield of syngas and determined that the interaction of the volatile components of both ingredients contributes to the mechanism (Liu et al. 2021b). Lu et al. (2023) conducted supercritical

Table 15 Emerging papers in cluster 3 in the biomass energy domain (top 10)

Probability	Title	Journals	References
0.9988	Toward enhanced understanding of synergistic effects in copyrolysis of pinewood and polycarbonate	Applied Energy	Liu et al. (2021b)
0.9986	Study on gasification characteristics and kinetics of polyformaldehyde plastics in supercritical water	Journal of Cleaner Production	Lu et al. (2023)
0.9985	Tunable syngas production from biomass: Synergistic effect of steam, Ni–CaO catalyst, and biochar	Energy	Yang et al. (2022)
0.9985	Techno-environmental-economic assessment on, municipal solid waste to methanol coupling with/without solid oxygen electrolysis cell unit	Process Safety and Environmental Protection	Sun et al. (2022)
0.9984	Gasification operational characteristics of 20-tons-Per-Day rice husk fluidized-bed reactor	Renewable Energy	Park et al. (2021)
0.9983	Green hydrogen production from decarbonized biomass gasification: An integrated techno-economic and environmental analysis	Energy	Cormos (2023)
0.9982	Biomass-Based Chemical Looping Gasification: Overview and Recent Developments	Applied Sciences	Nguyen et al. (2021)
0.9982	Hydrogen production, storage, utilization and environmental impacts: a review	Environmental Chemistry Letters	Osman et al. (2022)
0.9981	Quality improvement and tar reduction of syngas produced by bio-oil gasification	Energy	Hwang et al. (2021)
0.9980	Boosting the Conversion of CO2 with Biochar to Clean CO in an Atmospheric Plasmatron: A Synergy of Plasma Chemistry and Thermochemistry	ACS Sustainable Chemistry & Engineering	Zhang et al. (2022a)

water gasification experiments on polyoxymethylene waste plastics and clarified that the temperature increase is related to the yield of syngas (Lu et al. 2023). Yang et al. (2022) proposed a stepwise catalytic reaction of steam and biochar to increase the ratio of hydrogen and carbon monoxide in syngas through biomass gasification (Yang et al. 2022). Sun et al. (2022) compared the conversion efficiency, environmental impact, and economics of three types of processes (the integrated process of carbon capture and carbon storage, the process using a solid oxygen electrolysis unit, and the process using power generation by waste incineration) to convert municipal solid waste to methanol (Sun et al. 2022). Park et al. (2021) identified the optimum temperature conditions and the challenge of agglomerate generation in a fluidized bed reactor for biomass gasification using rice husk (Park et al. 2021). Cormos (2023) evaluated carbon dioxide capture technologies in the gasification of biomass for carbon negatives and reported that membrane separation is the most efficient and economical method (Cormos 2023). Nguyen et al. (2021) reviewed the latest trends in chemical looping gasification processes in which oxides are supplied to biomass as oxygen sources during the gasification of biomass (Nguyen et al. 2021). Osman et al. (2022) suggested that the storage of hydrogen in underground porous media may be useful for off-peak excess energy storage (Osman et al. 2022). Hwang et al. (2021) emphasized the importance of catalytic tar reforming to increase the hydrogen yield from synthesis gas in the gasification of biomass using a fluidized bed reactor (Hwang et al., 2021). Zhang et al. (2022a) investigated the ability of carbon monoxide production by the reaction of biochar with carbon dioxide using plasma technology and evaluated how various conditions in fixed bed reactors and fluidized bed reactors affect reaction performance (Zhang et al. 2022a).

Discussion

Comparison of cluster analysis results

Based on the results of the cluster analysis of the hydrogen energy domain and biomass energy domain, the positions of biomass-based hydrogen production technology and its neighboring technology domain in each domain are discussed.

First, from the results of the cluster analysis for the hydrogen energy domain shown in Table 2, Cluster 4 (thermochemical conversion and reforming of biomass) and Cluster 7 (microbial decomposition of biomass) are relatively old compared to the average age of the whole domain (5.97). These clusters are also older than the clusters related to hydrogen production (Cluster 1 and Cluster 2). From the above, it can be seen that biomass-based hydrogen production technology and its neighboring technology domain are the subject of mature discussion in the hydrogen energy domain.

On the other hand, according to the results of the cluster analysis for the biomass energy domain shown in Table 3, Cluster 1 (fermentation and pretreatment process of biomass) and Cluster 3 (thermochemical conversion of biomass) were the highest clusters. Moreover, in terms of the ratio of papers, Clusters 1 and 3, which are biomass-based hydrogen production technologies and neighboring domains, have become central discussions in the biomass energy domain in recent years. These are younger discussions than those in Cluster 2 (biomass supply chain) and Cluster 4 (perennial grass biomass), which are classic discussions in the biomass energy domain. Therefore, biomass-based hydrogen production technology and its neighboring technology domain have become popular research domains in recent years in the biomass energy domain.

Cluster 4 (thermochemical conversion and reforming of biomass) was in the hydrogen energy domain, and Cluster 3 (thermochemical conversion and reforming of biomass) was in the biomass energy domain; these two clusters share the same viewpoint on discussions related to thermochemical conversion by biomass. The share of the number of papers in each domain is approximately 10-11%, but the absolute number of papers is 12,760 in the hydrogen energy domain and 7,176 in the biomass energy domain. This indicates that most of the knowledge accumulated in the hydrogen energy domain is not related to the biomass energy domain, even for the same thermochemical conversion of biomass.

Cluster 7 (Microbial decomposition of biomass) in the hydrogen energy domain and Cluster 1 (Fermentation and pretreatment process of biomass) in the biomass energy domain share the same viewpoint on discussions related to biomass fermentation. Although the absolute number of papers in each cluster is approximately 8,000, their shares of the total number of papers are 6.7% and 13.0%, showing a different presence overall. In addition, the average ages of the individuals in the two clusters are 7.0 years and 5.5 years, respectively, which shows that this topic has been discussed in the hydrogen energy domain for a long time. From the viewpoint of researchers in biomass energy, they may have overlooked what has already been discussed by researchers in the hydrogen energy domain. On the other hand, from the viewpoint of researchers in the hydrogen energy domain, they may not have caught up with what has been discussed by researchers in the biomass energy domain in recent years. In any case, even though both clusters are technical domains related to biomass fermentation, the content of the discussions and the maturity level differ between the hydrogen energy domain and the biomass energy domain.

Comparing central papers in the citation network of the cluster

The central paper in the citation network of the cluster is the paper with the highest number of citations in the cluster. By checking central papers in the citation network of each cluster, it is possible to obtain insight into the center of the discussion in the cluster.

First, we observed the center of the discussion in the cluster in the hydrogen energy domain. Table 4 shows that in Cluster 4 (thermochemical conversion and reforming of biomass) in the hydrogen energy domain, the discussion centers on hydrogen conversion by thermochemical conversion and reforming using biomass and biomass-based products. Table 5 shows that in Cluster 7 (Microbial decomposition of biomass) in the hydrogen energy domain, the discussion centers on biomass-based hydrogen production technology by microbial metabolism, such as fermentation and microbial electrolysis cells. These clusters are discussed from the viewpoint of utilizing biomass to produce hydrogen. In other words, papers about hydrogen production using biomass as a means form citation networks.

We saw the center of the discussion in the cluster in the biomass energy domain. Table 6 shows that in Cluster 1 (fermentation and pretreatment process of biomass) in the biomass energy domain, the discussion focuses on the process of biomass fermentation and pretreatment for methane and alcohol production. The discussion focuses on fermentation and pretreatment and does not emphasize specific products. Table 7 shows that in Cluster 3 (thermochemical conversion of biomass) in the biomass energy domain, the discussion focuses on modeling by gasification of biomass through thermochemical conversion and understanding of the processing. No cluster is formed by generating hydrogen, but these clusters are separated by biomass processing. In other words, papers for the purpose of processing biomass have been formed in citation networks.

Next, we compare the centers of the discussion of each cluster for the related technology. First, we compared the clusters related to the thermochemical conversion of biomass. In Cluster 4 (thermochemical conversion and reforming of biomass) in the hydrogen energy domain, the center of the discussion is the hydrogen conversion of biomass and biomass-based products by thermochemical conversion and reforming, and the use of hydrogen as a product is also within the scope of interest. On the other hand, in Cluster 3 (thermochemical conversion of biomass) in the biomass energy domain, the center of the discussion is modeling the thermochemical conversion of biomass and understanding the process based on it, and it seems that there is strong interest in this process. Even with the same technology used for the thermochemical conversion of biomass, the objects of interest are very different between the hydrogen energy domain and the biomass energy domain.

Additionally, we compared the clusters related to biomass fermentation. In Cluster 7 (Microbial decomposition of biomass) in the hydrogen energy domain, the discussions focus on all three: biomass as a material; microbial metabolism as a processing process, such as fermentation and microbial electrolysis cells; and hydrogen as a product. On the other hand, in Cluster 1 (fermentation and pretreatment process of biomass) in the biomass energy domain, the discussions focus on biomass processing processes, such as pretreatment before fermentation. The center of the discussion on the same technology for biomass fermentation differs between the hydrogen energy domain and the biomass energy domain.

Finally, we compare the influence in central papers in the citation network of the cluster on the transition of the number of papers. Central papers in the cluster are published in the initial stage of the increase of the number of papers or in the middle of it. The presence of the cluster related to biomass-based hydrogen production technology in the hydrogen energy domain has decreased in recent years, and the presence of the cluster related to biomass-based hydrogen production technology in the biomass energy domain has been maintained. In other words, it is considered that the presence of the point which became the discussion center in the central paper in the cluster has changed in each domain. In the hydrogen energy domain, the attention of catalysts for reforming, supercritical gasification technology, dark fermentation of biomass, and microbial electrolysis cell has relatively decreased, while in the biomass energy domain, the attention of pretreatment technology of lignocellulose, gasification process, and modeling has been maintained.

Through the above consideration of the central papers in the citation network of the cluster, we can observe the difference in the center of the discussion in the clusters related to biomass-based hydrogen production technology and its neighboring technology domain. Although this cross-domain analysis targeted bibliographic information, this analysis seems to represent the interests and trends of researchers belonging to each domain. In other words, the difference in the focus of this analysis reflects the difference in the research purpose of the researcher community in each research domain. In Cluster 4 (Thermochemical Conversion and Reforming of Biomass) and Cluster 7 (Microbial Decomposition of Biomass) in the hydrogen energy domain, discussions toward the realization of a hydrogen society using biomass hydrogen production technology are being carried out in a balanced manner, but their presence has been fading in recent years. On the other hand, in Cluster 1 (Fermentation and pretreatment of biomass) and Cluster 3 (Thermochemical conversion of biomass) in the biomass energy domain, there is a strong interest in biomass processing processes and their presence in recent years has been maintained. There are differences in the research directions and objectives in each domain.

Comparing emerging prediction results

We compared the number of emerging papers about biomass-based hydrogen production and its neighboring technology domain in both the hydrogen and biomass energy domains. Table 9 shows that 45 emerging papers were extracted from Cluster 4 (Thermochemical conversion and reforming of biomass) and 31 from Cluster 7 (Hydrogen production by biomass fermentation), for a total of 76. On the other hand, in the biomass energy domain, Table 13 shows that 124 emerging papers were extracted in Cluster 1 (Fermentation and pretreatment process of biomass) and 142 in Cluster 3 (Thermochemical conversion of biomass), for a total of 266. A comparison of these numbers of emerging papers shows that the attention given to biomass-based hydrogen production technology and its neighboring technology domain is lower in the hydrogen energy domain than in the biomass energy domain.

Next, we present the emerging papers in the hydrogen energy domain. Table 10 shows that the 6 emerging papers were extracted from the top 10 emerging papers in Cluster 4 (Thermochemical conversion and reforming of biomass) in the hydrogen energy domain; these papers focused on methodology examination and efficiency improvement of steam reforming and thermochemical conversion for hydrogen production without limiting the scope of biomass as a raw material. Table 11 shows that the 5 emerging papers on biomass fermentation using microbial metabolism and efficient hydrogen production by microbial electrolysis cells are extracted from the top 10 of the emerging papers in Cluster 7 (Microbial decomposition of biomass) in the hydrogen energy domain.

We see the emerging papers in the biomass energy domain. Table 14 shows that the 5 emerging papers were extracted from the top 10 in the emerging papers of Cluster 1 (Fermentation and pretreatment process of biomass) in the biomass energy domain, focusing on processing such as fermentation and pretreatment of biomass and examining the improvement of the process or improving the efficiency of products such as biogas and hydrogen. Table 15 shows that the 6 emerging papers on attempts to improve gasification technology to increase the yield of syngas (a mixture of hydrogen and carbon monoxide) were extracted from the top 10 of the emerging papers in Cluster 3 (Thermochemical conversion of biomass) in the biomass energy domain. In both clusters, the discussion in the central papers in the citation network focused only on the processing biomass, but a certain number of the emerging papers in which the subject of the discussion is even the yield to the products were extracted.

We then compared the discussions of these emerging papers for each related technology. First, we compared the clusters related to the thermochemical conversion of biomass. Cluster 3 (Thermochemical conversion of biomass) in the biomass energy domain focuses not only on understanding the processing process but also on syngas yield. However, Cluster 4 (Thermochemical conversion and reforming of biomass) in the hydrogen energy domain was not limited to biomass as an ingredient, which differed in direction from the biomass energy domain. On the other hand, when we compare the clusters related to the fermentation of biomass, we can see that Cluster 7 (Microbial decomposition of biomass) in the hydrogen energy domain and Cluster 1 (Fermentation and pretreatment process of biomass) in the biomass energy domain both discuss biomass-based hydrogen production efficiency.

According to the above considerations of the emerging papers, there is a divergence in the discussion on biomass thermochemical conversion technology between the hydrogen energy domain and the biomass energy domain. On the other hand, regarding biomass fermentation technology, the hydrogen energy domain and biomass energy domain share the same purpose in terms of improving hydrogen production efficiency. However, from the comparison of the number of emerging papers, it can be seen that the attention given to any biomass-based hydrogen production technology and its neighboring technology domain is lower in the hydrogen energy domain than in the biomass energy domain.

Contribution

Cross-domain bibliographic information analysis in this study revealed that the hydrogen energy domain and the biomass energy domain have different focus on biomass-based hydrogen production technology. This indicates that the researcher communities have different research objectives, and such differences in values among the researcher communities in each field may cause disconnection between the communities and hinder innovation. Therefore, it is necessary to promote further interdisciplinary research. Specifically, we can promote exchanges among researchers and hold research meetings and academic conferences to integrate knowledge from different fields. In addition, in the current situation where the governments of various countries are urging the utilization of hydrogen energy and biomass energy, it is necessary to convene experts from both biomass energy and the hydrogen energy domain in governmental committees and make policy and investment decisions after exchanging opinions.

In addition, the emerging papers of this study refer to technologies that are likely to attract attention in the future. We discuss the impact of this prediction separately from the industrial perspective and the policy perspective. The emerging prediction results suggest the direction of technology development that companies in the industry should focus on. In addition, the Research domain, which is predicted to become increasingly important, suggests new business opportunities. This may promote the establishment of start-up companies and the development of new businesses by existing companies. In addition, the emerging prediction results of this research can be used as a reference when the government formulates a strategic support program for the domain, which is drawing attention. On the other hand, it is necessary to promote deregulation and the establishment of new standards to promote the practical application of promising technologies. This will contribute to the early identification of such technologies.

Conclusion

The purpose of this study was to evaluate and evaluate the trends in biomass-based hydrogen production from both the hydrogen energy domain as the entrance and the biomass energy domain as the exit and to clarify the knowledge gap between these research communities. To achieve this purpose, we conducted bibliometric information analysis and machine learning based on citation networks using a large amount of academic literature data to identify research trends and evaluation gaps in each domain.

The main findings of the research show that research in the hydrogen energy domain and biomass energy domain has different focuses and interests, even on the same theme. In particular, in the hydrogen energy domain, well-balanced discussions toward the realization of a hydrogen society are conducted using biomass-based hydrogen production technology. On the other hand, in the biomass energy domain, there is strong interest in processing biomass, and emphasis is placed on understanding this process. In addition, overall, there is little recent interest in relevant technology in the hydrogen energy domain, while interest in relevant technology in the biomass energy domain is high. On the other hand, in the hydrogen energy domain, there is a rich history and accumulation of research on biomass-based hydrogen, many of which cannot be observed in the biomass energy domain. These differences reflect differences in the purpose, culture, and consciousness of researchers in each domain. In other words, even for the same research topic, the formation of knowledge differs depending on whether the subject is considered a means or an objective.

These gaps indicate the necessity of interdisciplinary exchange between neighboring domains and can be considered a basis for companies to determine investment targets for advanced development themes. For the development of biomass-based hydrogen production technology, it is important to integrate the knowledge from both domains. It is shown that multilateral analysis is essential for obtaining knowledge that cannot be obtained by unidirectional observation. The development of more efficient and sustainable hydrogen production technology can be achieved by integrating research results from different viewpoints, such as those of this study. As interdisciplinary fusion advances, it becomes difficult to clearly demarcate boundaries in many scientific domains. The cross-domain bibliometric information analysis presented in this study will be an essential viewpoint for reviewing not only biomass-based hydrogen production but also many interdisciplinary domains.

This study has several limitations. First, the dataset used is provided by the Semantic scholar API and does not cover all bibliometric information. Future studies are expected to evaluate the robustness of the method based on differences in multiple databases. Second, the labeling of each cluster mainly refers to the central paper, so the papers included in that cluster cannot be uniquely represented. In reality, there are various papers, so subcluster analysis will be promoted, and discussion with higher resolution will be needed. In addition, the clustering method used in this study is classified into hard clustering, in which nodes and belonging clusters are associated one-to-one. Although actual papers are labeled uniquely, it is not always possible to do so. Therefore, the research obtained by the analysis result by soft clustering will be the next subject. Third, a potential limitation of the prediction model is that review papers tend to rank high. In this study, the existence of a review itself is not excluded from the results as evidence that attention is being paid to the subject. It is possible to filter only original papers in the future. Finally, it will not be known until three years after publication whether the prediction results produced by the emerging prediction model are realistic. This is because the performance of the prediction model is based on verifiable historical data. On the other hand, these are universal issues that arise when trying to demonstrate something with specific data. Future research will require a deeper understanding by combining a broader dataset with detailed technical analysis.

Based on this research, it will be possible to promote an integrated approach by strengthening collaboration between the biomass and hydrogen energy research communities, including corporate R&D managers, policy makers, and researchers. By promoting open innovation between different fields, it is expected that technical issues will be solved early and that innovative ideas will be generated. This study highlights the potential of biomass-based hydrogen production technology and shows that its development is important for realizing a sustainable energy society. We strongly hope that future research and policies will lay the foundation for supporting the advancement of this field.

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Author contributions
K.H. was responsible for Conceptualization, Data curation, Formal analysis, and Writing - original draft and Writing – review & editing.H.S. was responsible for Funding acquisition, Methodology, Project administration, Writing - original draft, Writing – review & editing, and Supervision.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethical approval
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Consent to participate
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Consent for publication
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Competing interests
The authors declare no competing interests.

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