Review

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Potential contribution of biomass gasification-based technology in energy transition: a technical review coupled with bibliometric studies

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Abstract: Biomass gasification technology has been extensively researched around the world; however, there is a need to evaluate the current research landscape and evolutionary direction of research in the broader context of energy transition. A systematic bibliometric analysis of the Web of Science database was performed for articles that fall within the keywords ‘Biomass gasification’ and ‘Energy transition’. A total of 1498 articles were identified; after applying inclusion and exclusion criteria, 1196 articles were selected for final analysis. VOSviewer and Biblometrix were used for the study. Trends in biomass gasification and energy transition were identified as the initial (1994–2008), rise (2009–2018) and prosperity stages (2019 to date). A significant portion (47%) of publications were concentrated in 10 journals, including *Renewable Energy*, *Energy* and *International Journal of Hydrogen Energy*. Among the countries, China leads with 672 publications, followed by the US, India, and Italy. The prominent research areas are hydrogen production, process optimization, exergy analysis, tar reduction and life cycle assessment. Currently, the active area of research is the production of hydrogen-rich gas through biomass gasification technologies and integrating bioenergy systems with carbon capture and storage to achieve sustainable energy transition goals. © 2025 The Author(s). *Biofuels, Bioproducts and Biorefining* published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

Key words: biomass gasification; energy transition; biomass; bioenergy; bibliometric review

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Introduction

The urgent need for global decarbonization is underscored by the fact that without significant transformation of the energy and industrial sectors, the long-term goals of the Paris Agreement cannot be achieved, which will in turn jeopardize human well-being.[1] Current climate pledges suggest a global temperature rise of 2.5–2.9 °C by 2100, highlighting the necessity for stronger action to limit this increase to below 2°, ideally closer to 1.5°.[1–3] Achieving these goals requires not only ambitious emissions targets but also effective implementation of policies and technologies, with renewable energy playing essential roles in driving sustainable decarbonization efforts.

The energy transition demands a comprehensive transformation of energy production, consumption, and distribution, extending far beyond simply replacing fossil fuels with an arbitrary set of renewable sources. This process involves rethinking energy systems to improve flexibility, efficiency, and sustainability.[4] Integrating renewable energy into the energy mix requires not only the use of available renewable sources but also a complete overhaul of energy systems. Innovative technological solutions are essential for the efficient and environmentally sustainable production, conversion, and utilization of renewable energy in this transition.[5]

Biomass, the only sustainable, renewable and CO_2-neutral carbon source, has gained considerable acceptance owing to its great potential to generate dispatchable heat, and electricity, and to be used as feedstock for biofuels. Globally, biomass is a significant source of renewable energy. In 2020, the world's supply of primary energy from biomass reached approximately 57.5 exajoules.[6] Biomass accounts for about 55% of renewable energy and over 6% of the global energy supply.[7] Biomass gasification is a promising technology for the transition to sustainable energy systems by converting biomass through a series of chemical reactions into a fuel gas known as syngas, a gas mixture consisting of H_2, CO and CH_4.[8]

Biomass gasification has been extensively explored as a renewable energy conversion technology with significant potential to reduce greenhouse gas emissions.[9] An extensive review of the literature reveals that, despite significant technological advancements and increasing integration of biomass gasification into energy systems, its full potential within the broader energy transition context remains underexplored. Current research is often fragmented, primarily addressing isolated topics such as improvements in gasification techniques, efficiency assessments, and environmental impacts,[10,11] without a comprehensive evaluation of its overall potential to support the energy transition. Furthermore, there is a limited understanding of the global research trends, key contributors, the evolution of knowledge and emerging research trends in this field. To address these gaps, a systematic bibliometric analysis is needed to critically assess the scientific output, collaboration networks, and thematic areas within biomass gasification research. Such an analysis would provide valuable insights into the current state of research, highlight this technology's contributions to energy transition, and identify future research directions.

This research aims to conduct a detailed, systematic bibliometric and technical analysis of the potential of biomass gasification-based technologies in driving the energy transition. This study will offer a holistic understanding of biomass gasification's place in the evolving energy landscape by mapping global research trends, identifying key themes, and assessing the technology's role in decarbonization efforts. Given this, the research questions are:

RQ1: How has research in biomass gasification and energy transition been progressing over time?
RQ2: Who are the key drivers in the research niche?
RQ3: What are the identified problems of energy transition, and how can biomass gasification technology contribute to their mitigation?
RQ4: What are the future research areas in biomass gasification technology?

Providing evidence-based answers to these questions will highlight the vital role of biomass gasification technology in the global energy transition.

Methodology

A systematic bibliometric analysis of scientific articles mapping was adopted according to the methodology described in Nogueira *et al.*[12] The survey carried out according to the questioning of the research questions presented studies from different parts of the world, institutions, and authors, based on citations, publications, impact factors, and other parameters. In addition, to provide a scientific landscape of the trends and perspectives of how the topic of biomass gasification and integration has evolved in the scientific community, an analysis of grouping by clusters was also conducted. The data collection process and analysis are presented in Fig. 1.

Data source

In this research, two major concepts were identified: (1) biomass gasification technology; and (2) energy transition. After an extensive literature review, a set of keywords was defined to facilitate comprehensive searches in academic

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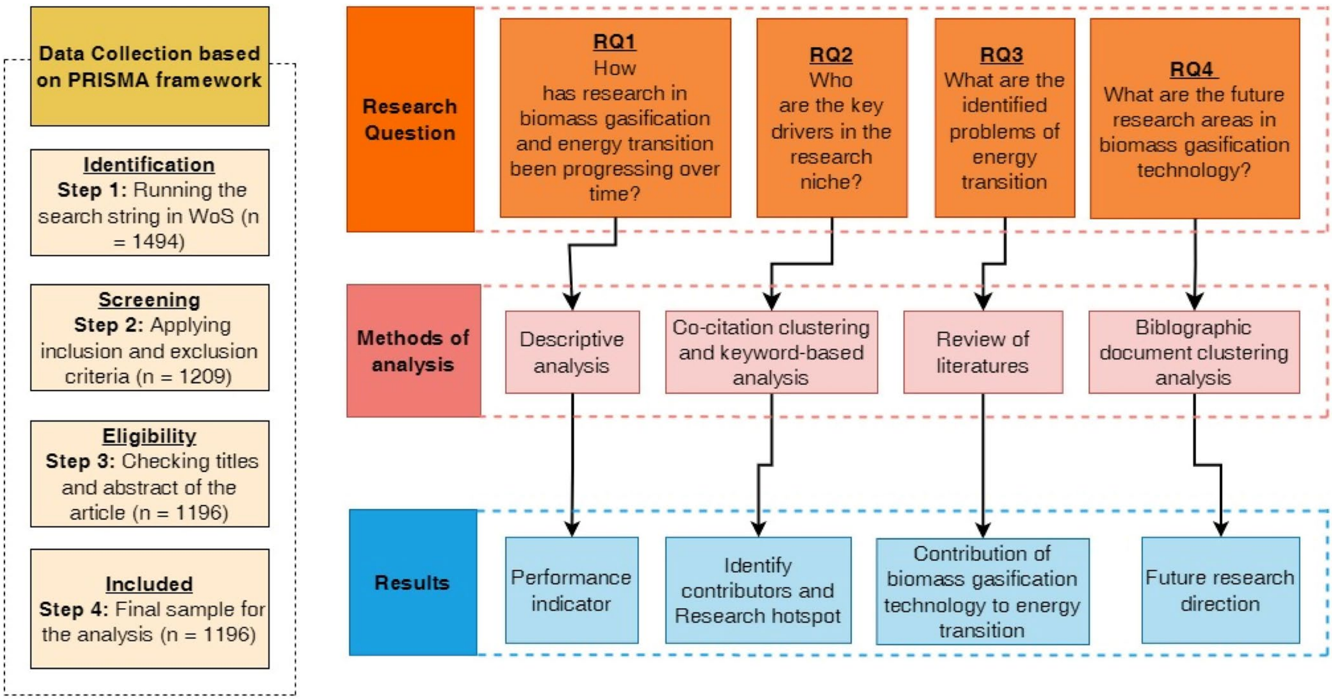

Figure 1. Data collection and analysis process using a hybrid methodology.

databases. For the first concept, biomass gasification technology, the identified keyword is 'biomass gasification'. This keyword will give a holistic view of related technologies associated with concepts such as catalytic gasification, biofuels, syngas, carbon capture, hydrogen production, etc. For the second concept, energy transition, relevant keywords include 'energy transition' OR 'renewable energy' OR 'sustainable energy' OR decarbonization given a combination of (ALL = ('Biomass gasification') AND ALL = ('energy transition' OR 'renewable energy' OR 'sustainable energy' OR decarbonization)).

The data for bibliometric analysis were obtained from the Web of Science (WoS) database because of its significant overlap in journal articles with other major databases that focus on the life sciences, physical sciences and technology area.[13] The keywords were searched on October 15, 2024. The initial search retrieved articles published between 1997 and 2024 (1498). Articles published in English were screened according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement (1196). Review papers, papers that were presented at conferences, and were still in preprint format were excluded.[14]

Data analysis

The free software VOSviewer (version 1.6.20) and Bibliometrix library in R[15] were used to create the bibliometric maps. Maps of journals, countries, prominent areas of research, and keywords based on correlation data were created using the data retrieved from WoS. Additionally, when applicable, data analysis and charting were done using Microsoft Excel spreadsheets.

Results

Trends and distribution of scientific journals

The number of publications analyzed was 1196 between 1994 and 2025 (Fig. 2). It was observed that the considered period could be divided into three stages, as proposed by Wang *et al.*[16] The period from 1994 to 2008, which accounted for about 4% of the total publications and the maximum production during this period, was 13 articles. During this time, the potential of biomass gasification had just been explored as the reality of environmental crisis was just becoming obvious. The work of Maniatis and Millich[17] represents a pivotal advancement in the field of biomass gasification. They emphasized that among all renewable energy sources, biomass holds the greatest potential and is widely recognized as a critical component in achieving global energy transition goals. Their assertion underscores the essential role biomass will play in meeting renewable energy targets, positioning it as a key driver in future sustainable

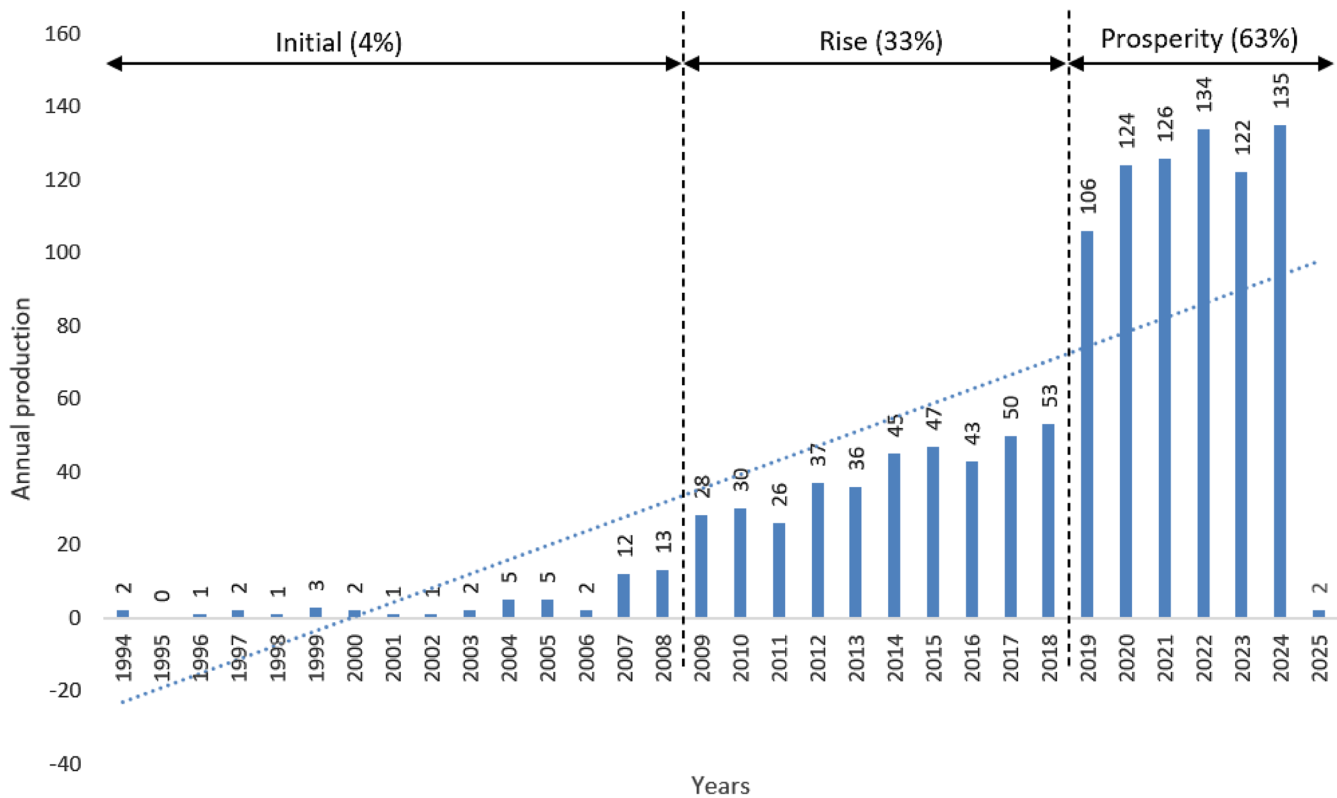

Figure 2. Research output on biomass gasification and integration between 1994 and 2024.

energy systems.[17] This groundbreaking work provides a solid foundation for further development of gasification technology and its optimization for energy generation as reported in the works between 2001 and 2008. As a result, this period represents what can be referred to as the 'initial' stage for biomass gasification technology.

Between 2009 and 2018, the publications in biomass gasification and energy transition fluctuated between 26 and 53 publications per year with the highest number of publications in 2018. This phase marks the 'rise' of significant interest in the topic with 29% increase in publication output. Researchers began to explore and publish more extensively, reflecting a rising momentum. During this time, researchers investigated areas such as the role of catalysts in enhancing biomass gasification and biofuel production,[18] integration of biomass gasification with other energy systems for cogeneration and electricity generation,[19] environmental and economic impacts of utilizing waste biomass for energy generation[20,21] and technological innovation in biomass gasification such as the use of fixed bed and fluidized bed gasifiers.[22,23] Since 2019, the study of biomass gasification has reached the 'prosperity' stage with more than 100 publications annually. The number of research outputs during this year accounted for about 63% of the total publications, demonstrating that it is now an active field of research.

Leaders in the generation of knowledge

By understanding the distribution statistics of the publications in terms of affiliation, country and journals, it will be easier to identify those that have achieved a significant milestone in biomass gasification in the context of the energy transition, thereby encouraging knowledge transfer via collaboration.

Prominent journals

In other to identify the key journals responsible for the dissemination of knowledge in relation to biomass gasification, Bradford's law was applied to the records as presented in the work of Lakshminarasimhappa and Kemparaju.[24] Bradford's law describes the scatter of citations for a given subject or field. It can be used to identify the most highly cited journals for a field or subject. Figure 3 shows the core journals that contributed a significant portion of the total number of articles published on the subject. Out of the identified 1196 journal articles, 47% were published in seven journals, which are *Renewable Energy* (199), *Energy*

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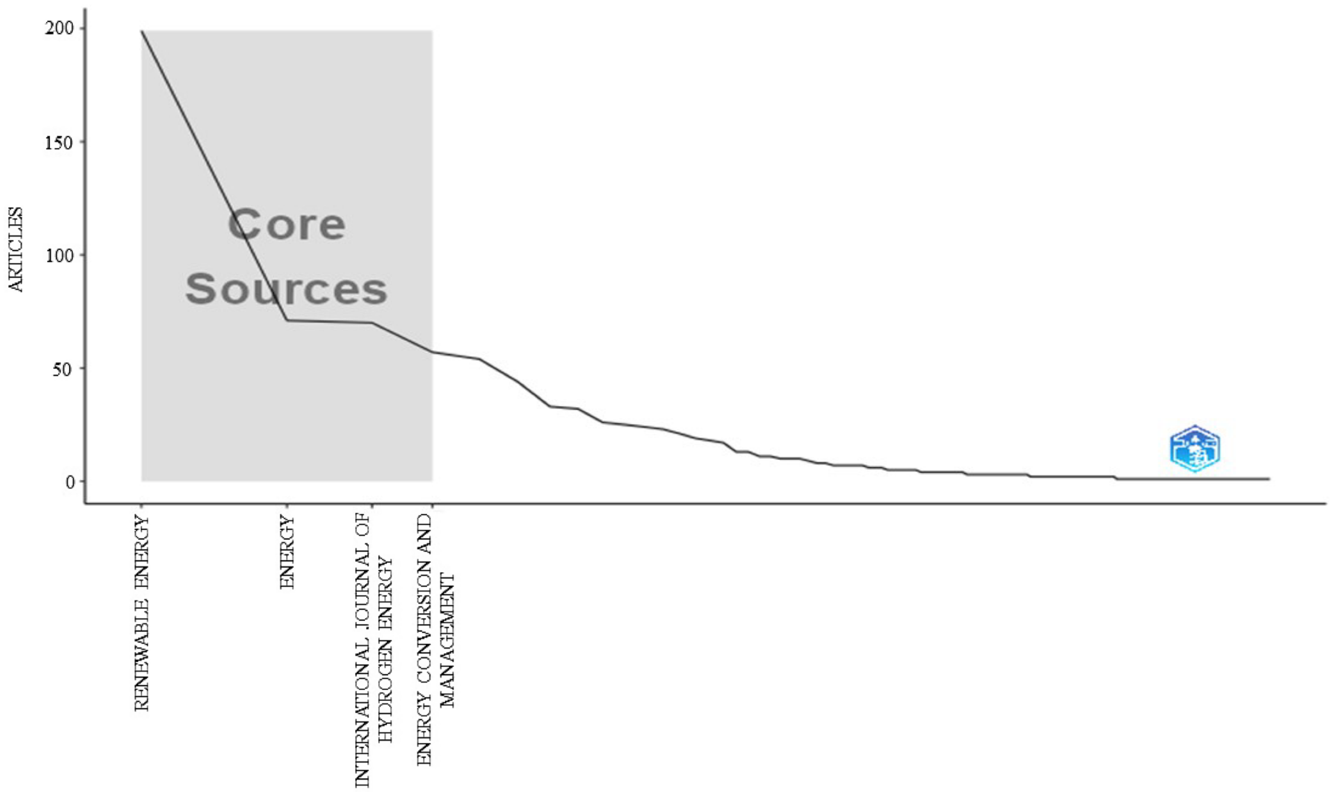

Figure 3. Number of publications by journal.

(71), *International Journal of Hydrogen Energy* (70), *Energy Conversion and Management* (57), *Fuel* (54), *Energies* (44), *Applied Energy* (33), and *Journal of Cleaner Production* (32) respectively.

Contributions by country

To expand our understanding of the global landscape of biomass gasification and integration research, we examined the geographical distribution of the publications. Our dataset includes contributions from 86 countries. The map (Fig. 4) shows China as the leading country with 672 publications, followed by the United States with 253 documents, India (187), and Italy (120). Other significant contributors include Iran (119), Brazil (117), UK (113), and Malaysia (112). In Africa, Egypt has made 30 contributions, while Nigeria and South Africa contributed 13 and 12 documents, respectively. East Asia, North America, and Europe show strong research involvement, while other regions like Africa, and Central Asia demonstrate lower but notable contributions.

The links between countries whose researchers collaborated in this research domain are presented in Fig. 5. This shows that China, USA, India and Canada have a significant number of international collaborations. This coincides with the fact that these countries have been identified by the International Energy Agency as the major key players in the energy transition.[25]

Prominent research areas

To better understand this research field, keyword analysis of the articles was done. The keywords used for the analysis are the author's keywords. The analysis will help to achieve an in-depth perspective of the emerging relevant keywords that are linked to the core concept of the research. Figure 6(a) highlights the dominant keywords from the analysis, focusing on terms with a frequency of occurrence adjusted to 30 or more. The chart displays the relative prominence of these keywords through larger node sizes, emphasizing their importance within the research corpus. Figure 6(b) provides an overlay visualization, illustrating how these key terms and research themes have evolved over time. The visualization uses node color and linkage thickness to show associations and trends, offering insights into the development and shifts in focus areas.

The keyword 'biomass gasification' is the most prominent (largest) node in the centre. This central position means that other research topics are frequently linked to biomass gasification, emphasizing its pivotal role in the field.

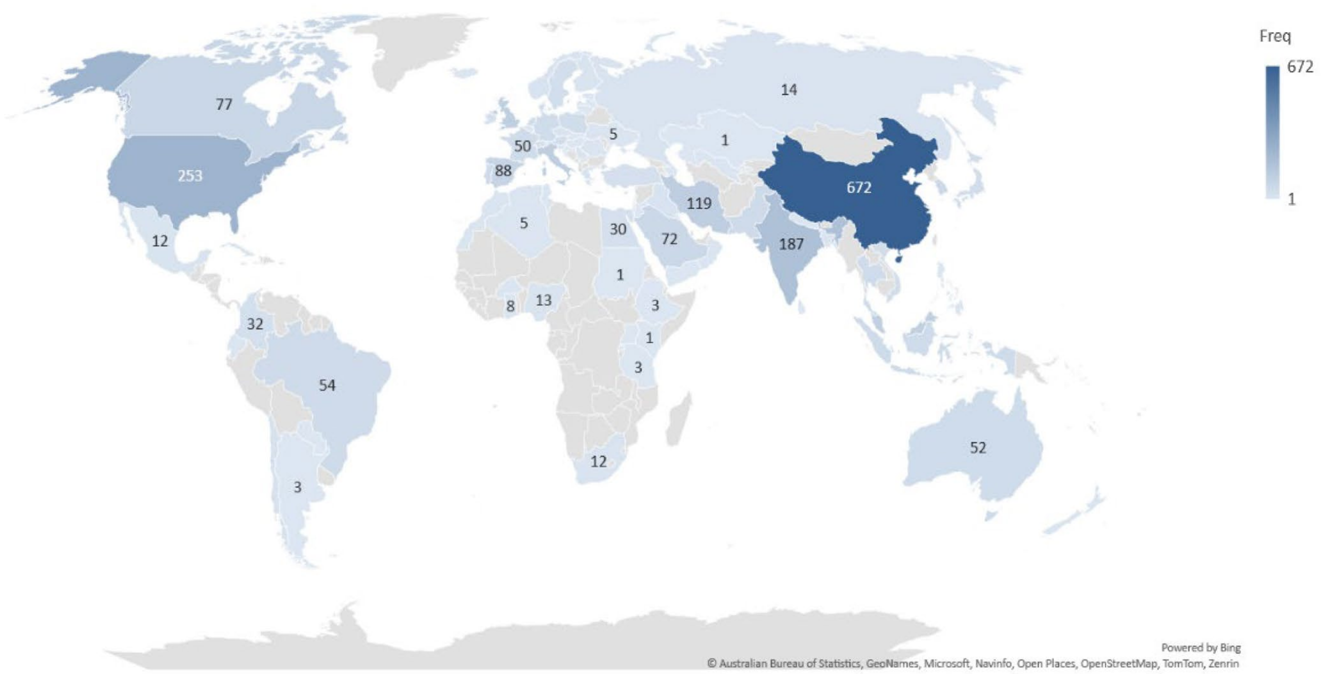

Figure 4. Knowledge contribution by countries.

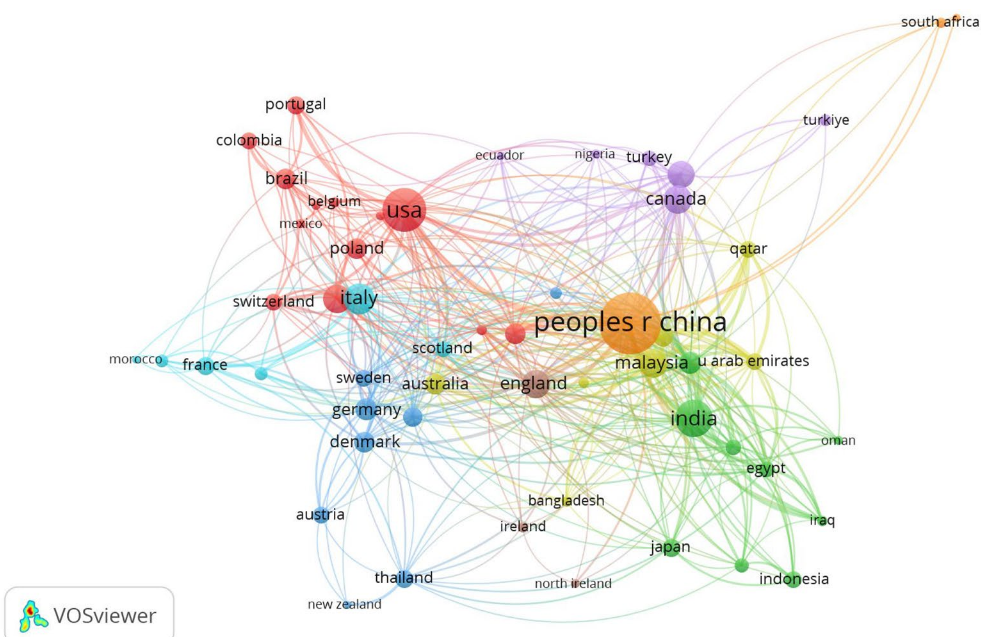

Figure 5. Partnerships between countries.

Green cluster: gasification technology and reactor design

The first cluster (green) in Fig. 6(a) focuses on the technical aspects of biomass gasification. Key terms like fluidized-bed gasifier, temperature, catalysts, kinetics, tars, and hydrogen production suggest research aimed at improving the efficiency of gasification processes, managing of by-products like tars, and enhancing hydrogen production. It also reflects significant interest in hydrogen production pathways from gasified biomass, highlighting a push toward cleaner fuels.

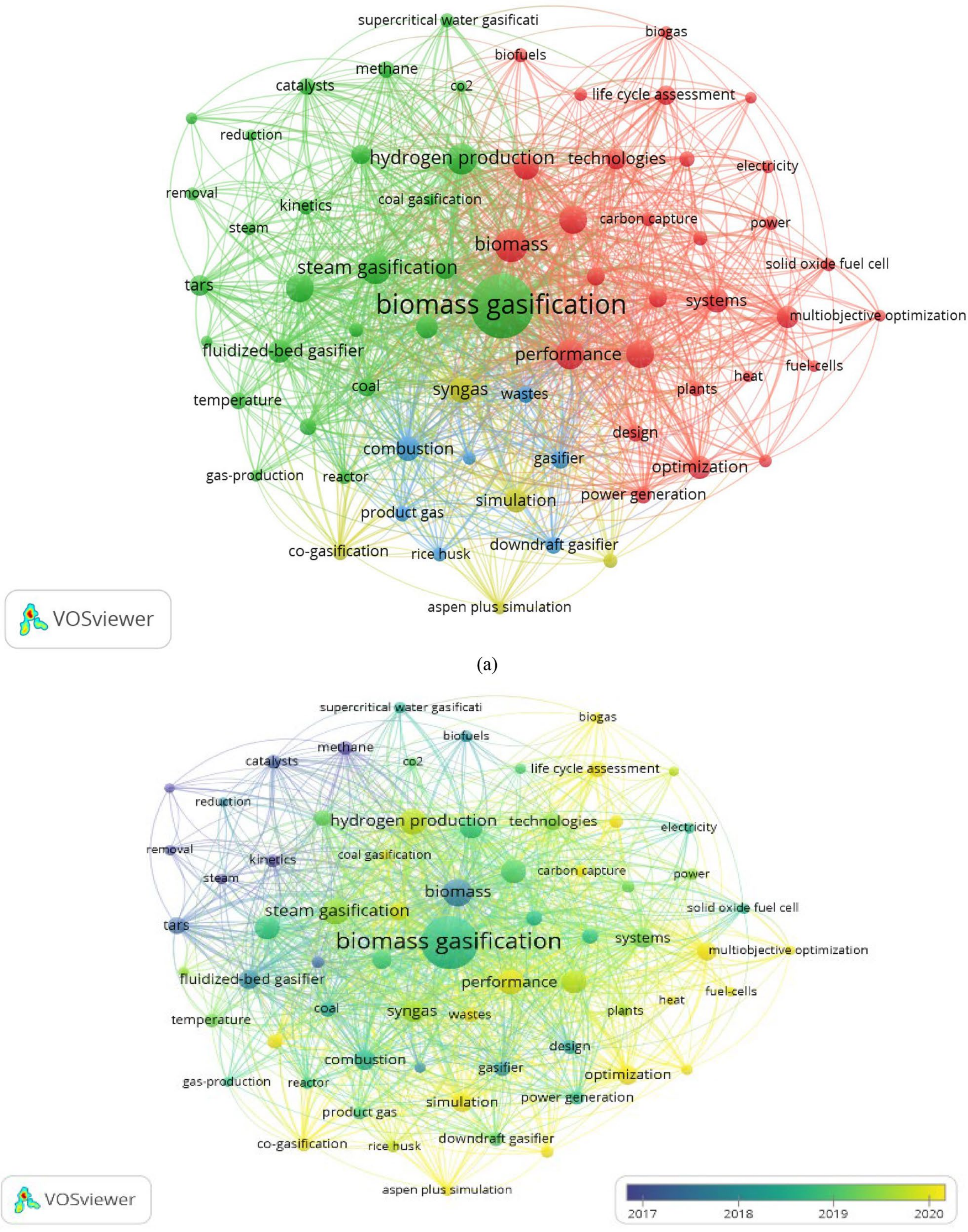

Figure 6. (a) Dominant keywords. (b) Overlay visualization of dominant keywords over time.

Red cluster: electricity generation and sustainability assessment of biomass gasification

The red cluster has keywords like optimization, life cycle assessment, technologies, performance, operation, power generation, plants, and electricity. It highlights a focus on exploring how biomass gasification technology can be integrated into real-world power systems to address energy demand, environmental sustainability, and operational efficiency. These terms reflect the transition from laboratory-scale or component-level research to broader energy applications, where the aim is to deploy gasification technologies as viable alternatives or supplements to fossil fuel-based electricity systems. The presence of keywords such as solid oxide fuel cell, multiobjective optimization and life cycle analysis further suggests an interest in hybrid energy systems that combine biomass gasification with advanced energy conversion technologies and evaluation of carbon foot print of the technology.

Blue cluster: thermochemical conversion of specific feedstock

The blue cluster focuses on the thermochemical conversion of biomass waste, particularly agricultural residues like rice husk, through gasification technologies. It emphasizes the relationship between specific feedstocks and gasifier types, and product gas. Rice husk is often studied owing to its availability and challenging combustion properties, prompting research into suitable gasifier designs such as downdraft and fluidized-bed systems. The use of 'wastes' as a keyword also highlights the role of biomass gasification in sustainable waste management by transforming residues into energy-rich syngas and biofuels.

Yellow cluster: modeling and system design in biomass gasification

This cluster comprises studies that focused on the simulation and computational modeling of biomass gasification processes. Keywords such as Aspen Plus simulation, Computational Fluid Dynamics (CFD), combustion, co-gasification, and syngas indicate the use of process simulation software and fluid dynamics modeling to predict system behavior and optimize design. The methodological orientation of this cluster is critical for computer-aided experimentation/simulation and the validation of theoretical models, enabling researchers to explore process improvements and scale-up strategies.

The clusters showed that the biomass gasification technology research landscape has a coherent structure, highlighting its multifaceted role in supporting global energy transition. They show how the research trend ranges from understanding the technical aspect of biomass gasification technology and reactor design, to system integration for electricity generation and sustainability, and the use of sustainable waste management. They also include the application of simulation and computational modeling for process optimization. This presents a clear picture of how biomass gasification technology has contributed to the energy transition.

Furthermore, the overlay visualization (Fig. 6(b)) provides the temporal context of the keywords. It showed that, while technical studies of gasification processes remain essential, recent years have seen growing research focused on performance optimization, sustainability, environmental assessment, and hydrogen production. This shift reflects a maturation of the field, from isolated technological advancements to comprehensive, systems-oriented approaches, positioning biomass gasification as a scalable and sustainable contributor to the energy transition. Table 1 presents some of the highly cited articles in this research domain.

Thematic map

Figure 7 represents a thematic map based on density and centrality, which are indicators of how developed and important certain topics are in a research field. The map is divided into four quadrants, categorizing themes as either motor, niche, basic, or emerging ones. The vertical axis (development degree – density) measures how well-developed the research themes are while the horizontal axis (relevance degree – centrality) measures how central a theme is to the overall research field. This figure reveals the topics currently leading biomass gasification research, those that are specialized, and areas that are still evolving or hold significant potential for future exploration.[36] In the context of energy transition, the thematic map highlights the evolving role and potential of biomass gasification-based technologies in advancing sustainable energy solutions. Table 2 summarizes the interpretation of these themes meaning within each quadrant.

Motor themes: central and well-developed

The motor themes represent the intellectual core of biomass gasification research. Prominent keywords in this quadrant include biomass, gasifier, and syngas. These topics are not only well-structured but also have high connectivity with

Table 1. Prominent articles in biomass gasification.

Title of article	Total citations	Total Citations (TC) per year	Normalized TC
Techno-economic assessment of hydrogen production processes for the hydrogen economy for the short and medium-term[26]	380	21.11	3.38
Steam gasification of biomass with subsequent syngas adjustment using shift reaction for syngas production: An Aspen Plus model[27]	255	31.88	5.68
An overview of hydrogen production: Current status, potential, and challenges[28]	254	84.67	14.92
Hydrogen-rich gas production from biomass air and oxygen/steam gasification in a downdraft gasifier[29]	253	14.06	2.25
Biomass gasification cogeneration – A review of state-of-the-art technology and near future perspectives[30]	240	20.00	5.05
Pretreated olivine as tar removal catalyst for biomass gasifiers: Investigation using naphthalene as model biomass tar[31]	239	11.95	1.55
A novel biomass air gasification process for producing tar-free higher heating value fuel gas[32]	199	10.47	1.49
Potential of hydrogen from oil palm biomass as a source of renewable energy worldwide[33]	198	11.00	1.76
Experimental study on biomass gasification in a double air stage downdraft reactor[34]	121	6.05	0.97
Biomass gasification in a downdraft gasifier with a two-stage air supply: Effect of operating conditions on gas quality[35]	117	5.85	0.93

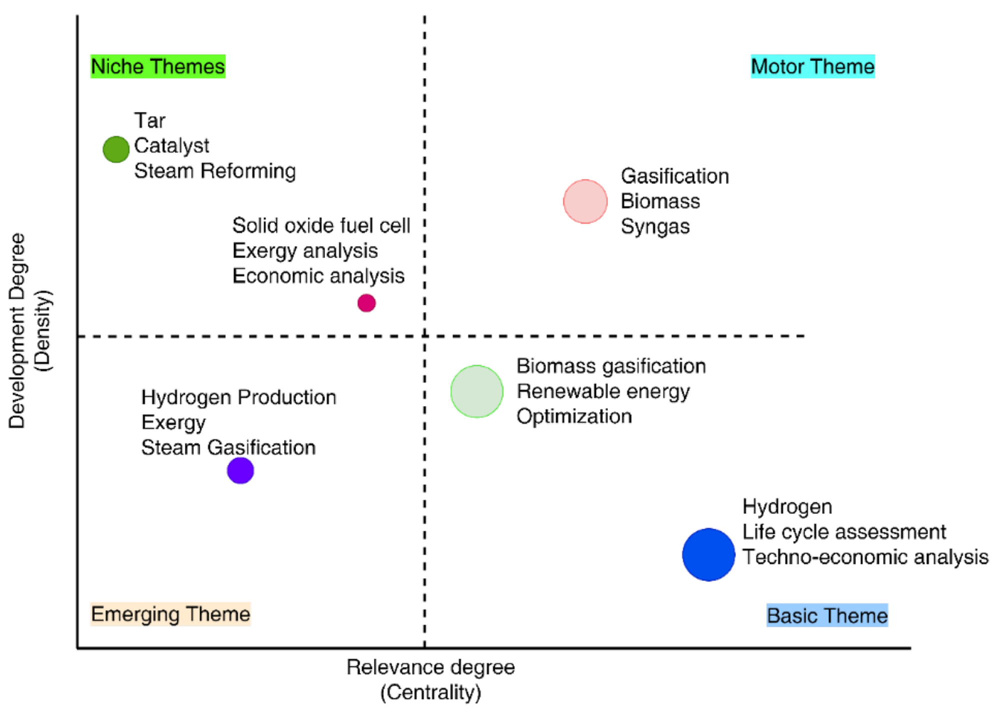

Figure 7. Thematic map of keywords.

Table 2. Interpretation of themes.[37,38]

Quadrant	What it means	Explanation
Upper right (motor themes)	Important and well developed	Topics that are both conceptually well developed and exhibit strong connectivity with other research areas, indicating their central role and sustained scholarly interest within the field
Upper left (niche themes)	Developed but less connected	Highly specialized topics characterized by internal coherence and maturity, yet with limited interaction or cross-topic referencing with broader research domains
Lower right (basic themes)	Central but inadequate depth of research	Foundational or cross-cutting topics that are widely referenced across studies but remain underdeveloped in terms of internal structure or depth of investigation
Lower left (emerging or declining themes)	Weakly developed and marginal	Underdeveloped and weakly connected topics, which may represent nascent research areas with growth potential or declining themes losing relevance within the academic discourse

other areas, reflecting their essential role in the field. Motor themes largely capture technological advancements in converting various biomass feedstocks into syngas through different gasifier designs such as downdraft, fluidized-bed, and updraft reactors.[8,39] The syngas composition and yield are influenced by operational parameters like the equivalence ratio (ER), steam-to-biomass ratio (S/B), and gasification temperature.[40,41] Increasing the ER raises gasification temperatures but reduces CO, H_2, and CH_4 concentrations, while higher temperatures improve carbon conversion, syngas yield, and gasification efficiency by increasing CO and H_2 levels, although CH_4 concentrations tend to drop.[42–44]

The choice of biomass feedstock, gasification agent (air or steam), and operating parameters like ER, S/B, and temperature, along with reactor type, significantly impacts syngas yield and composition. Notably, steam gasification generates more syngas at lower temperatures compared with air gasification.[45]

A major technological challenge addressed within this cluster is tar formation, which degrades syngas quality, clogs equipment, and increases operational costs.[46] Tar condenses at lower temperatures, leading to blockage in equipment, which, in turn, increases operational costs and decreases the efficiency of the system. It also reduces the quality of the syngas by lowering the heating value.[10,39] Recent innovations, such as dual-stage gasifiers and oxygen–steam co-injection, have significantly improved syngas quality while reducing tar levels.[47] These advancements demonstrate the potential of biomass gasification technology in producing high-quality syngas that can be utilized for various applications, including the synthesis of liquid fuels and chemicals.

Basic themes: central but underdeveloped

Basic themes are widely referenced across biomass gasification literature but lack internal maturity. The major topics in this quadrant include hydrogen, life cycle assessment (LCA), techno-economic analysis (TEA), biomass gasification, optimization and renewable energy. The prominence of hydrogen reflects the growing focus on biomass gasification as a low-carbon hydrogen production pathway. However, the hydrogen content in raw syngas is typically low (<18%), prompting ongoing research into enhancing its yield through methods such as catalytic gasification, reforming and system integration.[48] Detailed hydrogen production methods and technologies are presented in Table 3, including *in-situ* and *ex-situ* enhancement of hydrogen content. Similarly, the increased use of LCA and TEA indicates a shift toward holistic evaluations of sustainability and economic feasibility.[49,50] These tools are essential to evaluate the environmental and economic viability of biomass gasification technologies.

Niche themes: specialized but less connected

Niche themes are highly developed topics characterized by internal coherence and maturity, but with limited cross-topic referencing with broader biomass gasification research domains. Key topics in this quadrant include tar, catalyst, and steam reforming, solid oxide fuel cell, and economic analysis. These topics address operational bottlenecks, particularly tar mitigation, which remains one of the most critical barriers to commercial-scale deployment. Studies have explored the use of catalysts (e.g. Ni-based, CaO, olivine) for enhancing tar cracking and improving gas composition.[72–75]

Although well-explored, these areas tend to be specialized and lack broader conceptual linkages to overarching sustainability frameworks, which limits their visibility in interdisciplinary research settings. Nonetheless, these technologies are vital for the scaling up of biomass gasification systems.

Table 3. Key technologies in hydrogen production via biomass gasification.

Method of hydrogen production	Percentage output of hydrogen	Brief description	Limitations	References
Steam gasification	25–35%	Biomass reacts with steam at high temperatures and pressure to produce a gas mixture containing hydrogen, carbon monoxide, and carbon dioxide	Requires high temperatures and pressures (typically 700–1100 °C)	[51–54]
Autothermal gasification	50–60%	Involves partial oxidation of biomass using air, oxygen, or CO_2-enriched air as gasifying agents to provide the heat required for the endothermic gasification reactions. Using CO_2 or air–CO_2 mixtures can enhance CO production, potentially increasing the syngas heating value compared with conventional air gasification. The process can be further enhanced by incorporating CaO carbonation, which provides thermal compensation and shifts equilibrium toward higher H_2/CO ratios and overall gas yields	Complex process, potential for tar formation	[51,55,56]
Plasma gasification	50–73%	It uses high-temperature plasma arcs to convert biomass into syngas, primarily consisting of hydrogen and carbon monoxide. The extreme heat breaks down biomass, increasing hydrogen yield with minimal emissions	High energy consumption, expensive equipment	[57–59]
Sorption enhanced reforming	50–62%	It combines gasification, steam reforming, and CO_2 capture into a single, integrated process to produce high-purity hydrogen from biomass	Requires additional equipment and chemicals	[60–63]
Membrane separation	42–66%	It uses selective membranes to separate hydrogen from syngas. As syngas passes through the membrane, hydrogen is selectively filtered out while other gases like carbon dioxide and carbon monoxide are retained	High energy consumption, potential for membrane fouling	[64,65]
Water-gas shift reaction	40–65%	Involves reacting carbon monoxide (from syngas) with water (steam) to produce additional hydrogen and carbon dioxide	Requires additional catalyst and energy	[55,63,66]
Catalytic gasification	35–65%	Catalytic gasification uses catalysts to speed up the conversion process, improving hydrogen yield and efficiency while reducing energy consumption	Requires additional catalyst and fast rate of catalyst deactivation	[67–71]

Emerging or declining themes: peripheral and underdeveloped

Themes in the lower-left quadrant are characterized by low density and centrality, suggesting limited development and weak cross-topic referencing to the mainstream literature. In this analysis, exergy analysis, steam gasification, and hydrogen production appeared in this category. Interestingly, as hydrogen also appeared in the basic theme quadrant, it reflects its transitional status and also indicates that these topics are emerging and not declining. Its presence in both quadrants may indicate that while hydrogen is gaining scholarly attention, its integration with other topics is still limited, pointing to a fragmented knowledge structure.

The inclusion of exergy analysis and steam gasification as emerging topics indicates rising interest in optimizing energy efficiency and resource utilization.[76] Exergy-based evaluations are increasingly used to compare different gasifier configurations and identify losses, while steam gasification has shown promise for higher hydrogen yields under milder conditions.[45]

These findings suggest that while biomass gasification technologies are robust, there remains significant scope for innovation in process integration and decarbonization pathways to achieve the energy transition target. The field is progressively moving from isolated technological advancements toward system-oriented research, which is critical for achieving net-zero targets.

Biomass gasification technology, operating conditions and scaling challenges

Biomass gasifiers are mainly of three types: fixed-bed, fluidized-bed, and entrained-flow.[77] Operating conditions such as temperature, gasifying agent, and residence time significantly influence the gasification process and product quality.[78] Steam-assisted gasification has garnered attention for its potential to improve syngas quality and reduce tar formation. However, challenges persist, including the presence of impurities like polycyclic aromatic hydrocarbons and soot in the syngas.[78] Scaling up gasification technologies requires consideration of factors such as feedstock properties, gasifier type, and operating parameters.[77] Table 4 presents a concise summary of various reactors, their operating conditions and scaling-up challenges.

Role of artificial intelligence/machine learning in optimizing biomass gasification systems

Recent studies have explored the use of artificial intelligence (AI) in biomass gasification, with applications aimed at solving inherent process challenges. For instance, AI is being used to predict hydrogen concentration in syngas,[84–86] syngas yield,[87] and overall syngas composition, lower heating value, and cold gas efficiency using combined Extreme Gradient Boosting (XGBoost) and Shapley additive explanations machine learning (ML) models.[88] Several review articles further highlight these advancements.[89–91] This body of work shows that AI can help solve the complexity and non-linearity problems often encountered in biomass gasification modeling owing to its multivariable nature.

AI-based models, including artificial neural networks, support vector machines, random forests, and XGBoost, can predict syngas composition (H_2, CO, CH_4) and other product yields (tar, char) with high accuracy. For example, a trained artificial neural network model achieved an R^2 value of 0.92 for predicting H_2, CO, and CH_4 composition. XGBoost models have also shown significantly lower error margins for H_2 and CH_4 composition compared with traditional thermodynamic models like Aspen Plus.[92]

Furthermore, AI-driven optimization methods, such as genetic algorithms and reinforcement learning, can determine optimal operating conditions (e.g. reactor temperature, pressure, gasifying agent flow rates) to maximize syngas production while minimizing tar formation. Genetic algorithms, for instance, has been shown to increase syngas production by 15% and reduce tar formation by 20% compared with conventional methods.[91] Artificial intelligence can also improve traditional models by generating data that is difficult or expensive to measure directly, such as kinetic parameters.

This shows that integrating AI/ML offers significant potential to improve the efficiency, reliability, and sustainability of biomass gasification, which strengthens its competitiveness as a clean, adaptable technology for the energy transition.

Biomass gasification potential contribution to energy transition challenges

Biomass gasification has emerged as a pivotal technology in the transition to sustainable energy systems, aiming to reduce the environmental footprint and improve the efficiency of energy production. By converting biomass into syngas, a mixture of carbon monoxide, hydrogen, and methane, gasification allows the production of electricity, heat, and biofuels. Between 1997 and 2024, numerous studies have contributed to understanding how biomass gasification can contribute to energy transition, offering both technological advancements and critical assessments of feasibility (Fig. 8). However, there is a need to understand some of the challenges limiting energy transition and examine the promising pathway biomass gasification technology offers.

Grid stability and energy supply intermittency

One of the major challenges in the transition to renewable energy is the variability and intermittency of sources like wind and solar (Bakht *et al*., 2022).[93,94] Biomass gasification offers potential for a stable baseload energy supply, particularly in off-grid or weak-grid scenarios, complementing intermittent renewables and enhancing grid stability.[95]

Moreover, by adopting a poly-generation approach, simultaneously producing electricity, heat, hydrogen, and biofuels, biomass gasification systems can improve overall energy efficiency and enhance electric systems resilience.[96,97] These attributes not only support grid stability but also contribute to broader goals of energy security and climate change mitigation.

Energy storage limitations

Energy storage remains a bottleneck for renewable energy adoption, and biomass gasification provides a solution to this problem.[93,98,99] Biomass gasification converts organic matter into synthesis gas (syngas) and further into biofuels, a versatile energy carrier that can be stored and utilized flexibly. This flexibility helps to stabilize the energy supply, especially

Table 4. Comparative analysis of biomass gasification technology.

Reactor type	Design features	Typical operating conditions	Advantage	Disadvantage	Scaling challenges
Fixed-bed (downdraft)[10,79]	Carbon conversion efficiency: 60–80% Lower Heating Value (LHV): 3.72–11.32 MJ Nm^{-3} Cold gas efficiency: 60–70%	Temperature: 1000–1400 °C Needs dry feedstock (<20% moisture content) Large particles (10–100 mm) Pressure: low/atmospheric Gasifying agent: air Equivalence Ratio (E.R.): 0.14–0.5	High temperature promotes tar cracking, thereby producing a cleaner gas with low tar content (0.1–1.2 g Nm^{-3}), making it suitable for direct use in internal combustion engines	High exit gas temp (approx. 600 °C) requires cooling Lower overall thermal efficiency compared with the updraft design Non-uniform temperature distribution	Limited feedstock flexibility (low ash tolerance) Hard to scale up beyond small units (<1 MW) because of bridging and channeling Formation of uneven temperature distribution leading to a cold spot and increased tar formation.
Fixed-bed (updraft)[10,77]	Carbon conversion efficiency: 90–95% LHV: 4.1–6.2 MJ Nm^{-3} Cold gas efficiency: 70–90%	Temperature: (<900 °C) Particle size: flexible particle size (5–100 mm) Moisture content: (≤40%) Pressure: low/atmospheric Gasifying agent: air, steam	Simple design and its tolerance for high-moisture biomass. Produces cooler gas (approx. 300 °C) Can handle wetter feedstock Suitable for medium to large-scale operations (1.1–12 MW)	Very high tar (20–100 g Nm^{-3}) Non-uniform temperature distribution	Low efficiency Costly gas cleanup setup High cost of maintenance Frequent operational downtime
Fluidized-bed (BFB)[77,80]	Carbon conversion efficiency: 85–95% LHV (air): (4.1–6.0 MJ Nm^{-3}) LHV (steam): 10–16 MJ Nm^{-3} Cold gas efficiency: 50–90%	Temperature: 700–900 °C Particle size: 1–20 mm Moisture content: ≤50% Pressure: low/atmospheric Gasifying agent: air/steam/oxygen E.R.: 0.17–0.4	Moderate tar (1–15 g Nm^{-3}) Uniform temperature distribution High heat transfer rates Flexibility to use a wide range of fuels	Incomplete carbon conversion can occur Can be scaled up to 50 MW	Complex design/operation Moderate tar and particulates need cleanup More costly than fixed-bed
Fluidized-bed (CFB)[77,81]	Carbon conversion efficiency: 85–90% LHV (air): (4.1–6.0 MJ Nm^{-3}) LHV (steam): 10–16 MJ Nm^{-3} Cold gas efficiency: >80%	Temperature: 700–900 °C Particle size: 1–20 mm Moisture content: Pressure: low/atmospheric Gasifying agent: air/steam/oxygen E.R: 0.17–0.4	Better circulation and temperature uniformity	More complex and expensive to build owing to the need for cyclones and particle recycling equipment. Can be scaled up to 50 MW	High operational and maintenance cost Demands skilled labor and advanced control Erosion of the reactor's wall and cyclone owing to high particle velocity
Entrained-flow[82,83]	Carbon conversion efficiency: >98% LHV: 6–12 MJ Nm^{-3} Cold gas efficiency: >80%	Temperature: 1200–1800 °C Particle size: 0.1–1 mm Moisture content: Low moisture Pressure: 20–70 bar Gasifying agent: oxygen E.R.: 0.2–0.4	It is highly efficient and produces a very clean, high-quality syngas with extremely low tar formation (approx. 0.2 g Nm^{-3})	Need high-grade materials to build a reactor that can withstand high temperatures Expensive to operate owing to cost of preparing feedstock and oxygen generation	High material/operational cost (owing to ash melting, extreme temperature) Limited feedstock flexibility Clogging of the feedstock during feeding owing to the fine nature of the biomass Less suited for small-scale use

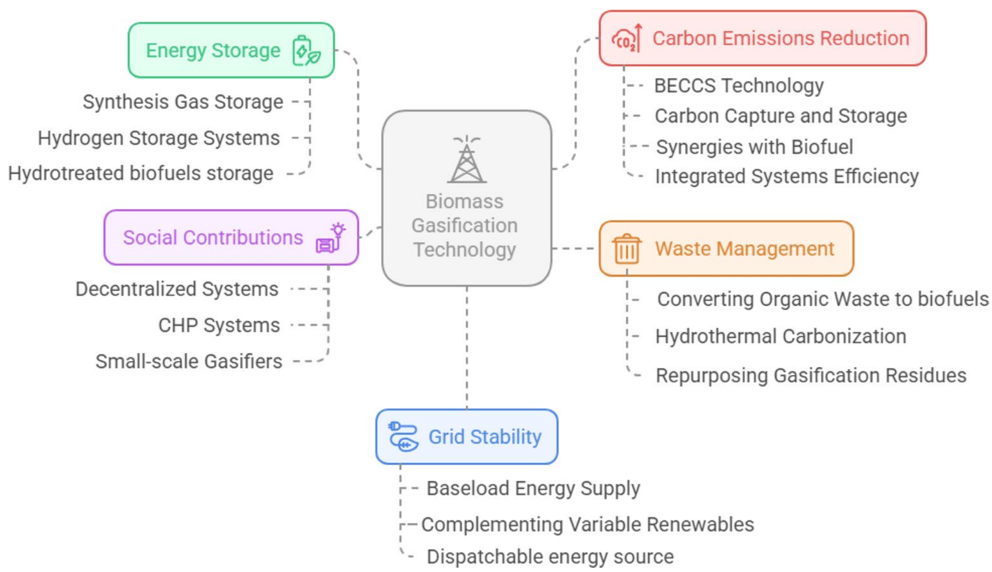

Figure 8. Biomass gasification technology potential contributions to energy transition.

when integrated with hydrogen storage systems.[100] By upgrading biogas into high-energy-density biofuels, biomass gasification offers a carbon-neutral solution for energy storage.[101] These advancements allow for efficient energy management and storage, ensuring a consistent energy supply during fluctuations in demand.

Carbon emissions reduction

One of the significant advantages of biomass technologies lies in their potential to mitigate carbon emissions in difficult to decarbonize sectors, particularly through bioenergy with carbon capture and storage systems.[102–104] In Indonesia, for example, the integration of carbon capture with biomass power plants could reduce greenhouse gas emissions by up to 2.2 million tonnes of CO_2 annually (Sutrisno *et al.*, 2021)[105]. Moreover, combining biomass gasification with other technologies such as solid oxide fuel cells and solar-driven hydrogen production has the potential to enhance system efficiency further while reducing CO_2 emissions. Under optimal conditions, this hybrid system could achieve an exergy efficiency of 24.85% with CO_2 emissions as low as 0.257 kg $(kWh)^{-1}$. This is a significant improvement compared with 20.0% and 0.368 kg $(kWh)^{-1}$ reported at baseline, demonstrating the effectiveness of the proposed system in minimizing environmental impact.[106]

Waste management and sustainability

Biomass gasification also plays a crucial role in sustainable waste management by the possibility of converting agricultural, industrial, and forestry waste into syngas to be used for biofuels synthesis. This process supports the circular economy by utilizing organic waste that would otherwise go to landfill or be burned.[107]

In addition, integrating hydrothermal carbonization prior to gasification can enhance overall efficiency and reduce environmental impact.[108] Moreover, gasification residues can be repurposed as CO_2 adsorbents, promoting a near-zero-waste system and enhancing the environmental sustainability of this technology.[109]

Social and geographic barriers

One of the social challenges in the energy transition is ensuring equitable energy access, particularly in rural or off-grid areas.[110,111] Decentralized biomass energy systems based on gasification can enhance local energy production, particularly in off-grid and rural areas, addressing energy access challenges.

Biomass-driven technologies, like combined heat and power systems, convert local agricultural and forestry by-products into electricity and heat, reducing transportation costs and improving energy security.[112] Small-scale gasifiers could benefit millions in rural regions.[113] Biomass systems also offer lower operational costs and greater resilience compared with traditional sources, with competitive levelized costs of electricity and enhanced sustainability.[114] Furthermore, gasification generates byproducts such as char, ash, tar, and liquid condensates, which can be repurposed for agricultural or industrial applications, supporting waste valorization and contributing to a circular economy.[115] This makes biomass gasification technology a viable pathway to attain energy transition goal.

Synergy between biomass gasification, low-carbon hydrogen and biofuels

Biomass gasification technology offers a promising pathway for producing low-carbon hydrogen. This hydrogen can be integral to biofuel production, especially in the sectors that prioritize the use of biofuels such as transportation, chemicals, and energy production. In this context, the generated syngas is processed using Fischer–Tropsch synthesis to convert the syngas into liquid biofuels.[116,117]

Hydrogen can play a key role in improving biofuel quality and energy content through hydrotreatment, a key chemical process in bio-refining. The integration of low-carbon hydrogen into these processes boosts production efficiency, biofuels yield and helps ensure that the overall life cycle emissions of biofuels remain low.[118] This is particularly significant in maintaining a low-emission profile for biofuels throughout their production cycle, contributing to the decarbonization of the transportation and energy sectors.[119]

Moreover, surplus energy from renewable sources, such as wind or solar, can be stored in the form of hydrogen, which can then be used to enhance biofuel production for electricity generation when renewable energy supply fluctuates.[100] This storage capability ensures that biofuel production remains consistent and stable, even in the face of intermittent energy generation, thus promoting a more resilient energy system.

An important performance indicator in this synergy is carbon usage efficiency (CUE), which represents the proportion of biomass carbon converted into useful energy carriers such as CO and H_2 rather than lost as CO_2, tar, or char. High CUE values are essential for maximizing the hydrogen yield via the water–gas shift reaction and for ensuring efficient carbon incorporation into liquid fuels during Fischer–Tropsch synthesis. Thus, CUE not only improves the overall productivity of low-carbon hydrogen and biofuels but also enhances the climate benefits of biomass gasification when assessed across the energy transition.

In addition to its role in production and refining, the blending of biofuels with hydrogen, creating hybrid fuels, offers further environmental and performance advantages.[120] Hydrogen-enriched biofuels are known to exhibit cleaner combustion characteristics, reducing harmful emissions and improving engine efficiency. These hybrid fuels not only contribute to lower emissions but also optimize fuel performance, showcasing the potential for combining biofuels and hydrogen to create a more sustainable energy solution (Fig. 9).

Policy and economic barriers to adoption

Beyond the technical hurdles, the transition of biomass gasification from research to widespread commercial adoption is significantly hampered by policy and economic barriers. While renewable energy policies such as feed-in tariffs, portfolio standards, and tax incentives exist, they are often designed for wind and solar rather than tailored to the specific needs of biomass gasification. As a result, developers face uncertain revenue streams, investment risks, and difficulties in accessing finance. Inconsistent policy frameworks, lengthy permitting procedures, and the limited integration of biomass gasification into national energy strategies further constrain adoption. In addition, many gasification technologies are still at pilot or demonstration stages, which means there is a need for sustained research and development support to improve efficiency, scalability, and reliability. Economically, high capital costs, underdeveloped feedstock supply chains, and the absence of established markets for syngas or biomethane make projects less competitive, while subsidies for fossil fuels or alternative technologies exacerbate the challenge. Addressing these challenges can significantly enhance the capability of biomass technology to meet the energy transition goal.

Future research direction

To identify future research directions in biomass gasification technologies and their role in the energy transition, a keyword trend analysis was conducted for articles published over the last five years (2019–2024), as presented in Fig. 10. The results highlight that improving and enhancing hydrogen production is a crucial area of research. Current hydrogen yields at the biomass gasifier outlet can be enhanced through techniques like catalytic gasification. Additionally, reducing tar formation and optimizing the gasification process are essential for increasing both the quality and economic viability of hydrogen-rich gas. To address these complexities, the disruptive potential of AI should be explored. Advanced AI models, including support vector machines, genetic algorithms, and random forests, can be employed to manage the complex interdependencies of gasification processes, enabling more sophisticated process control and simulation of reaction kinetics. Furthermore, because many renewable resources are intermittent, research into the effective storage of energy carriers like syngas, biofuels, and hydrogen derived from biomass gasification remains an active and critical field of study.

Research should also prioritize integrating carbon capture technologies with biomass gasification, particularly through bioenergy with carbon capture and storage systems.[121] This integration holds the potential to achieve negative carbon emissions, contributing significantly to global decarbonization efforts. Studies should focus on optimizing

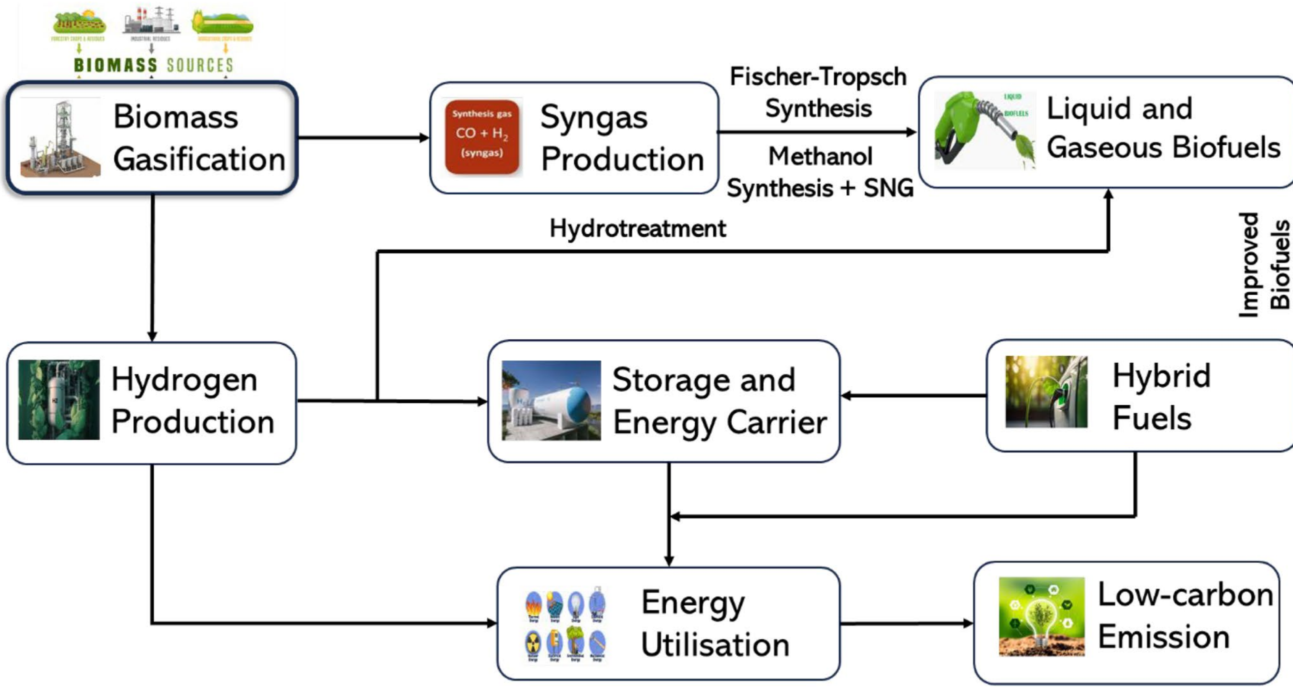

Figure 9. Synergy between biomass gasification, hydrogen and biofuels.

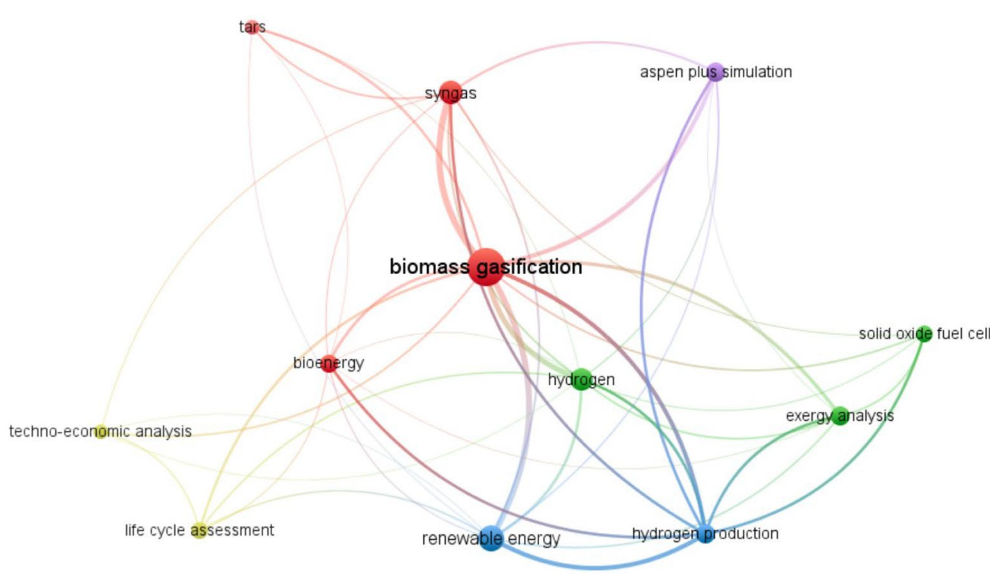

Figure 10. Keyword trend analysis for articles published between 2019 and 2024 for future research direction.

gasification parameters, such as temperature and the steam-to-biomass ratio, to optimize CO_2 capture. All these directions require the support of life cycle assessment of the product system.

Finally, assessing the techno-economic feasibility of biomass gasification technologies is crucial to its widespread adoption. Comparative analyses with other renewable technologies, along with LCAs and TEAs, will provide insights into its environmental and economic viability. Such studies will help guide policymakers and stakeholders in making informed decisions regarding the deployment of biomass gasification in global energy systems. Other identified areas are solid oxide fuel cells, exergy analysis and simulation studies.

| *Biofuels, Bioprod. Bioref*. (2025); DOI: 10.1002/bbb.70086

Conclusions

It was observed that despite significant technological advancements and increasing integration of biomass gasification into energy systems, its full potential within the broader energy transition context remains underexplored. This study therefore, analyses the academic literature on biomass gasification and energy transition using systematic bibliometric content analysis techniques and a technical analysis. It provides a comprehensive and up-to-date overview of the knowledge structure in this field by highlighting its development and evolution over time. The data for bibliometric analysis were obtained from the WoS database because of its significant overlap in journal articles with other major databases that focus on the life sciences, physical sciences and technology resulting in the selection of a robust body of literature, forming a trustworthy dataset. This dataset enables the identification of key trends, prominent research areas, and identifies future direction on biomass gasification technology. Based on the analysis, the conclusions of this study are drawn as follows:

1. The trends in biomass gasification and energy transition research from 1994 to 2024 reveal three distinct stages. The 'initial' stage (1997–2008) saw limited research. Interest grew in the 'rise' stage (2009–2018), marked by increasing publications and exploration of gasification's integration with power systems. The 'prosperity' stage (2019 onwards) has seen a surge in research, with over 100 publications annually, reflecting significant advancements and ongoing interest in the field.
2. The analysis of trends and distribution of scientific journals reveals that 47% of the publications on biomass gasification are concentrated in seven core journals, with *Renewable Energy* leading the contributions, followed by *Energy* and the *International Journal of Hydrogen Energy*. China, the United States, India, and Italy are the leading countries in biomass gasification research, with China producing the most publications, while international collaborations are primarily concentrated among China, the United States, India, and Canada.
3. Thematic analysis identifies key themes in biomass gasification research through a thematic map. Major findings show that hydrogen production, exergy, and steam gasification are active areas of research, highlighting the potential of biomass gasification as a viable solution for clean hydrogen production, energy optimization, and the development of more sustainable and scalable energy transition pathways.
4. Future research in biomass gasification should focus on efficient hydrogen production from biomass, alongside advancements in the storage of biomass gasification energy carrier products such as syngas and biofuels. Likewise, the techno-economic feasibility of biomass gasification technologies should be explored to facilitate widespread adoption of the technology.

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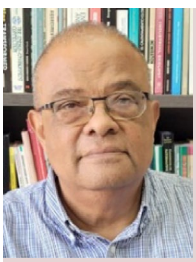

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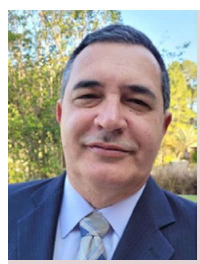

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