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Tar upgrading in biomass and waste gasification: Bibliometric insights and future directions

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Abstract

Tar upgrading is a major roadblock to the valorization of mixed waste (e.g., biomass and municipal solid waste) via gasification, and it remains a critical research focus. In this study, the Bibliometrix R package, CiteSpace, and VOSviewer were applied to conduct a bibliometric analysis of the research landscape in the tar upgrading domain over the period 2015–2024, based on a validated dataset of 1,190 documents retrieved from the Web of Science Core Collection (WoS). The primary analysis revealed a relatively low annual growth rate of 2.1%, a collaborative research environment with an average of 5.11 co-authors per document, and an international collaboration rate of 31.4 %. According to institutional and regional collaboration networks, Asian institutions, nearly 60 % of which are from China were identified as the most active in terms of publications and internal collaboration, while institutions in the United Kingdom were found to be more active in international collaboration. Word cloud keyword analysis showed that biomass gasification, hydrogen production, tar, and catalysts are the most influential terms, whereas biomass gasification and hydrogen production, with 1021 and 414 occurrences, are emerging as the core research topics. Furthermore, keyword clustering revealed that steam is the most influential medium, while non-thermal plasma and Ni-based catalysts constitute key themes in tar conversion toward desired products. Using thematic insights, this study identifies current knowledge gaps and suggests future practical directions for promoting sustainable practices in mixed waste gasification via reducing tar by-products.

Keywords: Mixed waste valorization, gasification, tar removal, bibliometrics, hotspots

1. Introduction

Global population growth and economic development are key factors of the significant and the steady growth of waste by 2050, expected to total 4.2 billion tons [1,2], accompanied by a rapid rise in energy consumption. The widespread application of non-renewable fossil fuels as energy sources, accounting for around 80 % [3], leads to major carbon dioxide emissions and is a primary driver of climate change, as well as associated social and environmental impacts [4,5]. Municipal solid waste (MSW) is a heterogeneous material composed of solid and energy-rich fractions, which can be processed through several mechanical steps to produce refuse-derived fuel (RDF) [6]. RDF primarily consists of plastics (20–60 %), cardboard, textiles, paper, and a small amount of biomass (wood) [7]. Thus, the use of RDF as a feedstock to produce energy, value-added chemicals, and fuels not only contributes to a greener environment but also fulfills energy requirements [8].

Similarly, biomass waste (BMW), considered as an alternative renewable energy source, is widely available and can be obtained from various sectors, including agriculture, livestock, forestry, and fisheries, which can serve as a sustainable feedstock for biorefineries [9]. In part, various forms of bioenergy (e.g., H_2 and other chemicals) derived from BMW might offer solutions to the energy crisis. In this sector, among all thermochemical routes, gasification is advanced and attractive technology for both MSW/BMW processing to produce several products to be explored in the energy transition. Gasification can be performed at temperatures ranging from 600–1000 °C [10], in the presence of gasifying agents to decompose carbonaceous feedstock into syngas (H_2+CO), solid (char), and liquid by-product (tar) [11]. Tar is an inevitable by-product of gasification, consisting of condensable hydrocarbons that can settle in the low-temperature parts of the gasification system and adhere to catalyst active sites, leading to the deterioration of both the system and the catalysts, resulting in reduction of syngas yield and overall system efficiency [12–15]. Char is another by-product; in contrast to tar, it contains carbon-rich materials that can usually be used directly or processed for use as catalyst supports and soil fertilizers.

Considering the three products of gasification, H_2 -rich syngas production is a hot research topic that has attracted significant interest due to its diverse applications, including energy generation in the form of heat and electricity via engine combustion and gas turbines, as well as catalytic synthesis processes for producing fuels and chemicals [16], as depicted in **Fig. 1**. Despite the benefits, syngas produced from gasification contain several contaminants, including tar, sulfur

(mainly as H_2S and trace amounts of COS), and chlorine (primarily as HCl), being the predominant undesirable species in raw syngas [17]. These impurities in MSW/BMW conversion into valuable products are, in fact, a critical roadblock to the large-scale development and implementation of this process. Amongst, tar stands out as a major unwanted impurity, causing significant problems in the system, including catalyst deactivation during sulfur or chlorine mitigation, equipment and pipeline clogging, and hindering subsequent syngas applications. Thus, upgrading or mitigating tar in MSW/BMW gasification systems is a critical step that depends on both the gasification environment and the intended applications.

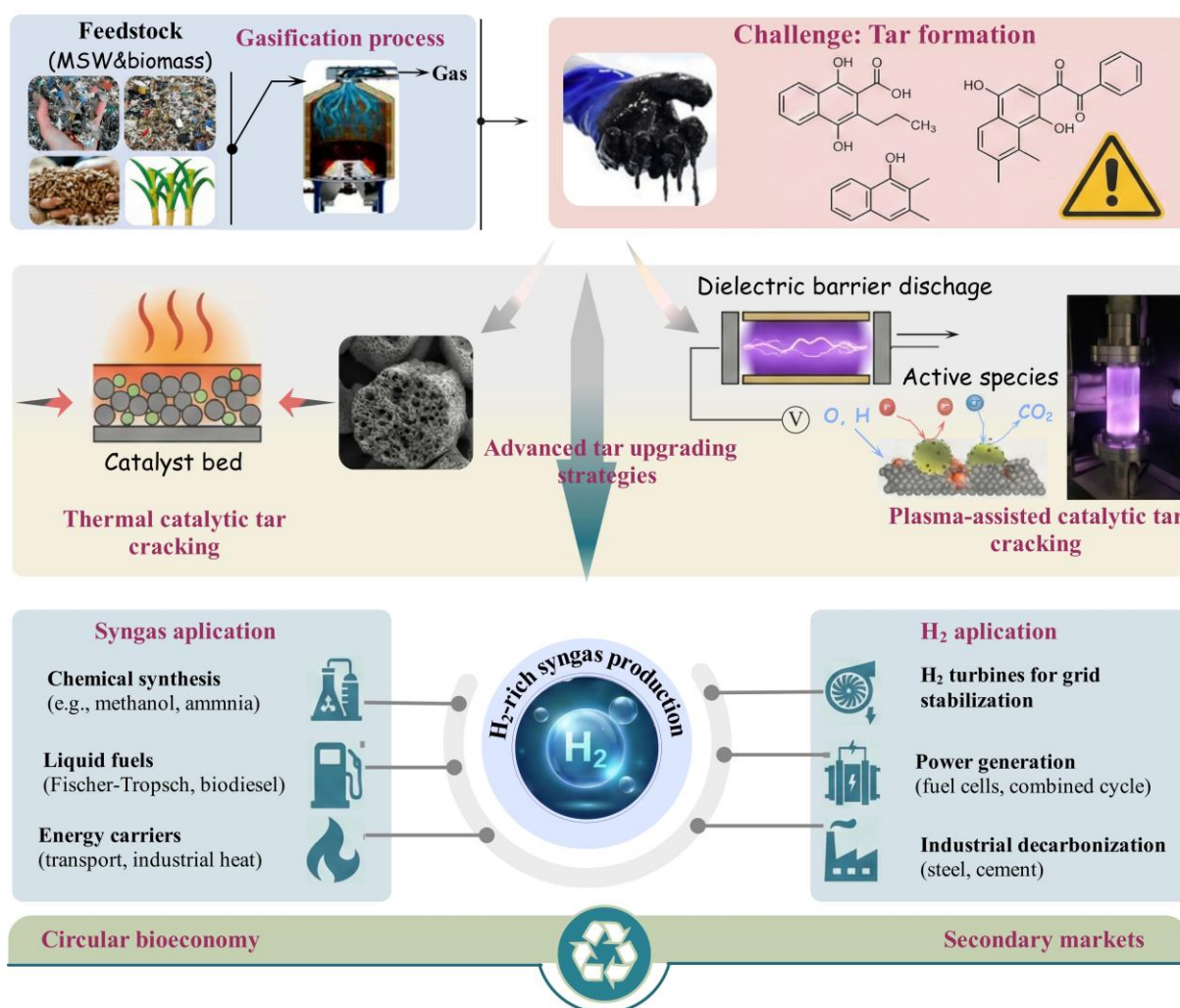


Fig. 1. MSW/BMW transforming into H_2 -rich syngas, by two advances tar upgrading systems, the benefits and applications of syngas and H_2 .

While numerous studies have addressed tar in MSW/BMW gasification, noticeable gaps remain, which can be attributed to the complex nature of tar, the variability of reaction conditions, and the challenges in developing durable and cost-effective catalysts, and thus require focused attention [18,19]. Therefore, a comprehensive quantitative and qualitative

analysis of the existing literature is required to systematically evaluate current knowledge, identify research hotspots and not well studied areas. Bibliometric analysis provides a robust framework to address this need by objectively assessing research productivity, topic development, and levels of collaboration in the field. This approach investigates the status of core studies and applies mathematical and statistical methods to comprehensively quantify existing knowledge and identify opportunities for future research [20]. Recently, numerous bibliometric insights have examined MSW/BMW conversion via gasification to produce value-added products; however, limited attention has been given to tar upgrading. Alao et al. conducted a bibliometric analysis of BMW and organic waste conversion into bioenergy; however, their study did not include a content analysis of tar removal [21]. Borges et al. provided valuable insights into BMW conversion and H₂ yield [22]. Nevertheless, only few studies focused particularly on tar abatement from syngas. Alsaedi et al. reported comprehensive study into biomass energy and gasification with a focus on tar removal strategies [20]; however, their analysis relied solely on the VOSviewer tool, which may limit the depth of insights into this research area.

- Accordingly, this study provides a comprehensive analysis to help scholars to figure out about the ongoing research status, key research topic, and trends in MSW/BMW valorization through gasification, with particular attention on tar upgrading to promote H₂-rich syngas production. It further aims to introduce new insights through comprehensive, visualized bibliometric analysis conducted using CiteSpace, VOSviewer, and the R-based bibliometric package, offering valuable guidance for future research directions. The data derived from the WoS related to the study field were analyzed and visualized with the following objectives:
- Conduct a comprehensive analysis of various aspects, such as statistical features, collaboration, and frequency, to explore key research directions and offer a valuable view of the field
- Examine the current research landscape, future characteristics, and key trends in this field, to offer researchers with important and critical output to support future studies.

To achieve these objectives, the following research procedures were conducted, as shown in **Fig. 2**.

- Statistical analysis was carried out to evaluate annual publication trends, identify the most active research areas, and highlight the primary domains contributing to this field.

- Collaboration dynamics were examined to explore the current collaboration networks among institutions, countries, and authors, thereby identifying the most prominent contributors in the study area.
- Hotspot analysis was performed to investigate the evolution of research hotspots related to waste gasification and tar upgrading and their conversion into H₂-rich syngas, as well as to predict keyword co-occurrences and keyword burst trends.
- Current progress and prospects were analyzed to provide comprehensive insights into this research domain, helping to better realize the field and to guide future research more precisely.

2. Methodology framework

2.1. Extraction of data

The data collection was conducted using the WoS platform due to its extensive index of academic literature and user-friendly search functions that enable highly customizable search criteria. The data retrieval took place between February 5 and 15, 2025, with search criteria of TS= ((“Biomass gasification” OR “Municipal solid waste gasification” OR “plasma gasification”) AND (“tar removal” OR “tar reduction” OR “catalysts” OR “catalytic cracking” OR “catalytic reforming” OR “Non-thermal plasma” OR “plasma-catalysis”)). The retrieval period considered the last 10 years, from January 1, 2015, to December 31, 2024, and language was limited to English. The document type was restricted into two most common documents (e.g., articles and review articles) which supply important information to prospect the knowledge structure in the related filed study. Based on data retrieval and screening, a total of 1,190 documents were selected as raw data and exported in the format of plain text, with full records and cited references.

2.2. Data visualization

In this study, VOSviewer 1.6.20, the R-based Bibliometrix package 4.5.2, CiteSpace 6.4.1, and Origin were applied, as they offer significant advantages and are widely used for correlation analysis and data visualization. First, the R-based Bibliometrix package was used to identify general statistical characteristics. Second, VOSviewer (v. 1.6.20) was utilized to visualize the overlay network, which enables robust temporal analysis of the related study area and is well-suited for large-scale datasets. Lastly, CiteSpace 6.4.R1 (64-bit), running in a Java-based

environment and grounded in citation analysis theory, was employed to remove duplicate data and subsequently evaluate the clustering and keyword bursts [24]. To improve the clarity of the patterns shown in the visualized networks, the key parameters, such as the Link Retaining Factor and Maximum Links Per Node was set to 10 and Look Back Years was set to 10 in the project configuration. Furthermore, the slice length was set to 1 year, with initial term extraction based on the Title, Abstract, Author, and Keywords Plus fields. CiteSpace facilitates deeper structural analysis through clustering, providing detailed insights into underlying themes, specific topics, and distinct research areas. To interpret the notable content of each cluster, three labeling function algorithms, Latent Semantic Indexing (LSI), Log-Likelihood Ratio (LLR), and Mutual Information (MI), are available to extract the most representative terms from the Title, Abstract, or Author Keywords [23].

The structural properties of generated clusters can be characterized by three key metrics: (1) Modularity measures the degree of the maps divided into independent clusters on a scale of 0 to 1, with high score indicates a well-structured network clustering; (2) Mean Silhouette evaluate the cluster structure ranging from -1 to 1 , with a higher score indicates better separation and distinction among clusters, and (3) Betweenness centrality quantifies the role of an node by measuring how often it is located on the shortest path between other nodes and normalized on a scale from 0 to 1.

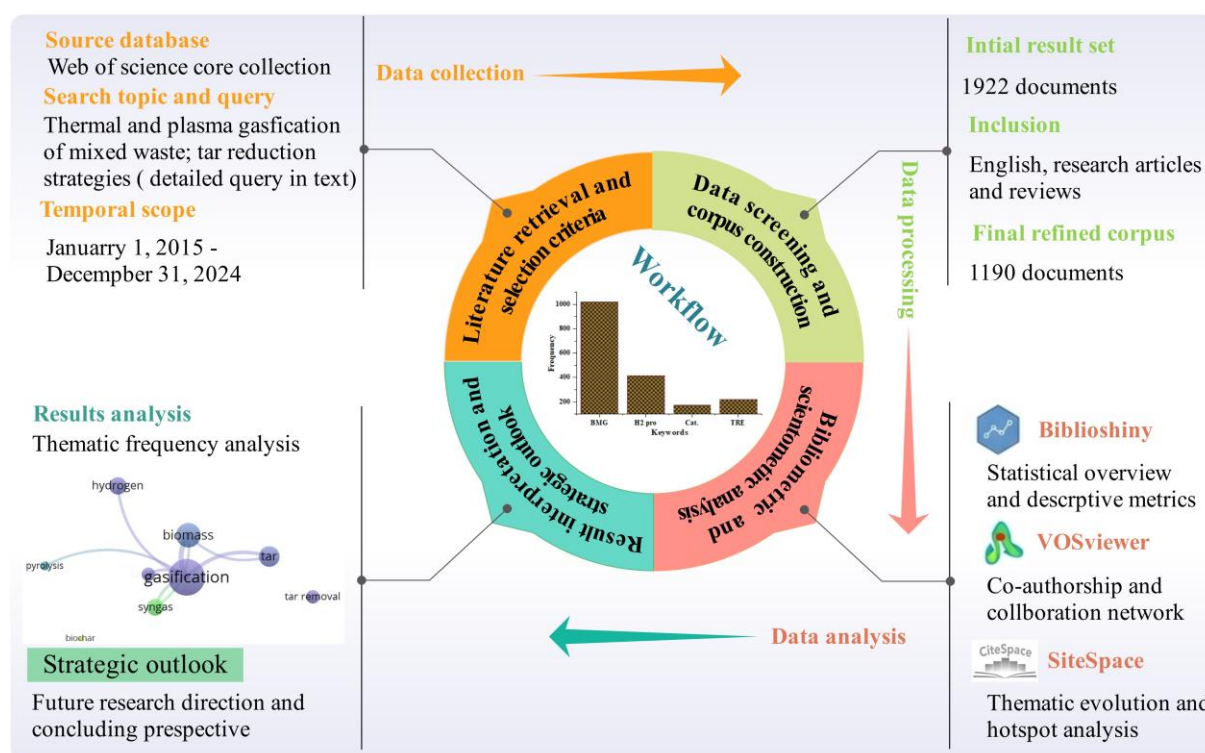


Fig. 2. Research methodology and bibliometric analysis workflow

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165 **3. Result and discussion**

166 **3.1. Analysis of statistical characteristics**

167 According to the WOS Core Collection database, the first articles on MSW/BMW gasification
168 tar removal and production of clean energy were published in 1984, with a total of two
169 documents, no significant study has been conducted in this research area from then until 2002.
170 The annual research growth in this domain was slow, with the number of publications reaching
171 around 50 in 2010. However, in the past 10 years (2015–2024), the generation of value-added
172 fuel from renewable sources has gained traction due to energy deficits and environmental
173 degradation, driven by the annual increase in waste generation and the continued use of fossil
174 fuels as an energy source. The upward trend in publications reflects the growing development
175 in this research area. Over the past 10 years a total of 1,190 documents were validated, with
176 the following key findings: (a) the annual growth rate of articles in this topic is 2.1 %, (b) a
177 total of 3,777 authors contributed to this research, of whom 19 authored documents
178 independently, (c) 31.4 % of the documents involved international collaboration, and (d) each
179 document had an average of 5.11 co-authors (R-based bibliometric package).

180 As shown in **Fig. 3a**, the validated documents were classified into four categories. Articles
181 ranked first, accounting for 83.7 %, followed by review articles (12.3 %) and proceeding papers
182 (7.6%). According to previous bibliometric reviews on MSW/BMW conversion into value-
183 added fuel, the proportion of review articles was 10.8 % [24], indicating a 2 % increase. The
184 annual publication numbers exhibit the trend of research field growth and can help scholars
185 predict the future development of the research area.

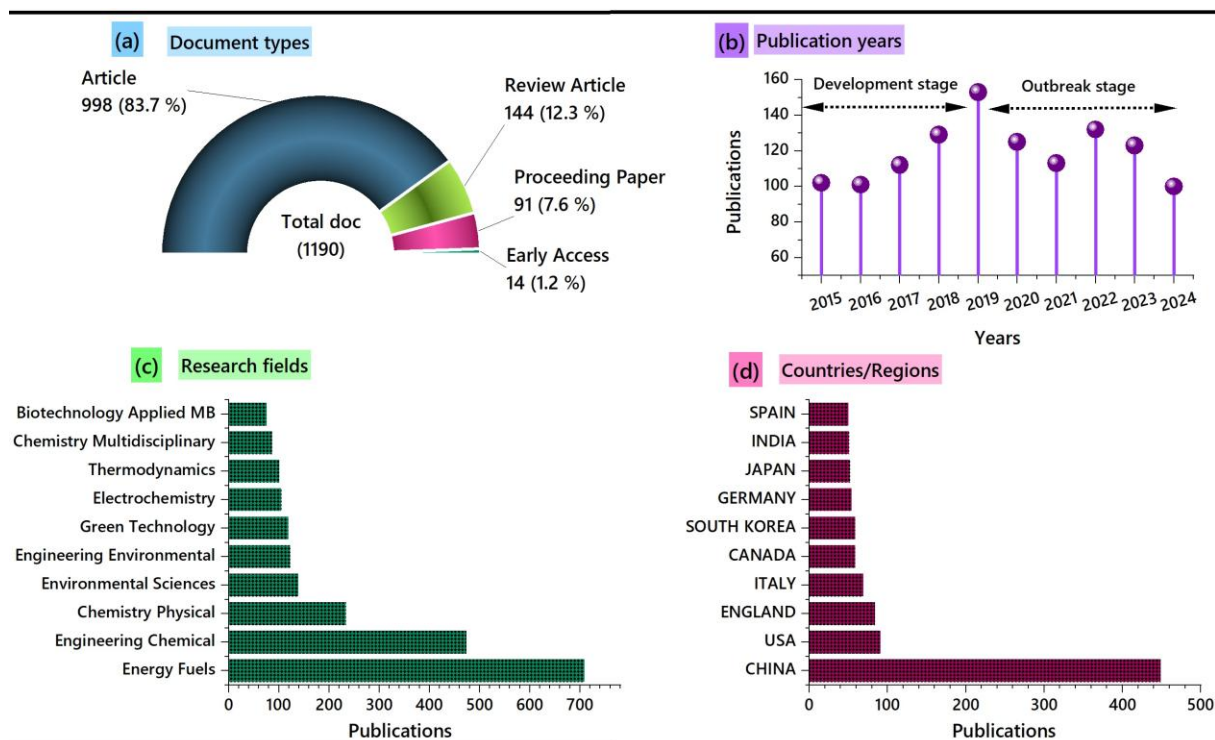


Fig. 3. Document characteristics analysis (bibliometrics) (a) Proportion of document types; (b) Trend in the variation of publication over the years; (c) Distribution based on research fields; (d) Countries with most publication numbers.

Fig. 3b demonstrates the progression of publication distribution, categorized into development and outbreak stages. In the development stage, research gained attention, with publication rising from 100 to 153 annually over four years, an increase of 0.5 times. However, the growth rate remained relatively low, primarily due to several major obstacles. These include feedstock quality especially the diverse blend of materials in MSW, making its processing challenging [25], and significant challenges in parameter optimization and catalyst integration, which together impede the efficient conversion of MSW/BMW into value-added products [26]. In the outbreak stage, there is a fluctuation in publication trends that can be attributed to the considerable negative impact of the COVID-19 pandemic on both the quantity and quality of research in science and engineering over a span of approximately three years. The pandemic also disrupted international academic collaboration, with a more pronounced effect on experienced (older) research groups and departments, thereby hindering long-term research excellence [27,28].

Analysis of the 1,190 publications reveals that energy, engineering, and environment constitute the core research fields. As shown in **Fig. 3c**, “Energy Fuels” outstanding category with 709 publications (59.6 %) followed by “Chemical Engineering” with 474 publications (39.8 %) and

“Environmental-related topics” with 262 publications (22.1%). This indicates a growing interest in energy-related, engineering, and environmental disciplines. The top ten contributing countries include both developing and developed nations, with significant contributions to the total number of publications is shown in **Fig. 3d**. As can be seen, China ranks high due to its significant scientific impact, reflecting the significant role of emerging economies in driving innovation and progress in this research direction [29]. The results indicate that China started research in this direction later than developed nations. However, their rapid economic growth, industrialization, and urbanization have necessitated the adoption of energy-efficient technologies and sustainable practices [30]. Moreover, fossil fuels as primary energy sources have been identified as having a major impact on human health and longevity [31], hence, the transition to renewable energy carriers, such as hydrogen-rich syngas derived from MSW/BMW, is crucial for achieving sustainability goals [32].

3.2. Analysis of collaboration characteristics

3.2.1. Regional collaboration

The regional cooperation network provides a clearer understanding of leading countries based on their scholarly international contributions on MSW/BMW gasification tar conversion, serving as a reference for researchers to identify more influential collaborators. Data derived from the WOS Core Collection database was visually analyzed using the VOSviewer tool to generate a network map. **Fig. 4a** illustrates the co-authorship network of regions as node types, created with a threshold set at a minimum of 10 documents. The node size represents the activity of leading countries in publication production, while shorter distances and thicker connection lines indicate a higher degree of relatedness, and lines color from “dark blue to the red” demonstrated the countries activity over times in this research direction. A network map is constructed based on links and total link strength. A link represents a connection between two items (e.g., co-authorship or co-occurrence) while the total link strength reflects the sum of the strengths of all links an item has with other items.

As shown, among the leading regions, China, South Korea, India, and Japan are from Asia; the USA and Canada are from America; and England, Germany, Italy, and France are from Europe, indicating that the conversion of waste into value-added products is a topic of widespread interest across multiple continents. However, the low level of active collaboration in Africa suggests that this research area has received limited attention in the region, with South Africa being the only actively contributing country. From a time perspective, research on the

conversion of MSW/BMW into energy carriers and the elimination of gasification tar has been conducted in Asian countries since 2019, while Japan is the only country that began research earlier.

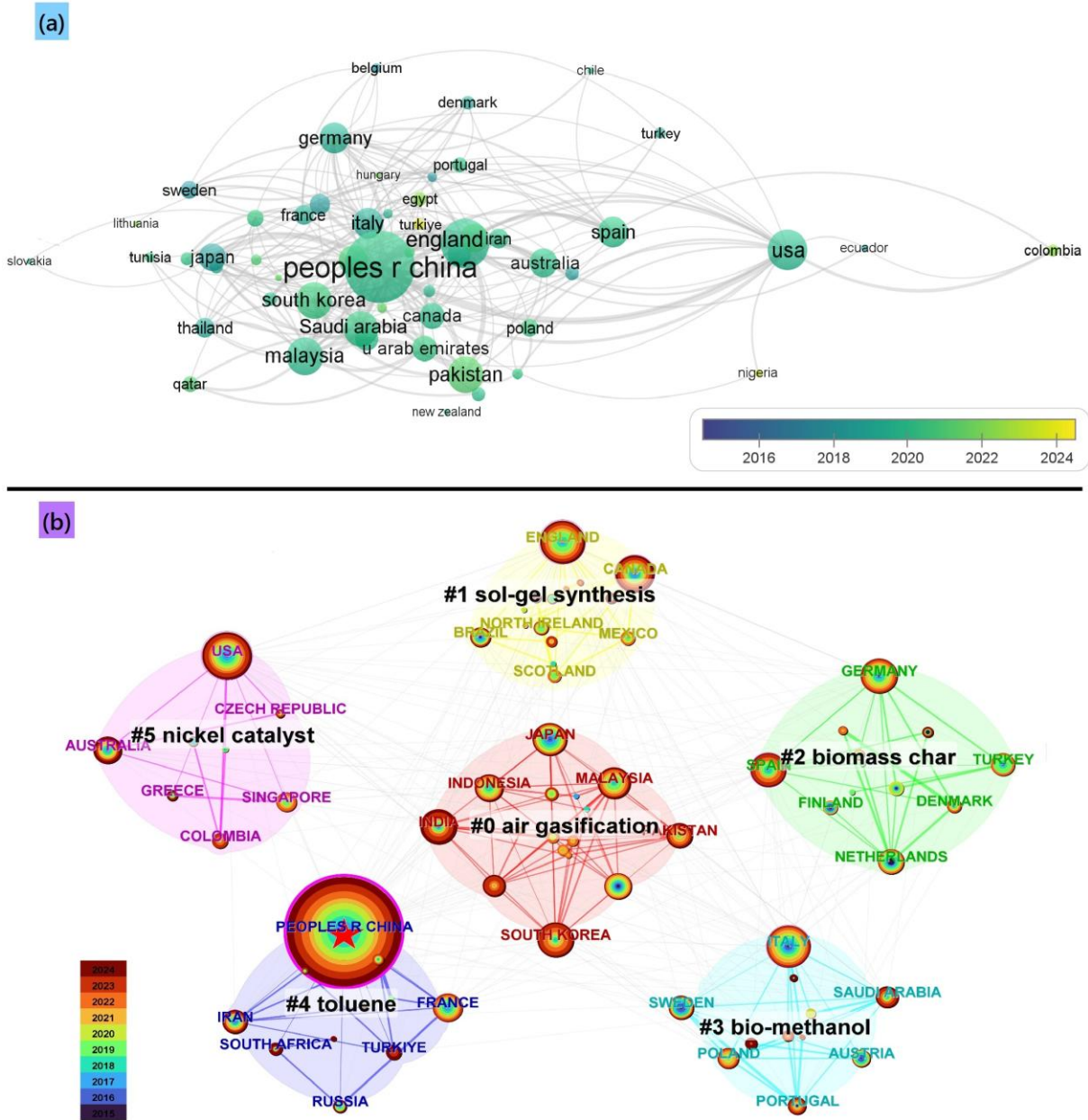


Fig. 4. Regional co-authorship visualizations: (a) Overlay visualization map based on the time dimension (VOSviewer), with a minimum of 3 documents per country; 57 countries were selected, with 314 links and a TLS of 683. (b) Clusters identified based on g-index criteria (CiteSpace), generated with a scale factor (k) of 10, resulting in 77 nodes and 376 links.

This suggests that in major developing countries, the large-scale production of waste and high energy consumption necessitates the generation of clean energy from waste to achieve carbon

neutrality and sustainability. Among the leading countries, China published 449 papers with a total link strength (TLS) of 180, the USA published 91 papers with a TLS of 55, and the UK published 84 papers with a TLS of 92. This suggests that the UK and China are more active in international co-authorship than the USA, indicated by their higher TLS values, with the UK exhibiting particularly intensive collaboration relative to its output. **Fig. 4b** illustrates the regionally generated clusters, which are labeled with the most representative terms extracted from keywords using the LLR algorithm. The LLR algorithm is specifically chosen for its tendency to extract the unique aspect of each cluster [33]. The identified clusters, with a mean silhouette score of 0.7628 and a modularity of 0.2924, highlight six main topics that reflect the comprehensiveness of research on MSW/BMW conversion into value-added products. In each cluster, the size of the nodes represents the number of leading collaborators.

The largest (0# cluster), “Air gasification” contains 17 active members and is dominated by South Korea, followed closely by Japan, and India. This concentration of research indicates that waste gasification is considered a preferred, viable option to address diverse waste management challenges, ranging from plant and agro-residues to industrial, kitchen, and farm waste, through the conversion of its carbonaceous materials into a mix of products, including syngas (CO and H₂), CO₂, CH₄, a solid carbonaceous residue (char), ash, and undesirable by-products such as tar [34,35]. For instance, producing H₂-rich syngas offers a valuable source of chemical energy with high demand, serving both as a fuel in the energy sector and as a key raw material for downstream processes such as ammonia and methanol production. Due to these inherent advantages gasification process has garnered significant attention from both industrial and academic researchers [36]. Analysis of node history reveals that the core topics of this cluster are syngas production and the evaluation of tar upgrading in syngas. The studies frequently investigate the use of various catalysts, with a major focus on Ni-based catalysts supported by carbon materials. Based on publication count and centrality data, South Korea (59 records, centrality 0.08) is the dominant nation in this cluster. The highly cited paper “Biochar as Catalyst”, published in 2017 in the journal *Renewable and Sustainable Energy Reviews* and cited 493 times [37], provides a comprehensive review of the catalytic applications of biochar in tar reduction, increased synthesis gas production, and overall biomass conversion to chemicals and fuels. South Korea is followed closely by Japan (52 records, centrality 0.04) and India (51 records, centrality 0.06). The prominent publications from these two nations are, respectively, “Catalytic steam reforming biomass gasification tar” published in 2016, *Renewable and Sustainable Energy Reviews*, with 471 citations [35], and “Recent advances in

the development of biomass gasification technology” published in 2017, Renewable and Sustainable Energy Reviews, 535 citations [34].

Cluster #1 labeled as “Sol-gel synthesis” presents the high volume of research focused on catalyst preparation and development methods with the goal of enhancing catalytic performance, specifically achieving high activity and stability for tar upgrading and selectivity towards low molecular weight compounds. The development of catalysts, especially with metal loading, is an important factor in determining catalytic activity; however, the physical structure and final chemical properties, including porosity, reducibility, and stability, are directly determined by the preparation process. Catalysts prepared via the sol-gel method exhibit several key advantages, such as high purity, homogeneity at the molecular level, and improved metal-base interaction over catalysts prepared via impregnation, coprecipitation, and hydrothermal synthesis[19]. Previous studies reported that Ni-based catalysts obtained by sol-gel methods demonstrate significantly higher Ni dispersion and performance achieved a high surface area of 305.21 m²/g with an average Ni particle size of 15.14 nm compared to those obtained by other methods. In contrast, the least effective performance was observed with catalysts prepared by co-precipitation, which suffered from non-uniform Ni dispersion and the formation of amorphous coke deposits [38]. England and Canada exhibit the highest activity in this cluster, with England contributing 84 publications (centrality 0.23) and Canada contributing 59 records (centrality 0.14). The node's high centrality indicates strong involvement of both countries, especially the UK, in this research area, a trend further supported by the visualization in **Fig. 4a**.

Biochar production during the gasification process (cluster #2) offers various exploitation routes, among which its application in catalysis, especially for tar upgrading to increase H₂-rich synthesis gas production, has attracted the most attention. This preference is due to the low cost, rich functional groups, and well-developed porous structure, which together facilitate the adsorption of reactants and the dispersion of active components. Germany, Spain, the Netherlands, Denmark, and Turkey are identified as active members of this cluster for biochar applications. Among them, Germany has 54 publications and a centrality of 0.09; Spain has 50 publications and a centrality of 0.04, outstanding given its high research output. The regional concentration analysis reveals significant research interest in the European Union (EU) in the practical application of biochar, often aligned with the EU's waste management and circular economy policies. Furthermore, the centrality analysis shows that German researchers play an active role in disseminating knowledge in this research area. Cluster #3, indicated as “Bio-

methanol” and led by Italy, Sweden, Austria, and Saudi Arabia, highlights the abundant potential of MSW/BMW as a primary feedstock for producing valuable products beyond H₂-rich syngas, specifically liquid fuels such as bio-methanol. However, reaction conditions, as influential factors including catalyst participation, must not be overlooked. This liquid fuel is highly valued both as an energy source and as a key feedstock for synthesizing numerous organic compounds that currently rely on fossil resources (coal, natural gas, and petroleum) [39,40].

“Toluene” (cluster #4) indicates that researchers primarily focused on it as a major tar model compound to isolate and study the fundamental mechanisms of aromatic tar cracking and reforming, due to its inherent simplicity, relevance, and manageability. However, the decomposition mechanisms of actual tar are very difficult to predict due to their complex multi-component composition. Furthermore, tar cracking significantly affected by several factors, including the nature of the tar present in the syngas stream. China is identified as the leading country in this cluster with 449 records and a centrality above 0.4. This score reflects their pivotal role in bitumen upgrading, with a particular focus on bitumen model compounds. Cluster #5 “Nickel catalyst” focuses on the pivotal role of catalysts in converting carbonaceous feedstocks into desirable products. Nickel-based catalysts are the established benchmark, known for facilitating the cracking and reforming of heavy organic compounds into combustible gas and achieving tar conversion efficiency (TCE) above 90 % under steam- or dry-reforming conditions at 700–800 °C [41]. However, their widespread application is faced by deactivation through carbon deposition and sintering. As shown in **Fig. 4a**, in this cluster, the United States is the leading member, published 91 papers and exhibited a centrality of 0.23, indicating its active participation in this research area. In conclusion, international scholarly collaboration in MSW/BMW gasification and gas cleanup is multifaceted. Therefore, it is recommended that researchers evaluate the primary research strengths of different regions to inform the selection of potential collaborators.

3.2.2. Institution collaboration

Institutional network analysis reveals research directions, capabilities, and collaboration patterns, enabling the identification of key institutions and potential collaborators. The top 15 leading institutions were identified among 121 institutions and are presented in **Table 1**. Notably, Asian institutions have made significant contributions on MSW/BMW gasification and gas cleanup. Specifically, only 3 of the 15 active collaborating institutions are from non-Asian countries, including three from the UK, while 9 are from China, accounting for nearly 60 % of the top institutions.

347 **Table 1.** Institution collaboration

No.	Institutions	Country	Cluster	Links	TLS	Documents	Citation	Norm. citation	APY
1	Chinese acad sci	China	6	22	79	61	1965	67	2020
2	Xi an jiao tong univ	China	2	9	11	35	1414	51	2019
3	Univ seoul	Korea	3	11	57	27	847	34	2020
4	huazhong univ sci & technol	China	5	17	25	26	1051	30	2019
5	Southeast univ	China	1	6	11	26	1008	32	2020
6	China univ min & technol	China	1	5	6	25	1208	40	2020
7	Univ chinese acad sci	China	6	8	36	21	551	16	2019
8	Tianjin univ	China	10	4	18	20	360	15	2020
9	Univ leeds	England	2	7	17	17	939	20	2018
10	Nanjing forestry univ	China	7	9	20	15	465	19	2021
11	Natl univ singapore	Singapore	5	12	15	15	1109	39	2019
12	Tokyo inst technol	Japan	1	2	3	15	756	18	2017
13	Newcastle univ	England	8	4	17	14	422	15	2020
14	Zhejiang univ technol	China	9	5	9	14	254	10	2021
15	Univ liverpool	England	5	12	21	13	633	20	2020

348 Note: TLS=Total link strength; APY= Average publication year

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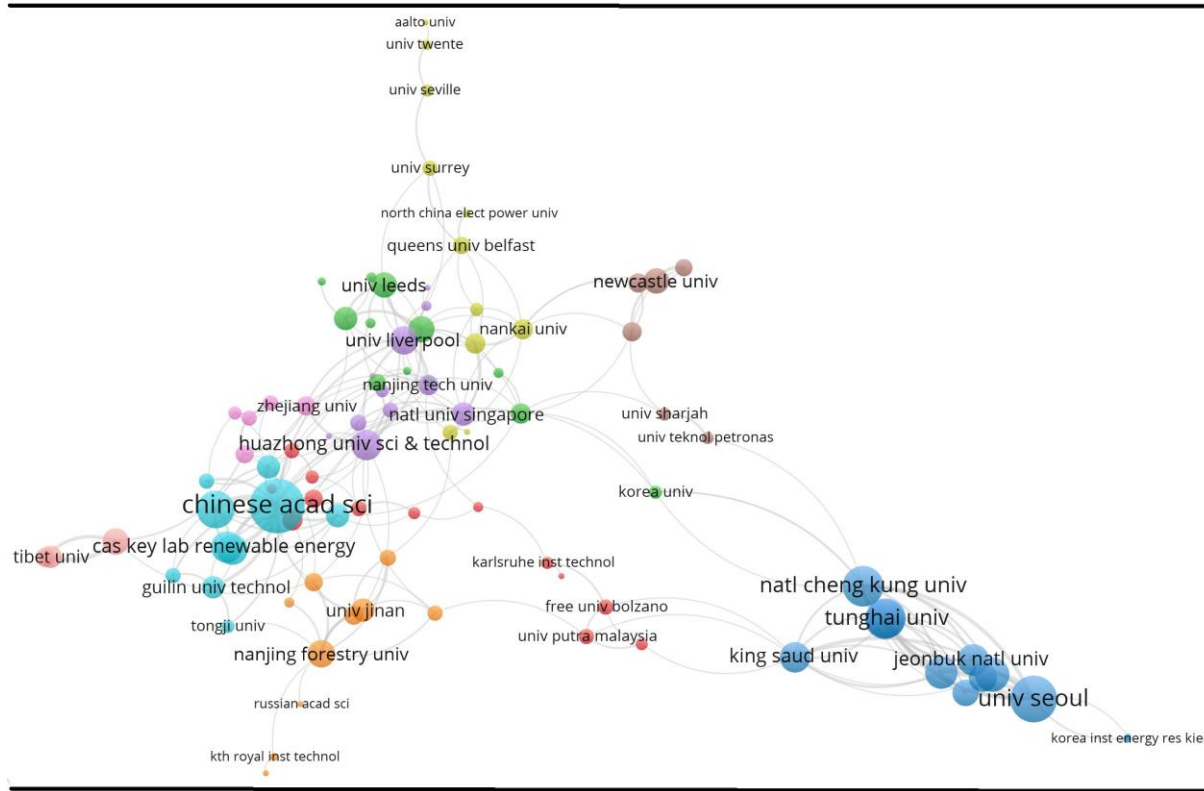


Fig. 5. Organization Co-authorship: Visualization parameters were set as follows: minimum documents per organization was 5; 121 organizations were selected. The resulting network contains 93 linked items (organizations), and visualization weights are based on the TLS.

This suggests that the generation of energy and energy carriers from waste has become a major research focus in Asia, particularly among Chinese institutions. China's energy landscape has long been dominated by coal, which accounted for 58.4% of the national grid in 2022, well above the global average of 35%, making it a major contributor to nations' carbon footprints [4]. To address its high reliance on coal, China has implemented strategies to promote alternative energy sources, such as BMW, which has emerged as a viable option for energy production and clean energy generation[42], and represents a highly collaborative research theme among Chinese institutions. Therefore, **Table 1** clearly establishes these institutions as key leaders, highlighting their substantial role in shaping research priorities and fostering international teamwork in this vital domain.

The network analysis of the institution collaboration generated using VOSviewer (**Fig. 5**) includes 93 institutions, 10 clusters, and 240 links, yielding a TLS of 537. Node sizes are proportional to each institution's TLS, while links between institutions represent the number of collaborations, with thicker and shorter links indicating stronger collaborative activity. Among the active institutions, the Chinese Academy of Sciences (CAS) had the largest collaborative network, comprising 22 internal and external institutions, 61 records, and

a total of 1965 citations, with one of the key publications titled “Review of Recent Advances in Catalytic Applications of Biochar-Based Materials” (published in 2020), with 145 citations [43]. Outside Chinese academia, Seoul National University (South Korea) has 11 links and a total link strength (TLS) of 57, indicating its influential role in publication output. The university actively collaborates internationally with institutions such as National Cheng Kung University and Tunghai University (Taiwan), and King Saud University (Saudi Arabia), among others. It received a total of 847 citations, from which the publication “Biomass Evaporation through Gasification for Green H₂ Production” was particularly notable, with 91 citations. The University of Leeds in the UK also collaborates domestically with the University of Liverpool. At the international level, both universities exhibited collaboration with major institutions, including the Chinese Academy of Sciences and Huazhong University of Science & Technology (China), the University of Sydney, and the National University of Singapore. However, among the remaining institutions, collaborations are relatively weak; therefore, structured institutional partnerships to valorize mixed wastes for a sustainable energy environment are necessary to enhance knowledge transfer and research impact.

3.2.3. Author collaboration

Analysis of the author collaboration revealed that 4,150 researchers were involved in the extracted dataset, of whom 213 met the thresholds; while some of them are not connected within the network, indicating that researchers in this field tend to work relatively independently and that collaborations remain limited. The total link strength (TLS) of co-authorship among authors was calculated, and 81 authors with the highest TLS values were selected. As shown in **Fig. 6**, the size of each node represents the number of research articles contributed by that author, while the thickness of the links between nodes reflects the frequency of collaborative relationships between local and external researchers. The color of each node indicates the author's activity by publication year, with the most activity occurring between 2015 and 2020. As can be seen, most collaborations occur within individual groups, while activity between external groups is relatively low, highlighting the limited extent of scientific exchange at the international level in this field. However, in recent years, researchers have increasingly sought global partnerships, and academic cooperation has become more emphasized.



Fig. 6. Author collaboration network (Overlay Visualization): links 193, TLS 556, visualization weights are based on TLS, colors representing the APY, and the network is normalized via the association strength method.

The overlay visualization was conducted based on a minimum of 4 articles per author, resulting in 11 clusters, with 193 links and a TLS of 556, indicating the importance of both internal and external collaboration among researchers in MSW/BMW tar reduction. It is clear from the network that most collaborations take place within a country, likely due to shared research challenges, and that Chinese researchers have emerged as a central hub in the field, making significant contributions within the country and partnerships with foreign researchers, particularly from Asian countries such as Pakistan. Internal collaborations may be driven by funding mechanisms and shared policy goals in the field of waste valorization, especially MSW, which has shown significantly increasing generation rates, while collaborations with Pakistan may be linked to joint efforts in applying mixed waste as a source of energy. Furthermore, the top 15 authors by publications, citations, and collaborations are presented in **Table 2**. Collaboration among these top authors is high, with all having more than 5 collaborations. However, the overall network visualization (**Fig. 6**) indicates a different trend, confirming that researchers in this field tend to work within highly localized groups. Suggesting the need for scholars from different regions to strengthen collaboration and academic exchange across broader geographical boundaries. As can be seen, Paul T. Williams is the most productive author, contributing 15 published papers with 6 links to other authors, demonstrating a focus on overall output. In contrast, Tu Xin is

the most active author, contributing 12 co-authored papers, indicating broader activity with a specific focus on plasma-assisted catalytic applications. In general, researchers worldwide should further improve the cooperation and effectiveness of their research and achieve more significant breakthroughs.

Table 2. Author collaboration in terms of published papers on research interests.

No.	Author	Papers	Citation	Links	TLS	Norm. cita.	APY
1	Williams, P.T.	15	781	6	18	17	2018
2	Chen, G.	14	216	8	38	8	2020
3	Wu, Ch.	14	993	12	28	26	2017
4	Yan, B.	14	216	8	38	8	2020
5	Li, J.	12	216	6	31	8	2021
6	Saleem, F.	12	383	6	37	14	2020
7	Tu, X.	12	531	14	33	19	2020
8	Yoshikawa, K.	12	413	11	24	10	2017
9	Zhang, K.	12	383	6	37	14	2020
10	Zhang, Sh.	12	460	11	20	15	2019
11	Harvey, A.	11	330	6	36	12	2020
12	Liu, L.	11	644	12	23	21	2020
13	Xu, G.	10	355	8	23	11	2019
14	Yang, H.	10	634	10	22	18	2018
15	Zeng, X.	10	326	3	20	10	2020

3.3. Analysis of hotspot evolutions

3.3.1. Keywords frequency

A keyword co-occurrence network allows researchers to easily identify the dynamic evolution of research frontiers in their field [44]. The keyword co-occurrence was conducted using CiteSpace (clustering), VOSviewer (overlay), and Biblioshiny (word cloud). Based on the keyword co-occurrence analysis, the high density of keywords indicates a well-integrated research field. As shown in **Fig. 7 a**, a keyword co-occurrence network was performed using VOSviewer, with a minimum frequency threshold of 10; 61 keywords were selected and optimized using the association strength method. The generated network was categorized into four distinct groups comprising 635 links, where node size represents keyword frequency, and link thickness

reflects co-occurrence strength, highlighting that keywords are frequently investigated together and suggesting the most concentrated research areas in the field.

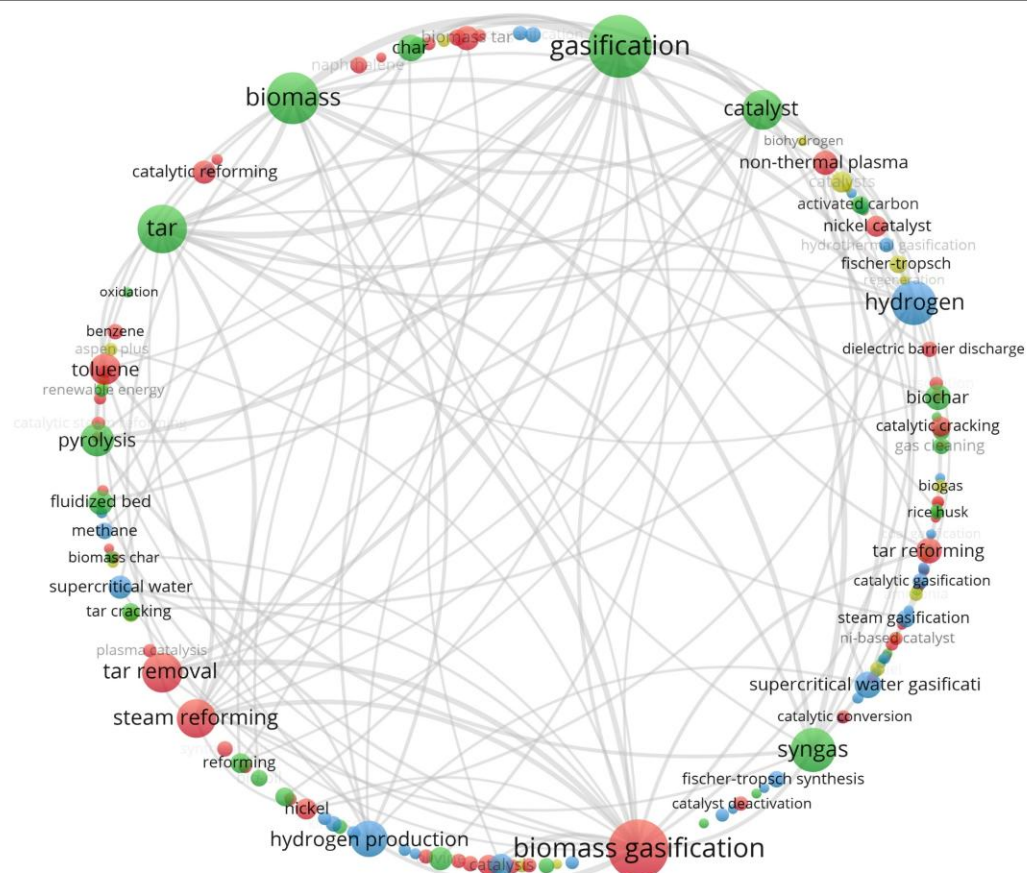
Group 1 (Red) contains 27 items, and the most significant keywords include biomass gasification, tar removal, steam reforming, toluene, catalytic reforming, nickel catalysts, and NTP. This cluster highlights a primary research focus on the conversion of biomass into H₂-rich syngas by tar cracking under steam and catalytic conditions, particularly using monometallic Ni catalysts. NTP systems are effective methods for tar removal due to their mild reaction conditions and high efficiency. However, the non-selective nature of plasma-induced reforming can generate unwanted by-products, thereby reducing selectivity toward useful products. To address these limitations, the coupling of NTP with catalysts (plasma-catalysis) has been explored [45]. This synergistic effect improves catalytic properties, stability, and activity while significantly improving H₂ selectivity and suppressing the formation of undesirable by-products. To better understand the distribution of tar constituents during conversion, numerous scholars have frequently employed tar model compounds (e.g., single compounds or their mixtures) [46]. These compounds are considered surrogates for real tar, allowing conversion to be conducted under controlled conditions and helping to investigate catalytic activity, reaction mechanisms, and conversion pathways.

Group 2 (Green) primarily focuses on thermochemical conversion processes, such as the gasification and pyrolysis of biomass feedstocks to produce syngas and biochar. Central keywords in this cluster include gasification, biomass, catalyst, tar, syngas, pyrolysis, bio-char, and tar cracking. This group indicated a strong research interest in the transformation of biomass into high-quality syngas by utilizing catalytic conditions to mitigate tar formation. The high degree of interconnectedness within this cluster suggests that researchers are investigating the full spectrum of the thermochemical pathway, ranging from process optimization to the downstream applications of the resulting products.

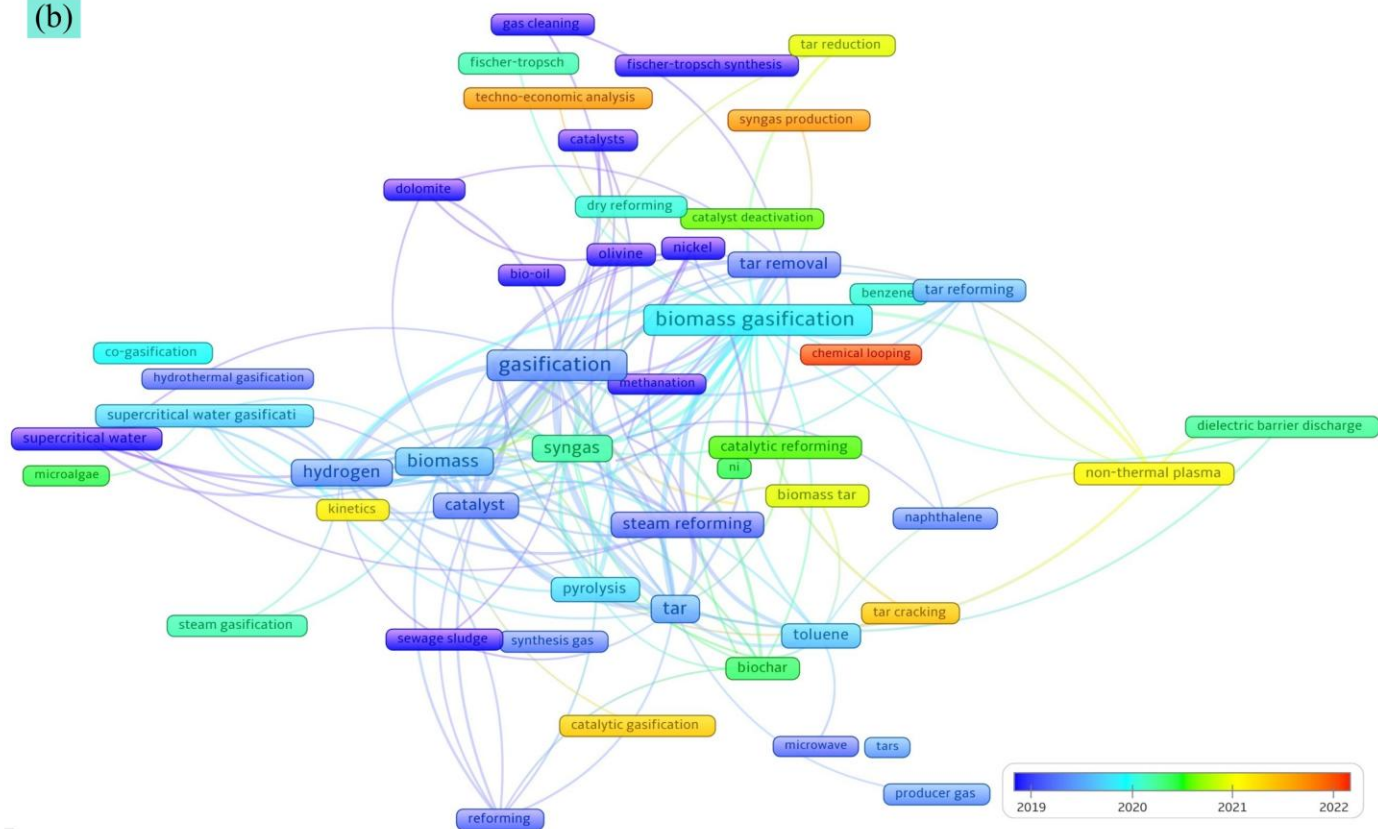
Group 3 (Blue) emphasizes the production of sustainable energy carriers, with a specific focus on high-yield hydrogen synthesis. In this group, the most frequent co-occurring keywords, hydrogen, hydrogen production, and methane, indicate a substantial core of research on converting biomass and organic waste into H₂, highlighting the shift from traditional gasification toward targeted hydrogen-rich syngas production. While the presence of methane indicates a focus on steam methane reforming and the simultaneous production of synthetic natural gas.

Cluster 4 (yellow) with keywords such as catalysts and Fischer-Tropsch, which highlights research on the conversion of syngas to high-value liquid fuels and emphasizes the development of specialized catalytic systems to optimize hydrocarbon selectivity and improve the stability of the conversion process.

(a)



(b)



record dataset, highlight the main thematic pillars of mixed waste valuation research. Betweenness centrality shows that the dominant keywords in the dataset act as pivotal nodes that connect different research topics. High values of betweenness centrality were observed for tar removal and conversion (1.0), followed by biomass gasification (0.94), indicating that these keywords act as critical structural bridges in the research network (**Fig. 8 b**). Notably, “biomass gasification” shows the greatest temporal continuity (**Fig. 8 c**), underscoring the established nature of the field's primary research themes. Tar formation is an inevitable by-product that contributes significantly to catalyst deactivation, system blockages, and process failures [18]. Consequently, tar removal has remained a core research hotspot in mixed waste valorization from the past to the present, attracting considerable interest among scholars worldwide.

Fig. 9 shows the clustered keyword frequencies arranged chronologically, highlighting the evolution of research hotspots over time. The network's structural characteristics are summarized in the upper-left of the visualization, where the modularity (Q) and mean silhouette (S) values serve as key metrics for assessing network stability and cluster validity; the high modularity value ($Q = 0.8199$), well above the threshold of 0.3, indicates clearly defined and distinct thematic modules. The mean $S = 0.9779$ reflects cluster homogeneity and consistency. Together, these metrics confirm that the identified clusters are stable and highly reliable, providing a solid foundation for subsequent thematic analysis.

The most prominent thematic investigations identified through this temporal analysis are summarized in the preceding sections. First, it is evident that the most influential research topic is “steam gasification” (denoted as #0 Cluster). Based on the time span and node degree, steam gasification has remained a core study area from the early stages to the present. Reaction conditions, particularly the selection of operating temperature and gasification agent, are key factors influencing the yield of tar-free syngas from mixed-waste conversion, whereas steam markedly promotes char gasification, the water–gas shift reaction, and CH_4 reforming, resulting in hydrogen yields three to five times higher than those obtained with air gasification systems [47]. This suggests that steam as a gasification medium is a key factor contributing to the frequent co-occurrence of this keyword. Furthermore, in the #0 cluster, the main products of biomass gasification are gas (producer gas), with the latter being the primary focus. The selection of the gasifying agent also strongly influences the tar reduction in the syngas. Steam has demonstrated high efficiency by promoting reforming reactions, reducing tar from $5.5\text{--}0.097\text{ g/Nm}^3$ at reaction temperatures between 600 and 1000 °C [18,49]. Even greater improvements were observed when steam and CO_2 were combined, resulting in a 21.4 % reduction in tar and a 13.4 % increase in hydrogen yield at 900 °C [48].

The second important topic in mixed wastes valorization is supercritical water gasification denoted as (Cluster #1) which mainly focuses on the production of hydrogen-rich syngas. In this process, supercritical water at reaction conditions above 374 °C and 22.1 MPa serves as both medium and reactant [49]. This technique

offers a significant advantage by enabling the processing of feedstocks with high moisture content (> 50 wt.%) which allows direct conversion with efficiencies nearly 100 % and H₂ yields exceeding 50 %. This eliminates the need for energy-intensive pre-drying. During this process, the carbon–steam reaction facilitates the generation of non-condensable gases with H₂ as the primary product (#2 Cluster). The deposition of coke commonly occurs during catalytic gasification [50]. Among the operational parameters, reaction temperature is one of the most important factors in biomass and waste gasification which typically ranges between 700 and 1200 °C. As the temperature increases, tar molecules undergo cracking and reforming boosting the production of H₂ and CO while lowering CH₄ and tar levels. For example, raising the operating temperature from 700 to 900 °C reduced tar by nearly 97 %, reaching as little as 0.2 g/Nm³ when bottom ash was present [51]. While these conditions strongly promote tar removal, they can also encourage the formation of polycyclic aromatic hydrocarbons (PAHs) which are far more difficult to eliminate.

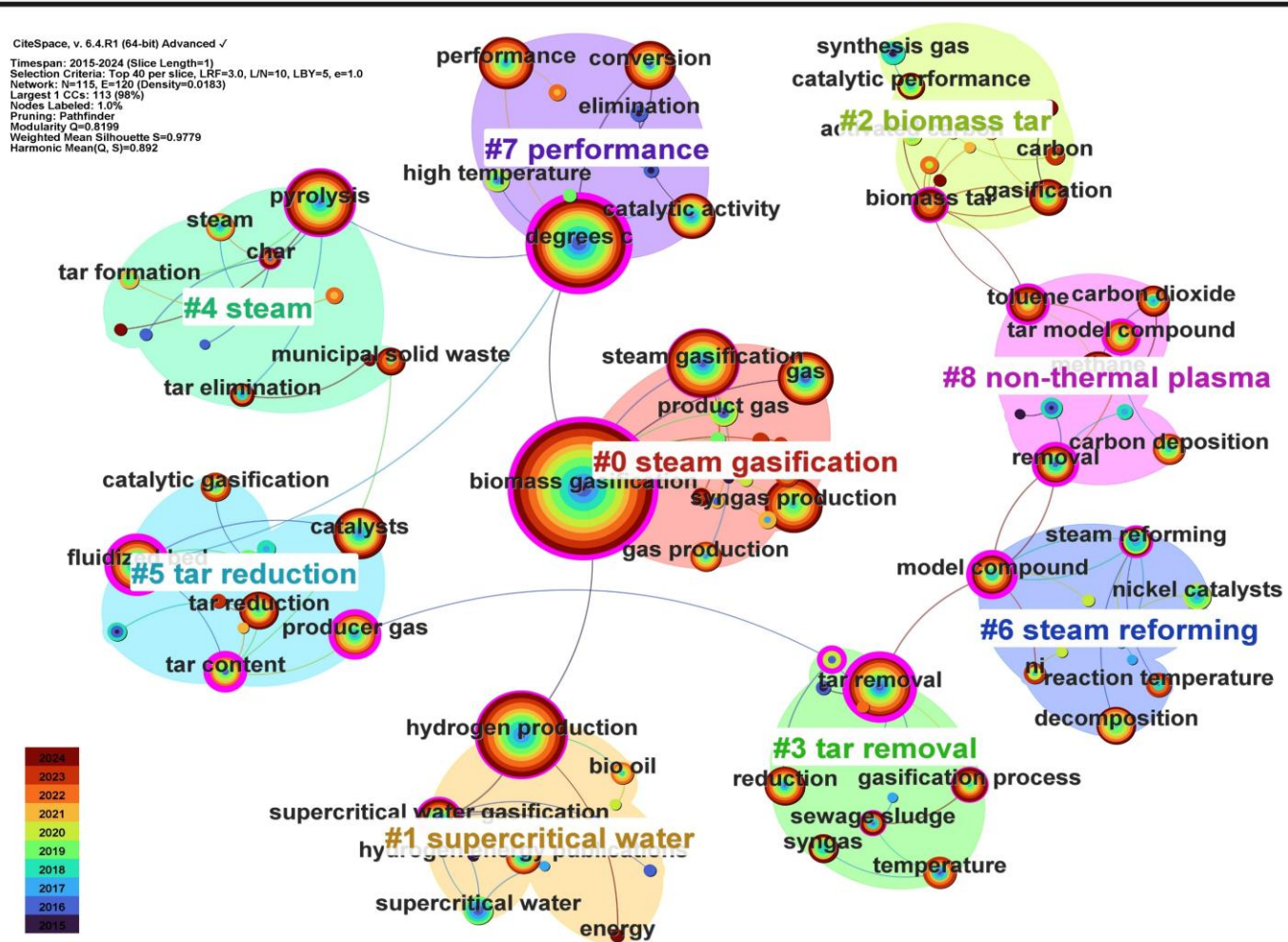


Fig. 9. Keyword co-occurrence clusters. Network parameters: Nodes = 115, Links = 320; selection: top 40/slice (LRF 3.0, L/N 10, LBY 5); pruning: pathfinder (sliced and merged); metrics: modularity Q = 0.8199, silhouette S = 0.9779.

Third, (#3 Cluster) “Tar removal” is a critical challenge in the valorization of mixed wastes, as it's an inevitable byproduct and a primary barrier to industrial-scale application of gasification [18]. It consists of a complex mixture of high-molecular-weight organic compounds, whose high viscosity leads to deposition within gasification systems and downstream pipelines. The complexity of tar by-products is further pronounced by the composition of the feedstock: cellulose-rich feedstock typically produces lower tar content, while lignin- and plastic-rich MSW feedstock significantly higher amounts, reaching up to 15.6 g/Nm³ at 850 °C [52]. To mitigate this problem, pretreatment strategies such as torrefaction have been employed. Torrefaction is a pretreatment process for feedstock that helps mitigate tar by-products to up to 60%, while simultaneously enhancing hydrogen yield [53]. Consequently, tar upgrading has emerged as a top research priority in gasification technology [54].

Among the various in-situ and ex-situ tar-removal methods, the catalytic steam tar-upgrading system (#4, #5, and #6 clusters) has emerged as a vital route for reducing tar formation and enhancing H₂-rich syngas production. The catalysts play an important role in in situ strategies, where conventional catalysts, such as natural minerals (e.g., olivine and dolomite), can reduce tar content to below 5 g/Nm³; but their catalytic activity remains relatively low [55]. Transition-metal catalysts, such as nickel/ or iron-based catalysts, exhibited significantly higher conversion efficiencies; however, they are highly prone to coke deposition, which can lead to catalyst deactivation [56]. To address these limitations, catalyst systems modified with bimetallic catalysts such as Fe–Ni and Ni–Co have been tested, achieving over 95 % tar conversion and approximately 3.5 times greater stability than their monometallic ones [18]. Novel approaches, such as plasma-assisted and photothermal catalysis, are emerging, achieving tar removal rates above 90 %, though they are still at the experimental stage [57,58].

In ex-situ techniques, physical cleaning methods such as scrubbers, filters, and electrostatic precipitators are relatively simple to operate. For example, the OLGA (Oil-based gas absorption) system achieved 92 % removal under hot-gas conditions. However, these methods rely on condensation and solubility, without tar cracking/reforming, thereby transferring tar contaminants from the gas phase into secondary waste streams. Similarly, washing with waste cooking oil represents a more sustainable alternative but remains ineffective in conversion of PAHs [59]. Thermal cracking at temperatures above 1200 °C can achieve complete tar decomposition; however, its practical feasibility is limited by high energy requirements and soot formation [59]. Catalytic tar reforming is an advanced ex situ method in which monometallic catalysts, such as Ni or Fe, operate under steam or dry reforming conditions at 700–800 °C, achieving tar conversion efficiencies above 90 % [41]. Despite their high activity, they are hindered by deactivation caused by carbon deposition and sintering, whereas bimetallic systems (e.g., Ni–Fe, Ni–Co, Ni–Cu), due to improved Ni dispersion, suppress

coke formation and increase oxygen mobility. Ni–Fe catalysts achieve >99% conversion of refractory compounds, such as toluene [60].

Combining plasma with catalysts in tar reforming systems is a modern innovation, while non-thermal plasma (#8 cluster) can drive reactions that would not occur at normal conditions. In which high-energy electrons can effectively break down stable tar molecules without the extreme thermal requirements of conventional methods. Highly energetic electrons facilitate the formation of free radicals, ions, and reactive species and serve as the primary drivers of subsequent tar reforming, enabling high conversion rates at significantly lower bulk temperatures [61]. As shown in **Fig. 8b**, dielectric barrier discharge (DBD) is an effective and scalable technology for tar upgrading that can be easily combined with catalysts, reducing energy requirements, improving product selectivity, and limiting carbon deposition. The plasma-catalyst interaction offers a reliable solution to the deactivation issues common in conventional reforming [62]. Therefore, future research should focus on advanced catalyst modifications to optimize system efficiency and carbon conversion.

3.3.2. Keywords burst

A citation burst serves as a key indicator of the most dynamic areas of research which identifies “burst events” that may span a single year to over a decade. This metric provides empirical evidence of a temporal surge in citations associated with a specific publication [33]. CiteSpace visualizes citation bursts as horizontal bars along a chronological timeline. The red sections represent peak years of research activity, indicating a sharp increase in scholarly interest, while the blue sections represent periods of normal citation activity. Furthermore, burst strength quantitatively measures the intensity of these increases and describes the impact of a specific topic on the research areas [23]. **Table 3**, shows the keyword burst analysis of biomass tar removal in gasification. It predicts tar removal as one of the most critical issues over the past five years, with both the longest burst duration and the highest intensity, followed by Ni-based catalysts. The persistent citation bursts of biomass tar (2020–2024), toluene (2020–2024), and Ni-based catalysts (2021–2024) highlight their central role and continued relevance in this research field [59].

Table 3. Keywords (top 20) with the strongest citation bursts

Keywords	Year	Strength	Begin	End	2015 - 2024
biomass tar	2020	12.34	2020	2024	
ni based catalysts	2021	11.44	2021	2024	
nickel catalysts	2017	11.22	2017	2020	
steam reforming	2016	10.47	2017	2018	
supercritical water	2015	9.73	2015	2019	
elimination	2015	8.99	2015	2016	
activated carbon	2019	8.76	2019	2020	
municipal solid waste	2019	8.25	2022	2024	
x-ray diffraction	2017	7.91	2017	2018	
synthesis gas	2015	7.89	2017	2018	
tar formation	2019	7.59	2019	2021	
hot gas	2015	7.51	2015	2016	
coke deposition	2021	7.47	2021	2022	
coke formation	2021	7.47	2021	2022	
bed material	2015	7.22	2015	2018	
toluene	2019	7.17	2020	2024	
biomass gasification technology	2020	7.16	2020	2022	
kinetics	2017	6.92	2017	2018	
catalytic conversion	2015	6.87	2015	2016	
partial oxidation	2015	6.87	2015	2016	

As a result, tar upgrading in raw syngas remains a key focus for advancing gasification processes, whereas toluene is frequently selected as a model tar compound because it accounts for about 24% of total tar. It has a stable aromatic structure, and due to its simplicity, is easy to use while effectively representing the aromatic and alkyl-substitute features of real tar [63]. Keywords such as biomass tar, Ni-based catalysts, and steam reforming showed the highest burst strengths of 12.34, 11.44, and 10.47, respectively. This indicates that they have attached significant interest and are likely to remain hot themes in MSW/BMW gasification and the production of value-added chemicals. In particular, the first two keywords represent critical areas of ongoing research and can help scholars stay aligned with the latest trends in this field.

4. Future strategic directions

Based on the quantitative evidence and structural mapping of waste valorization through tar upgrading discussed through the preceding sections, this study identifies primary factors for tar reformation and enhancing H₂-rich syngas production. The future work may focus on the following areas:

- First, to thoroughly evaluate the influence of feedstock (MSW/BMW) composition and its blending ratios on the syngas composition and its impurities. Since tar formation remains a critical bottleneck (a fact confirmed by the prevalence of related clusters in this bibliometric analysis), could be point out the synergistic effects of mixed feedstocks such as MSW is essential for developing robust technologies.
- While considerable attention has been paid to the tar in biomass gasification, the number of publications and research collaborations on MSW gasification remains significantly lower. The formation and upgrading of tars in MSW gasification require greater focus in future research.
- The Ni-based catalysts, particularly those by carbon materials, demonstrate high performance for H₂ enrichment. However, their long-term stability remains a challenge. Future efforts should focus on structural modifications to reduce coking and poisoning, which extending catalyst life and reusability.
- Considering the emerging global demand for hydrogen, catalytic steam reforming is a critical pathway for maximizing H₂ yields. By effectively converting tar into useful syngas, this process significantly reduces the energy requirements and complexity of downstream gas upgrading.
- Integrating NTP with heterogeneous catalysts is a transformative area, and synergy between plasma-generated reactive species and active catalytic sites enables tar cracking at lower temperatures while promoting in-situ catalyst regeneration. This combination significantly enhances H₂ yields and prolongs catalyst longevity by suppressing carbon deposition.
- To ensure commercial viability, the experiments should focus on actual tar rather than model compounds. Further, experimental validation should transition to pilot-scale facilities to assess the performance of plasma-catalytic systems against real-world contaminants (H₂S, HCl).

5. Conclusion

This study provides a comprehensive bibliometric evaluation of research on tar upgrading in biomass and municipal solid waste (MSW/BMW) gasification from 2015–2024. By combining measurable indicators with thorough science mapping and visualization tools, the analysis gives an overall view of the research field and collaboration trends. The bibliometric results revealed a steady expansion of research activity, reflected in an annual growth rate of 2.1 % and a validated corpus of 1,190 documents authored by 3,777 researchers.

628

629 The presence of multi-authored publications, a high average of 5.11 co-authors per document, and international
630 collaboration in 31.4 % of publications highlight the across different fields and globally networked nature of
631 this domain. Institutional and country-level network analyses demonstrated a pronounced geographical
632 concentration of research activity in Asia, particularly in China, South Korea, Japan, and India. Chinese
633 institutions, with their high publication output, make up nearly 60% of the top contributing institutions,
634 showing the urgent need in fast-growing economies to manage large amounts of waste and meet rising energy
635 demand through sustainable conversion technologies.

636 From a collaboration view-point, China and the UK exhibited strong international co-authorship networks, as
637 evidenced by their high total link strength (TLS) values. Cluster analysis and the word cloud map identified
638 “biomass gasification”, “hydrogen-production”, “tar”, and “catalysts” as the most influential thematic terms.
639 These findings are supported by the frequency data, showing BMW gasification and hydrogen production with
640 co-occurrence of 1021 and 414, respectively, as the main research focuses. Most studies in these clusters
641 examined catalytic strategies, especially Ni-based catalysts on carbon supports, to improve tar conversion and
642 increase hydrogen-rich syngas production.

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