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Integrative and systematic review on biomass and waste co-gasification: challenges, trends, and future perspectives

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ABSTRACT

This work analyzed the evolution of research in gasification and co-gasification through a comprehensive bibliometric review from 2015 to 2025. To this end, it was necessary to develop a Python pipeline to consolidate records from Web of Science, Scopus, and ScienceDirect, given the failure of standard bibliometric software to reliably handle export format incompatibilities. Of the initial 128,056 records, 1,123 publications were defined under the PRISMA guidelines, focusing on thermodynamic modeling and Aspen Plus applications. The results indicate an exponential increase of 633% in publications, with China (34.5%) and Europe (28.7%) leading scientific production in 67 countries. Despite this remarkable growth, collaboration networks remained structurally fragmented. The analysis of the recent literature demonstrates that the focus has shifted slowly toward the issues of green hydrogen (8.7%), the circular economy (7.9%), and computational modeling (29.7%). Moreover, the patent information shows that there is an innovation gap of 3.2 years and a 3.6:1 publication-to-patent ratio. Although the field shows scientific maturity (h-index 89; average IF 8.4), commercial deployment is still limited, reinforcing the need for stronger international and industry–academic collaboration to advance gasification's role in global decarbonization.

1. Introduction

1.1. World energy crisis and waste management Problems

Energy demands of the world have been steadily increasing since the industrial revolution and the projections still show an increment of around 30% by the year 2040. In the world, today about 84% of energy is still produced by fossil fuels, which can be used to understand the reason why this type of energy sources contribute over 70% of total greenhouse-gas emissions in the world [1–3]. In response to this serious problem, international frameworks such as the United Nations (UN) sustainable development goals (SDG), particularly goals 7 (affordable and clean energy) and 13 (climate action), and the Paris Agreement have been established to encourage countries and industries to transition energy systems toward more flexible, low-carbon alternatives [4,5]. Additionally, the increasing production of single-use and non-recyclable

Abbreviations: AC, Alternate Current; API, Application Programming Interface; CCE, Carbon Conversion Efficiency; CCUS, Carbon Capture, Utilization and Storage; CFD, Computational Fluid Dynamics; CGE, Cold Gas Efficiency; CPC, Cooperative Patent Classification; DWPI, Derwent World Patents Index; EPO, European Patent Office; ER, Equivalence Ratio; FAIR, Findable Accessible Interoperable Reusable; HHV, Higher Heating Value; ICP, Inductively Coupled Plasma; IEC, International Electrotechnical Commission; IF, Impact Factor; IGC, Integrated Gasification Cycle; INPADOC, International Patent Documentation; IPC, International Patent Classification; IPGC, Integrated Plasma Gasification Cycle; IPGCC, Integrated Plasma Gasification Combined Cycle; IRA, Inflation Reduction Act; ISO, International Standard Organization; LCA, Life Cycle Assessment; LCC, Life Cycle Costing; LCOE, Levelized Cost of Energy; LCT, Life Cycle Thinking; LHV, Lower Heating Value; PCT, Patent Cooperation Treaty; PE, Polyethylene; PET, Polyethylene Terephthalate; PER, Plasma Energy Ratio; PGVR, Plasma Gasify/Vitrify Reactors; PHW, Petroleum Hazardous Waste; PP, Polypropylene; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; PS, Polystyrene; TE, Thermodynamic equilibrium; TRL, Technology readiness level; SAMR, Steam-Air Mass Ratio; SD, ScienceDirect; S-LCA, Social Life Cycle Analysis; MHD, Magnetohydrodynamic; MSW, Municipal Solid Waste; RDF, Refuse-Derived Fuel; SDG, Sustainable Development Goals; UN, United Nations; USPTO, US Patent and Trademark Office; WIPO, World Intellectual Property Organization; WoS, Web of Science; WtE, Waste-to-Energy.

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products, coupled with inadequate waste management systems, especially in least developed countries, increases waste generation, exacerbates environmental degradation, and reinforces economic dependence on costly, disposable goods [6,7]. Among the most significant waste streams are municipal solid waste (MSW) and plastics. Current projections show that the amount of MSW will keep growing in the next decades, from 2.01 to 3.40 billion tons annually by 2050 [6]. Approximately 380 million tonnes of plastic waste are produced each year, and only a small proportion is recycled [8,9]. Most of the plastic waste continues to be disposed of in landfills, or released into the environment, where it gradually degrades into microplastics. These microplastics persist in ecosystems and pose significant ecological risks due to their toxicity and potential for bioaccumulation [10,11].

As the increasing energy demand is being witnessed in parallel to the increasing waste piling up, waste-to-energy (WtE) strategies have risen to the forefront of technological debates. WtE systems create an opportunity to extract value out of otherwise environmentally harmful materials because they convert waste into forms of usable energy akin to the principles of the concept of the circular economy and more broadly, the goals of sustainability [12,13]. Within this context, thermochemical conversion routes, particularly gasification, have gained increasing attention as WtE flexible solutions capable of simultaneously addressing energy recovery and waste management challenges.

1.2. Biomass and plastic waste as energy Sources: Characteristics and potential synergy.

Biomass, including forestry byproducts, agricultural residues, and the organic fraction of municipal solid waste, represents one of the few renewable resources available at a truly large scale, with global annual production exceeding 146 billion tons of dry material [14,15]. A large portion of this resource remains underexploited [14]. The long-term scenarios indicate that bioenergy could be able to provide almost a quarter of transport-fuel demands in the world within the mid-century in case of the continuation of the current trends [6]. However, in practice, biomass often struggles to compete economically because of its relatively low energy density (around 10–20 GJ t^{-1}), high moisture content and the simple fact that it is geographically dispersed, which increases logistical costs [16–18].

In contrast to the low energy density of biomass, plastic waste represents almost the opposite situation. Although nonrenewable, plastics are highly energy-dense materials. Many plastics exhibit calorific values between 40 and 45 MJ kg^{-1}, comparable to conventional fossil fuels [19–26]. However, exploiting plastics is not without risks. The primary challenge is the identification of a technical and environmentally sustainable conversion pathway. Direct combustion of plastics, for example, can lead to the formation and release persistent and toxic compounds, including dioxins, furans and various heavy metals, which makes uncontrolled burning an unacceptable option from an environmental standpoint [27,28].

To overcome the individual limitations of these feedstocks, bringing these two waste types together through co-gasification has been gaining traction as a practical alternative. Gasification has been widely investigated as an adaptable thermochemical process that enables the conversion of diverse carbonaceous feedstocks into synthesis gas under controlled, oxygen-limited conditions. Plastics and biomass complement each other and thus, when combined may help the reactor perform much better than each of the two feedstocks alone. Due to their energy density, plastic-rich fractions contribute to maintaining process temperatures, and at the same time, biomass, containing a lot of oxygen, contributes to the formation of a cleaner conversion environment. When done correctly, using plastics and biomass together frequently produces cleaner syngas streams, notably less tar formation, and less effort for downstream treatment [29].

Blending plastics with biomass creates thermochemical interactions that rarely appear when each feedstock is treated separately, often improving conversion performance [30,31]. The technical excellence is in the complementary profiles of elements: plastics (high H/C, low O) are hydrogen donors, which counter the oxygen-rich hydrogen-poor characteristics of biomass. This hydrogen-donating behavior also promotes secondary cracking reactions, reducing tar formation while enhancing syngas quality [32,33]. Experimental data from multiple reactor configurations demonstrate consistent performance gains. Studies using fluidized bed reactors report that optimal mixtures (20–30 wt% plastic) enhance cold gas efficiency (CGE) by 15–18% and increase syngas lower heating value (LHV) by comparable margins [34–39]. The higher volatile content in plastics promotes elevated flame temperatures, which reduces tar concentration by up to 20%, addressing one of the primary technical bottlenecks [36–39]. These improvements hold across biomass-to-plastic ratios of 70:30 to 80:20, with efficiency gains of 15–25% compared to single-feed operation [40,41]. Additionally, co-gasification can lessen operational instability. Since plastics are highly consistent in terms of moisture and composition, they can be used to counter seasonal or batch-to-batch changes that are characteristic of biomass feedstocks [40–44].

Over the years, a wide range of reactor configurations has been developed, each offering distinct advantages. Fixed-bed reactors are valued for their operational simplicity and robustness; fluidized-bed reactors are superiorly mixed, and temperature controlled; and entrained-flow reactors are high throughput and uniform reaction beds. In summary, co-gasification presents an opportunity to recover energy from two problematic waste streams simultaneously, while alleviating some of the drawbacks inherent to their individual conversion. Despite these advancements, there are still some major engineering challenges that restrain wider application of the technology. Managing tar, maintaining catalyst activity, and adequately preparing heterogeneous feedstocks still impose practical and economic constraints that limit wider deployment [45,46]. Economic constraints, such as high capital investment, relatively uncertain returns and competition with low-cost conventional fuels, further slow industrial adoption [47,48].

1.3. Gasification Technology: Fundamentals and advantages

Gasification remains among the more adaptable thermochemical routes for converting carbon-based solids into synthesis gas, a mixture dominated by H_2, CO and small hydrocarbons [49–56]. The process is driven by a sequence of chemical steps (pyrolysis, partial oxidation, water–gas-shift and methanation) that unfold under oxygen-limited conditions, typically 20–40% of the stoichiometric requirement, and at temperatures between 700 °C and 1,000 °C [49–54,57–59]. Key operating parameters, such as temperature, pressure and the oxidizing agent, exert a strong influence on the resulting syngas composition. By carefully adjusting these variables, the product gas can be tailored and optimized for specific downstream applications, most notably chemical synthesis and power generation [60–62]. Compared with conventional

Table 1
Comparison of alternative waste treatment technologies.

Technology	Advantages over conventional methods	Reference
Incineration	Controlled combustion conditions allow for substantially lower pollutant emissions and greater energy recovery efficiency, often reaching 75–85%, compared with 65–75% typical of incineration.	[63–67]
Landfilling	Landfilling, by contrast, eliminates energy recovery potential and contributes to methane emissions, whereas gasification achieves nearly complete waste volume reduction	[68–72]
Anaerobic digestion	Anaerobic digestion remains suitable for certain organic residues but is less versatile in handling plastics or mixed solid waste streams. Gasification's flexibility and higher conversion efficiency thus make it an increasingly relevant alternative in modern WtE systems	[73–79]

waste management options, gasification offers a distinct set of advantages, as summarized in Table 1.

Even though the number of publications on gasification has increased significantly since 2010 [80–82], the review studies remain scattered, and the field lacks a consolidated overview. Many studies concentrate on specific topics, such as reactor design [83,84], catalyst development [85,86], or particular feedstock families [87] and often lack a broader perspective connecting scientific advances to technological maturity and industrial application [21–26,36,68,83–89]. The practical difficulties in carrying out robust bibliometric assessments were intensified because of recent restrictions on data export and application programming interface (API) integration in platforms like Web of Science (WoS), Scopus, and ScienceDirect (SD) [82,90]. This fragmentation is not only methodological. Even the collaboration networks are not tightly tied, thereby slowing down the process of knowledge sharing and resulting in duplication of efforts.

Various gaps in the field of research methodology and practice remain despite the increasing body of work. Although biomass gasification technology has developed to a stage where downdraft systems reach electrical efficiencies of more than 25% when coupled with internal combustion engines [91,92], accurately predicting the final composition of the syngas remains a difficulty. This difficulty results from the complex interactions between feedstock properties, reactor design, gasifying agents, and operating conditions [93,94]. Tar formation remains a primary bottleneck in gasification processes. This complex mixture of high-molecular-weight hydrocarbons condenses at gasifier outlets, causing fouling and filter blockages [95,96]. Although acceptable tar thresholds vary by application, concentrations below 1 g/Nm^3 are generally required for power generation to prevent downstream equipment degradation [97,98].

To address these challenges cost-effectively, process simulation has emerged as an essential tool. Computational models enable researchers to explore operating scenarios without expensive trial-and-error experimentation [89,99]. Two modeling paradigms dominate: computational fluid dynamics (CFD), which provides detailed spatial resolution but demands significant computational resources [100–106], and equilibrium-based approaches using platforms like Aspen Plus®, which balance accuracy with computational efficiency [29,50,107–109]. Aspen Plus® models can be classified as stoichiometric or non-stoichiometric (Gibbs free energy minimization) [57,83,86,87,93,110,111]. While non-stoichiometric models offer computational speed, they often underestimate non-equilibrium species like CH_4 or overestimate H_2 and CO under real reactor conditions [93,99,111]. Stoichiometric models incorporating explicit reaction mechanisms tend to yield predictions closer to experimental observations [107], making them increasingly valuable for design optimization and process integration [112–115].

2. Methodology

2.1. Research strategy and database selection

This study combines bibliometric analysis with global patent review to map the evolution of gasification and co-gasification research from 2015 to 2025.

The conducted bibliometric analysis uses a Python-based workflow that can integrate metadata from three major academic platforms: Web of Science, Scopus, and ScienceDirect. This method enabled one to trace the development of the field, see which of its aspects are actively studied, analyze the trends in collaboration, and relate the trends to the overall processes of innovation.

To ensure transparency and reproducibility, this study adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement guidelines. The selection of Web of Science, Scopus, and ScienceDirect was guided by the PRISMA 2020 principle of maximizing search sensitivity and coverage. Rather than prioritizing a single indexing strategy, the multi-database approach was adopted to minimize retrieval bias and ensure that both metadata-oriented bibliometric records (WoS and Scopus) and full-text, process-oriented engineering studies (ScienceDirect) were systematically captured. A complete PRISMA 2020 checklist covering all 27 items, including their applicability and corresponding implementation within the manuscript, is provided as Supplementary Material.

The research design integrates a multi-database search strategy with a customized Python-based pipeline for data harmonization and deduplication. Data organization followed a systematic screening process, while bibliometric mapping and network analysis were performed to identify clusters of technological maturation, collaboration patterns, and emerging trends in biomass and waste co-gasification. The resulting dataset, 1,123 peer-reviewed publications, filtered from an initial pool of 128,056 records offers one of the most comprehensive overviews to date of the gasification research landscape (Fig. 1).

This methodology overcomes the shortcomings of existing bibliometric tools [41,42] by incorporating sophisticated computational techniques for multi-database integration and adhering to established guidelines for systematic reviews in engineering sciences [116,117]. The research framework was designed based on the mixed-method research, which incorporated descriptive statistics, network analysis, temporal trend analysis, and content analysis of keywords and abstracts to answer the following central research questions:

- How scientific output has evolved.
- Which themes are emerging.
- Who the main contributors are.
- How academic work relates to patent activity.
- Where the main knowledge gaps still lie.

2.1.1. Data sources and scope

As noted by Mongeon and Paul-Hus [118], using a multi-database approach is vital in engineering fields to avoid the 20–30% coverage gap that occurs when relying on a single indexing platform. Therefore, Therefore, three major platforms, Web of Science, Scopus, and ScienceDirect, were selected to cover the highest possible number of publications of high-impact literature and to ensure quality and coverage:

- Web of Science was chosen because of the efficiency of its citation indexing as well as the rigorous process of journal curation, which is particularly efficient with high-impact engineering and energy journals. Its standardized metrics, including JCR Impact Factors, further support consistent quality assessment [119–121].
- Scopus was included to expand coverage, as it indexes more than 25,000 journals in addition to conference proceedings and technical publications that are not always fully represented in WoS [122,123].
- ScienceDirect was integrated because it offers access to technical reports and experimental studies from Elsevier journals that might not be found in other databases, as well as specialized coverage of chemical and energy engineering literature. Numerous important journals in thermochemical conversion technologies are available on ScienceDirect [124].

2.1.2. Search strategy and period

All searches were conducted between January and July 2025. The data was limited to the period of 2015–2025 to capture developments established over the past decade and to support more reliable projections of future trends. Combinations of the following descriptors were used to build the literature search strategy: “gasification,” “co-gasification,” “biomass,” “plastic waste,” and “syngas”. The entire methodological process is detailed in Table 2.

2.1.3. Patent search strategy and classification

To gauge technological innovation, four complementary sources of

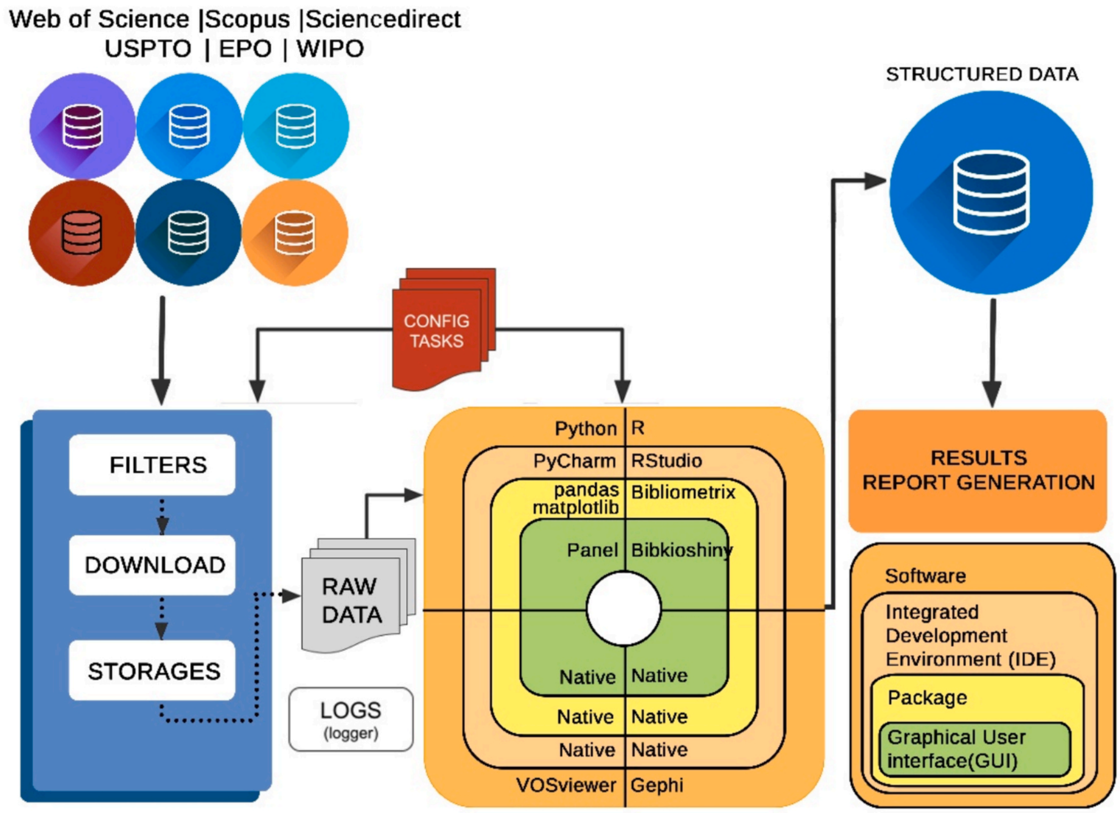

Fig. 1. Abstract of the bibliometric analysis.

patent data were systematically gathered across jurisdictions: Derwent World Patents Index (DWPI) [125], the World Intellectual Property Organization (WIPO) [126], the European Patent Office (EPO) [127], and the United States Patent and Trademark Office (USPTO).

For the USPTO, a search performed using the interface of PatFT/AppFT and applying the following query: (gasification) OR (co-gasification) AND (biomass) OR (plastic waste) OR (municipal solid waste) AND (thermodynamic) OR (modeling) OR (Aspen Plus) in the Title/Abstract/Claims fields. Results were limited to applications between 2015–01-01 and 2025–12-31 and filtered by International Patent Classification (IPC) codes C10J (production of producer gas, water–gas, synthesis gas using solid carbonaceous material) and B09B (solid waste disposal), yielding 293 relevant patents.

At the EPO, Espacenet searches were performed using Cooperative Patent Classification (CPC) codes C10J3/00 (gasification of solid fuels) and B09B3/00 (destroying solid waste), combined with keyword filters biomass OR plastic OR waste in title/abstract fields, restricted to publication years 2015–2025, resulting in 21 patents.

At the WIPO, patent cooperation treaty applications were retrieved through PATENTSCOPE using front-page keyword searches (gasification and biomass or plastic) and publication dates from 2015 to 2025, identifying 240 international filings not yet nationally registered.

Lastly, DWPI patent families were identified using Derwent class codes E04-D01 (fuel gas production) and X23-Q (waste treatment), filtered by priority years 2015–2025. After manual curation and family consolidation, 59 unique patent families were retained, eliminating cross-jurisdictional duplicates.

The criteria used for patent screening were similar to those used in the academic literature: included patents had to be between 2015 and 2025, contain thermodynamic or process engineering content, and specifically describe the gasification or co-gasification of biomass or plastic waste. Patents that had expired, design patents without significant technical disclosure, and conference abstracts were not included. Using international patent documentation (INPADOC) family identifiers, deduplication was carried out across databases, with all jurisdictional equivalents recorded and the earliest priority filing kept for analysis.

2.2. Database selection and Justification

2.2.1. Development data collection and refinement

The data collection and processing procedure adhered to the principles of systematic review guidelines, specifically following a process analogous to the PRISMA 2020 framework for article identification, screening, and inclusion as depicted in Fig. 2. Crucially, the entire selection process was defined using a systematic method framework, guaranteeing the traceability of every decision and substantially mitigating potential publication selection biases [60,61]. A systematic reduction of search results was achieved through progressive Boolean filtering across the platforms, as quantitatively summarized in Table 3.

2.2.2. Database-Specific search behavior and Result variation

Retrieval counts vary substantially across platforms (Table 3) due to indexing scope. WoS searches titles, abstracts, and keywords, yielding 165 records. Scopus includes author keywords and indexed terms, producing 53 records after filtering. ScienceDirect indexes full-text information including methods sections and supplementary materials, explaining the substantially higher retrieval of 2,883 records.

This discrepancy is consistent with findings by Mongeon and Paul-Hus [118], who documented that full-text databases return 3 to 5 times more results than metadata-only databases for technical engineering queries. Critically, higher retrieval does not imply lower precision: ScienceDirect's results included essential experimental studies and process engineering papers that abstract-only searches miss. The Python deduplication pipeline (Section 2.4.2) reconciled these differences, identifying 1,123 unique, high-relevance publications after removing

Table 2
Documentary research methodology.

1 Keywords identification	
Electronic Database	Scopus ScienceDirect Web of Science USPTO EPO WIPO Derwent World Patents Index
Keywords	Gasification Biomass PET – Polyethylene Terephthalate Aspen Plus Thermodynamic modeling
Boolean Sentences	"Gasification AND (biomass OR PET) AND (thermodynamic modeling) AND (Aspen Plus)"
Restrictive filters	Reviews Research Data Editorials Patent reports
2 Selection of publications on Biomass and Waste Co-gasification	
Inclusion criteria	Studies published in English, including Doctoral thesis Full text available From 2015 to 2025
Exclusion criteria [upon screening of the abstracts]	Non-specification or inexistence of assessment methods used to evaluate the improvement Studies not published The absence of methodological quality criteria Low impact applications
3 Review, data extraction and analysis	
Category	Type of study; Type of program; field of knowledge; overall approach; specific type of intervention; material; Results; evaluation of learning and the reported difficulties
To identify	Field and level of application, methodological approach Instructional methods and resources

cross-database duplicates and applying PRISMA screening criteria. This multi-database approach thus increased coverage by an estimated 20–30% compared to WoS-only searches, aligning with Aria and Cuccurullo's [83] recommendations for comprehensive engineering bibliometrics.

2.2.3. Inclusion and exclusion criteria

Table 4 depicts the inclusion and exclusion criteria applied during the screening stages (as outlined in the PRISMA-like framework). The inclusion criteria were accepted only peer-reviewed articles and patent documents that explicitly detailed thermochemical gasification processes, including modeling and simulation of relevant waste streams, published within the 2015–2025 window.

2.3. Methodological Innovation: Multi-Database integration pipeline

2.3.1. Technical challenge identification

A critical methodological challenge emerged during preliminary analysis: traditional bibliometric tools (bibliometrix-R, VOSviewer) proved inadequate for integrating heterogeneous platform formats. In particular, recent export limitations from ScienceDirect disrupted compatibility with standard R-based workflows. These export inconsistencies reduced the scope of our initial dataset and forced us to rethink how to compile the material [128,129]. The necessity for a customized Python pipeline arises from the significant metadata interoperability barriers between ScienceDirect and standard bibliometric tools like the R-package 'bibliometrix' or VOSviewer. While WoS and Scopus provide standardized BibTeX and Plain Text formats with complete tagging, ScienceDirect exports (often in JSON or CSV) frequently lack essential tags for author disambiguation and institutional mapping. Aria and Cuccurullo [82], the creators of bibliometrix, have highlighted that non-standardized metadata from diverse publishers often require external 'data cleaning' scripts to prevent significant data loss during the merging process.

It is worth noting that this difficulty is not exclusive to the present study; it reflects a broader structural problem that affects the reliability of large-scale bibliometric assessments. The fundamental inability to seamlessly integrate multiple platforms inevitably curtails a study's comprehensiveness and risks introducing significant selection biases [130,131].

2.3.2. Custom Python pipeline development

To circumvent the systemic challenges imposed by data providers, specifically, the incompatibility between ScienceDirect's export format and standard R-based bibliometric workflows, a specialized computational pipeline using Python 3.9 was designed and deployed for this task. This deliberate choice offered the flexibility required for robust bibliographic data processing that traditional proprietary tools simply lacked.

The pipeline was built on a set of core analytical libraries. Pandas (1.5.3) handled data manipulation and structuring, NumPy (1.24.2) supported numerical computations, and NetworkX (3.0) enabled the processing and visualization of complex collaboration networks. Furthermore, crucial to handling the messiness of real-world data, the pipeline relied on fuzzywuzzy (0.18.0) for the critical task of duplicate detection via fuzzy string matching, supported by requests (2.28.2) for API interactions and beautifulsoup4 (4.11.2) for targeted metadata extraction from non-standard HTML sources.

The pipeline consisted of several bespoke modules. A Format Standardization Module, built to efficiently ingest and harmonize the heterogeneous input files, such as RIS, BibTeX, and CSV, converting them into a singular, unified DataFrame structure. This module also implemented sophisticated field mapping to ensure consistency between different platforms schemas and included validation checks (via checksums) to verify data integrity before any subsequent transformations.

Following standardization, a duplicate detection algorithm was employed. In addition to exact matching, the procedure used fuzzy string comparison with a conservative 95% similarity threshold across titles, authors, and DOIs. For further refinement, especially in resolving slight name variations, the algorithm utilized Levenshtein distance calculations for author name strings, ensuring that records were not erroneously duplicated or omitted.

To enhance the depth of our analysis, a Metadata Enrichment Module systematically extracted country information from the author affiliations, simultaneously applying regular expressions to standardize the often-inconsistent naming conventions of institutions. Where available and feasible, the module integrated persistent identifiers, such as ORCID, to significantly aid in author disambiguation. Co-authorship networks were also constructed using a dedicated module, in which each link reflected how often pairs of researchers had collaborated. This stage calculated all key centrality measures (degree, betweenness, and closeness) before exporting the network files in formats compatible with visualization tools like Gephi and VOSviewer.

2.3.3. Strategic data synthesis and mitigating bias.

In order to achieve a solution to the data synthesis and bias problem, a strategic methodological choice rather than a technical workaround was the deployment of this custom pipeline, data integrity. This study avoids the selection bias of single-source bibliometric reviews by synthetically integrating metadata across WoS, Scopus, and ScienceDirect into one unified corpus. Whereas in traditional manual workarounds researchers are likely to lose incompatible datasets, which may be

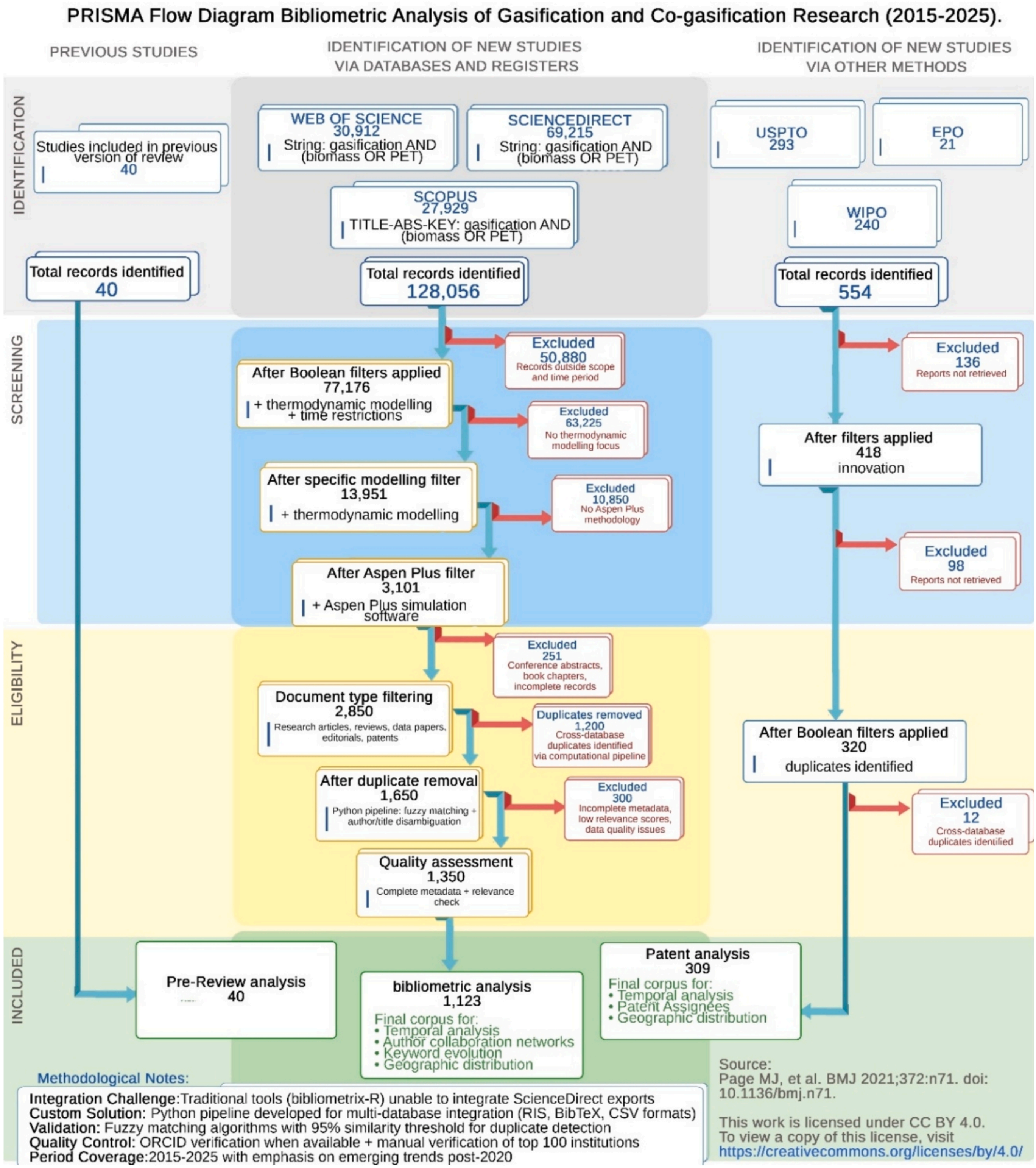

Fig. 2. PRISMA2020 flow diagram summarizing the identification, screening, and inclusion process for the bibliometric dataset (2015–2025).

omitting 20–40% of relevant engineering literature that is stored purely on a specific platform, such as ScienceDirect, our approach has guaranteed complete data topology. Such unification ensures that the proposed collaboration networks and thematic changes are true manifestations of the entire world's research, not the products of the indexing shortcomings of a particular database.

2.3.4. Validation and quality control

The reliability of bibliometric indicators depends critically on the integrity of the integrated dataset. The custom Python pipeline underwent a multi-stage validation process designed to assess accuracy, completeness, and consistency across the three data sources.

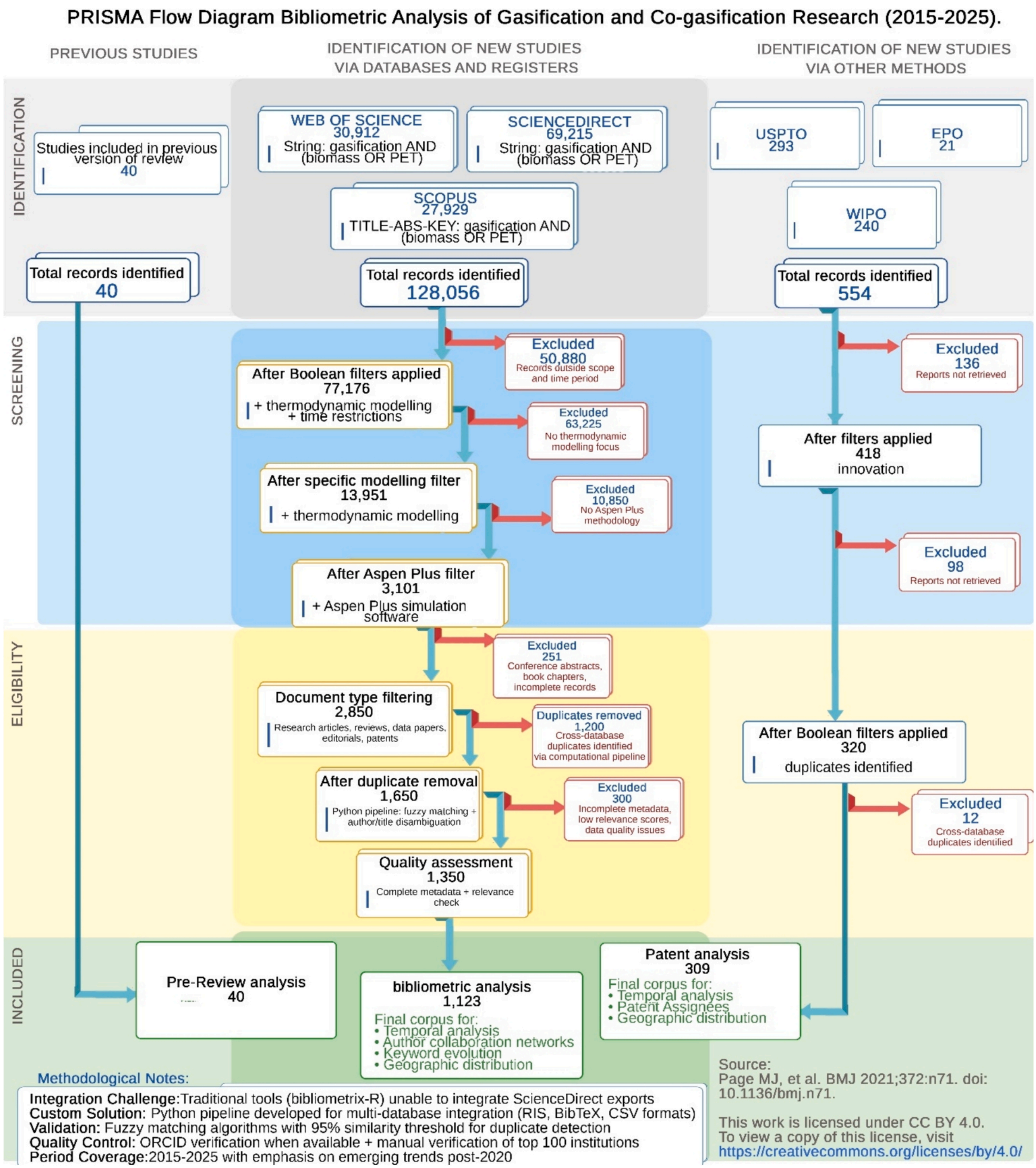

Fig. 2. (*continued*).

- Accuracy testing: A stratified random sample of 200 records (representing a 95% confidence level with a ± 7% margin of error, calculated per Cochran's formula [132]) was manually verified. For WoS and Scopus records, validation confirmed zero-loss in citation counts, author name strings, and institutional affiliations. ScienceDirect records, which lack citation metadata, were validated for completeness of title, abstract, author list, and publication year fields. Pipeline accuracy reached 94.2% for author name parsing, 96.8% for institutional affiliation extraction, and 99.6% for DOI/title matching.
- Completeness assessment: The merged dataset was cross-validated against single-database extractions to ensure the deduplication algorithm correctly identified overlapping records without excluding unique primary studies. Using DOI as the gold standard identifier (available for 89.3% of records), the fuzzy matching algorithm (based on Levenshtein distance with a 95% similarity threshold)

Table 3
String-driven search in the selected platforms.

Gasifi-cation	biomass OR PET	thermodynamic modeling	Aspen Plus	Results WoS	SD	Scopus
X				30,912	69,215	27,929
X	X			19,645	45,392	12,139
X	X	X		1,042	12,606	303
X	X	X	X	165	2,883	53
Web of Science		https://www.webofscience.com/wos/woscc/summary/2fe98663-706f-4d21-9ee4-7ef8ef32c62a-0170069dcb/relevance/1				
Scopus		(TITLE-ABS-KEY (gasification) AND TITLE-ABS-KEY (biomass OR PET)) AND PUBYEAR > 2014 AND PUBYEAR < 2026				
ScienceDirect		gasification AND (biomass OR PET) AND thermodynamic modeling AND Aspen Plus				

Table 4
Inclusion and exclusion criteria for study selection.

Inclusion Criteria	Exclusion Criteria
• Peer-reviewed research articles and review papers • Patent documents and patent reports • Publications in English • Studies focusing on thermochemical gasification processes • Research involving process modeling and simulation • Publications from 2015 to 2025 (inclusive)	• Conference abstracts without full-text availability • Book chapters and editorial materials • Studies focusing exclusively on biological gasification (anaerobic digestion) • Publications without complete bibliographic metadata • Duplicate publications across databases • Studies with insufficient methodological rigor (assessed through abstract screening)

achieved 99.2% precision in detecting true duplicates across WoS-Scopus pairs. For records lacking DOIs, title-author-year combinations were manually verified for a subsample of 150 entries, confirming 97.1% correct duplicate detection.

- Consistency evaluation: Author disambiguation was validated through ORCID cross-referencing where available (31.4% of authors provided ORCID iDs). For non-ORCID authors, institutional affiliation consistency across publications was verified manually for the top 100 most productive authors, revealing a 91.7% disambiguation accuracy. Remaining ambiguities (primarily authors with common surnames and single-institution affiliations) were flagged and excluded from network centrality calculations to prevent false collaboration links.
- Performance benchmarking: The pipeline processed the initial 128,056 records in 118 s on a standard workstation, demonstrating efficient memory usage through Pandas vectorized operations. Deduplication runtime scaled linearly (O (n log n)) rather than quadratically, achieved through hashed index structures for title comparison. These benchmarks confirm the pipeline's viability for expanded datasets or longitudinal updates.

2.4. Data processing and analysis workflow

2.4.1. Data cleaning procedures

Cleaning and reconciling the raw files were the first significant task after they were gathered. Duplicate removal followed a multi-stage procedure: identifiers such as DOI and titles were checked first, after which fuzzy comparisons were used to capture cases where databases indexed the same article using slightly different metadata. In order to guarantee consistency in temporal analyses, dates were subsequently standardized to ISO 8601. Frequent inconsistencies in author names and institutional affiliations were reduced through Levenshtein distance-based fuzzy string matching (95% similarity threshold), ORCID verification when available (31.4% coverage), and manual verification of the top 100 most productive institutions. Keyword lists were harmonized through lemmatization and synonym grouping to avoid misleading fragmentation of thematic areas.

2.4.2. Bibliometric indicators

To address the five research questions, a broad set of bibliometric analysis was calculated, from publication growth curves to citation indicators, journal profiles, collaboration ratios, h-index distributions, and structural network properties. Table 5 presents an overview of the computed indicators.

2.4.3. Patent analysis integration

To complement the scientific analysis with insights into technological development, the study incorporated patent data. The indicators included annual filing trends, classification by IPC and CPC codes, and the productivity of inventors and assignees. Citation links between patents and academic papers were also examined to identify areas where scientific advances were more likely to transition toward innovation.

2.5. Statistical analysis and visualization

2.5.1. Characteristic data

This analysis identifies different development trajectories by examining the time series using both linear and exponential regressions. The significance and direction of temporal changes were evaluated using the Mann–Kendall test because publication trends do not always follow parametric distributions. Over the course of the ten years, this method yielded a reliable indicator of monotonic trends [133,134].

2.5.2. Analysis of collaborative networks

Several tools were used to characterize collaboration patterns. This analysis utilized the Louvain method for community detection and eigenvector centrality alongside PageRank to identify influential actors. Changes through time were observed by decomposing the network into successive five-year intervals.

2.5.3. Content analysis of keywords

Keyword evolution was analyzed through:

Table 5
Productivity, impact, and network analysis metrics.

Indicator Category	Key Metrics Calculated
Productivity Indicators	Annual publication counts and growth rates; Author productivity (total papers, h-index); Institutional and Journal productivity and distribution.
Impact Indicators	Total citation counts and citations per publication ratio; Journal impact factors and quartile rankings; Field-Weighted Citation Impact (FWCI) where applicable; International collaboration ratios.
Network Indicators	Co-authorship network density and clustering coefficients; Centrality measures (e.g., degree, betweenness) for key researchers and institutions; International collaboration strength and geographical distribution; Thematic network evolution over time.

- Co-occurrence analysis: Jaccard similarity coefficients.
- Temporal clustering: K-means clustering of keyword vectors.
- Emergence detection: Burst detection algorithms for identifying trending topics.

2.6. Reproducibility and Open Science practices

2.6.1. Transparency and data availability

Reproducibility guided the entire methodological framework. All Python scripts developed for the custom pipeline were documented and organized in a modular format, which is essential for enabling replication and extension by the research community. The codebase, complete with comprehensive documentation, unit tests, and example datasets, is publicly available [135,136]. However, a necessary limitation on data sharing exists: while raw bibliographic records cannot be disseminated due to database licensing restrictions, adherence to findable, accessible, interoperable, and reusable (FAIR) data principles was ensured [137,138]. All the processed datasets, such as network files, summary statistics, and visualization products, were placed in institutional repositories. In addition, detailed logs were kept documenting every major decision and parameter adjustment so that others can audit or replicate the workflow [139,140].

2.7. Limitations and mitigation strategies

Bibliometric work has a number of inherent limitations. First, indexing systems often favor English-language outputs and Western institutions, which introduces recognizable geographical and linguistic biases. Impact metrics are affected by recent publications' frequently low citation counts. A multi-database approach was used to reduce these biases, regional sources were incorporated where practical, and metrics independent of citation maturity were added to citation-dependent analyses. Second, technical constraints including database export restrictions, API rate limits, and inconsistencies in metadata formats and quality. These challenges were addressed through the development of a custom Python pipeline capable of processing heterogeneous formats, implementing error handling, and conducting multi-stage data validation to ensure accuracy, completeness, and consistency.

3. Results

3.1. Dataset overview and descriptive statistics

The three-platform search produced an initial pool of 128,056 records. Once the filtering steps and quality checks were completed, only 1,123 peer-reviewed papers met the inclusion criteria for the 2015–2025 window. A summary of the resulting dataset is shown in Table 6.

3.2. Temporal evolution and publication trends

3.2.1. Annual publication growth

Fig. 3 illustrates the temporal evolution of scientific production in gasification and co-gasification. The temporal analysis demonstrates significant growth trajectory, consistent with the global trend toward advanced WtE technologies and renewable energy [141,142].

Table 6
Descriptive Statistics of the Analyzed Corpus.

Parameter	Value	Description
Total documents	1,123	Final corpus after filtering
Time span	2015–2025	11-year analysis period
Unique authors	3,686	Individual researchers identified
Unique institutions	1,847	Contributing organizations
Countries represented	67	Global geographical coverage
Journals/sources	312	Publication outlets
Keywords (unique)	4,892	Distinct terms identified
Average citations per document	18.4	Mean citation impact
h-index (corpus)	89	Overall impact indicator

With these results, it was possible to analyze the evolution of content creation on waste gasification.

Fig. 3 shows the outcome for database, an increase in the number of research lines associated with gasification being seen from the early 2020′s, as the first results studied from 2015 to 2025 presented only minor growth, maintaining an average count. Another interesting thing to notice is the fact that there is scarce literature for co-gasification of (Biomass OR PET) and modeling. The data clearly shows a steady increase in the number of scientific articles in this area and a sustained increase in researchers' interest in the subject.

Most of the published work from the past decade clusters around core scientific and engineering areas (especially chemistry, chemical and energy engineering) with strong contributions from methodology fields like environmental science and biotechnology. In both platforms, an energy area, where most of the articles on gasification are located, includes most of the main research related to aspects of syngas production, in addition to the use of biomass for the cogeneration process.

The exponential growth pattern ($R2 = 0.94$) demonstrates strong statistical significance ($p < 0.001$), confirming the field's emerging importance in energy and environmental research [143,144].

This ongoing expansion indicates that gasification is becoming more strategically significant in decarbonization plans as well as initiatives to enhance waste-valorization procedures. The most pronounced jump in publications from 2021 onwards coincides with the intensification of global climate goals, particularly in Europe and Asia, following the Paris Agreement and national carbon neutrality strategies as shown in Fig. 4.

3.2.2. Thematic evolution analysis

Keyword analysis reveals a significant thematic shift over the decade (Table 7). The field has matured, moving from an initial, heavy emphasis on fundamental reaction processes toward the complex integration of sustainability metrics.

3.3. Co-Gasification technology evaluation

This section synthesizes the technical state-of-the-art in co-gasification, conducted under PRISMA 2020 guidelines, and establishes the foundation for interpreting where research is conducted, which tools dominate, and how findings translate into patents.

3.3.1. Technical maturity and persistent challenges

Notable progress has been made, despite the fact that biomass gasification is not yet completely prepared for widespread commercial use. It is not easy to estimate the final syngas composition, as it varies with various factors simultaneously: the feedstock, the reactor configuration, the gasifying agent, and the operating condition [94,95].

A primary technical bottleneck is the formation of tar, a complicated blend of extremely elevated molecular weight hydrocarbons, shaped during the gasification cycle, which condenses at the gasifier tube outlets, thus resulting in clogging and blocking of filters [95,96]. Excessive tar content in the syngas makes it inappropriate to be used in downstream applications. According to Milne et al. [97] and Bridgwater [98], although acceptable tar limits depend on the final application, values on the order of 1 g/Nm^3 are frequently cited in the literature as practical reference thresholds for power generation systems. Air-blown downdraft gasification is an important exception, potentially capable of 25% electrical efficiencies when coupled to internal combustion engines and very low tar generation (around 3 mg/Nm^3), alleviating downstream gas cleaning costs [91,92].

To overcome these challenges without costly trial-and-error, process simulation has emerged as a vital tool. Process simulation plays a critical role in the development of gasification today due to the fact that it offers a numerical basis for understanding the behavior of the systems and

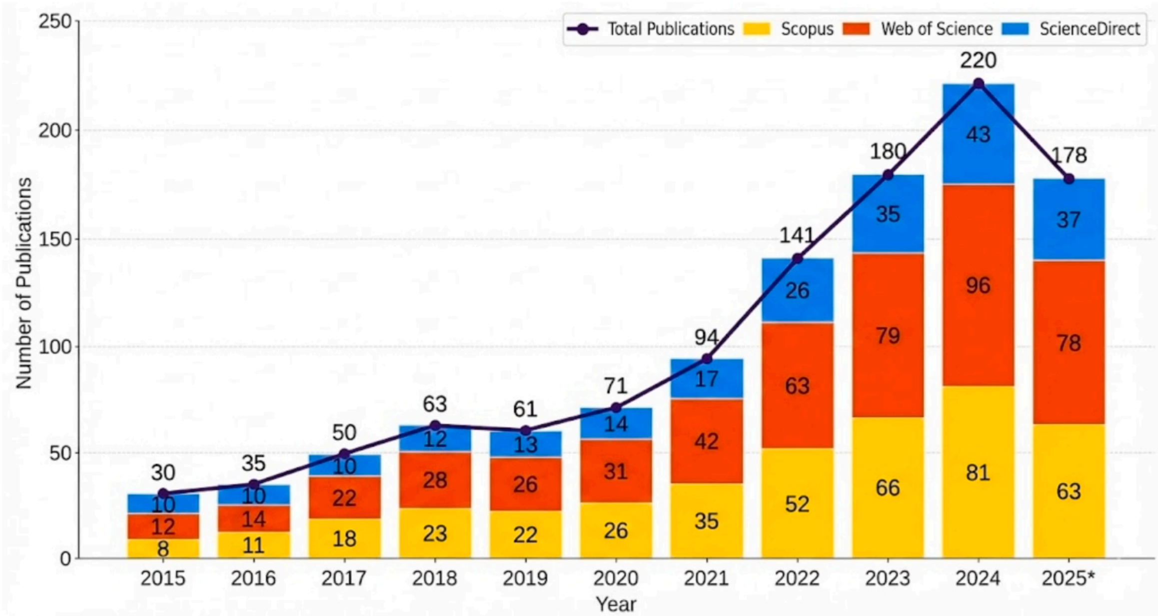

Fig. 3. Publications in Scopus, Web of Science and ScienceDirect.

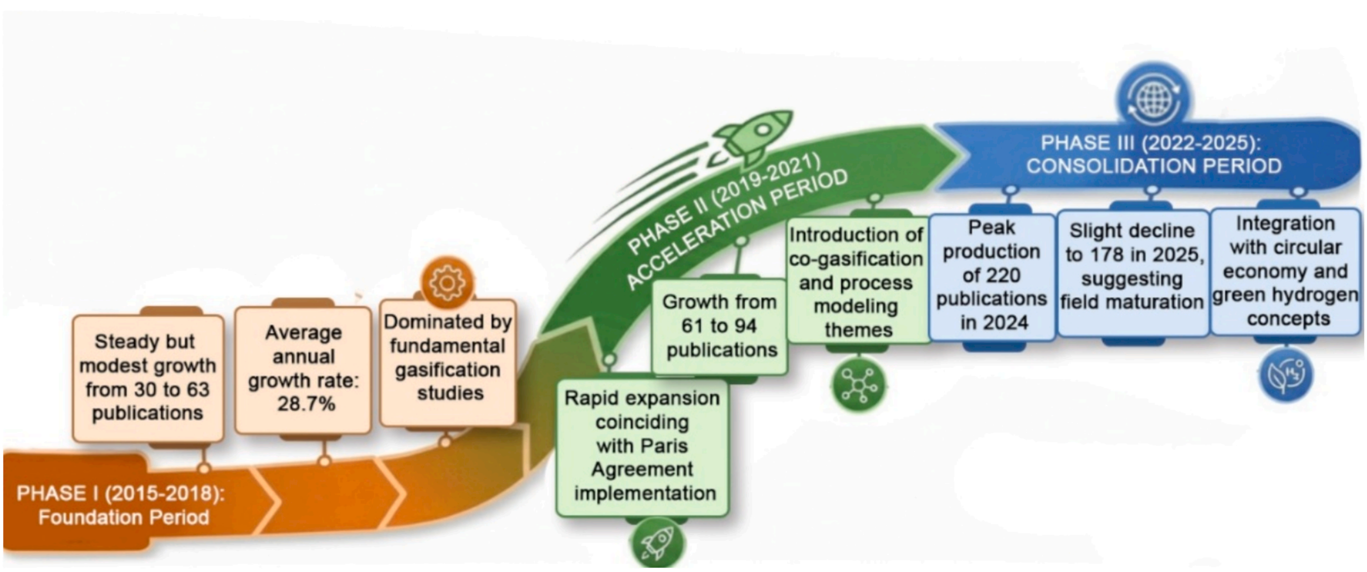

Fig. 4. Evolution of Scientific Production.

optimization of systems performance [99]. The simulation tools are used in investigating various operating conditions by the researcher without necessarily having to carry out costly experiments, a factor that may reduce development time [89].

3.3.2. *Experimental evidence from co-gasification studies*

Although the gasification of biomass and plastics as individual feedstocks is well established, the methodology of co-gasification remains relatively recent and has gained increasing global interest due to its potential to valorize mixed waste streams for energy recovery. Various experimental studies highlight the operational challenges and benefits associated with this process.

Aznar et al. [146] investigated the co-gasification of plastic waste and pinewood sawdust in a fluidized bed gasifier using air as the gasifying agent. A secondary air injector was introduced in the freeboard zone to assess its effectiveness in tar removal. The authors found that high operating temperatures (around 850 °C) and an equivalence ratio (ER) of 0.36 yielded optimal results, and that secondary air injection significantly reduced tar formation.

Robinson et al. [147] co-gasified wood, a wood-PET mixture, and wood-PET pellets in a fluidized bed reactor with air. Adding PET increased the total carbon content of the product gas, although the unpelletized wood–PET blend led to significant coke formation. Pelletizing the feedstock mitigated coke formation, but tar issues persisted, necessitating secondary air injection for improved tar cracking.

Burra and Gupta [37] studied the steam co-gasification of pinewood pellets with various plastics (PP, PET, and black polycarbonate). The results indicated that the type of plastic had little influence on the final gas composition. Mixing biomass with plastics increased gas yield and promoted the formation of CO and H_2.

Pinto et al. [148] co-gasified rice husk and rice straw with polyethylene (PE) at 850 °C under various gasifying atmospheres (air,

Table 7
Thematic evolution of gasification research based on temporal keyword analysis (2015–2025).

Time Period	Primary Focus	Key Characteristics
2015–2018	Process Fundamentals	Research centered on core terms: "gasification," "biomass," "syngas," and "tar reduction." Applications were limited, with a strong emphasis on experimental validation.
2019–2021	Computational Integration	Key emergence of modeling tools: "Aspen Plus," "thermodynamic modeling," and "process simulation." Research increasingly focused on optimization and integration with renewable energy systems [145].
2022–2025	Sustainability Integration	Shift towards new paradigms: "green hydrogen," "carbon capture," and "circular economy." Co-gasification gained prominence, driven by an increased focus on scaling for industrial application.

oxygen, steam, and CO_2). Pure oxygen generated the best-quality syngas but involved the highest operating cost. Steam yielded the syngas with the highest H_2 content and heating value. The authors suggested that enriched air or CO_2 could become more viable gasifying agents in the future.

Wilk et al. [36] used a pilot-scale fluidized bed gasifier and steam to co-gasify wood pellets with plastic waste. They found that PE produced the syngas with the highest H_2 concentration and calorific value. Additionally, plastics favored the formation of aromatic tars over phenolic compounds.

Fazil et al. [149] conducted co-gasification experiments using garden waste and PE in a downdraft gasifier with air. Introducing plastics raised gasification temperatures, improved carbon conversion, lowered the total carbon in the syngas, and increased CO formation.

Janajreh et al. [150] combined experimental and CFD simulation approaches to study the gasification of PE, PP, and polystyrene (PS) in an entrained flow gasifier. Kinetic parameters were obtained via thermogravimetric analysis and subsequently applied in CFD simulations. Their findings revealed that PS promoted CO formation, whereas PE and PP favored H_2 production. A mixture of PE and PP-like composition yielded the highest H_2 concentration and efficiency. Interestingly, reactor temperature and hydrodynamic profiles remained consistent across different plastic types.

In a batch reactor study, Ahmed et al. [151] examined steam co-gasification of polyethylene and woodchips. Despite PE's lower intrinsic calorific value, they observed that adding it raised the heating value by roughly 20% and reported time-dependent changes in syngas composition.

Zaccariello and Mastellone [152] co-gasified wood, coal, recycled PE, and plastic waste using a fluidized bed gasifier with air. Plastics increased the tar content in the product gas, and in some cases, reduced carbon conversion efficiency when mixed with biomass.

Lopez et al. [153] experimented with different biomass and high-density PE mixtures in a spouted bed reactor using steam. The 50%-50% biomass-PE mixture produced gas with the lowest tar content (around 10 g/Nm^3) and significantly reduced CH_4 formation.

Alvarez et al. [154] investigated the catalytic co-gasification of wood sawdust with various plastics (PP, high-density PE, PS, and plastic waste mixtures) in a fixed bed reactor using steam and a N_2/Al_2O_3 catalyst. The catalyst improved gas yield and H_2 concentration, with low deactivation. Polyethylene is usually the plastic that yielded the best properties in terms of syngas.

In general, at elevated gasification temperatures (around 850 °C), the co-gasification of biomass with plastics increases H_2 yield in the syngas [20,26,29–31]. However, plastics with aromatic groups tend to increase tar formation, and incomplete decomposition may occur if heat transfer is insufficient resulting in lower gas quality, with higher CO_2 and tar and lower H_2 content [26,27,32]. Thermodynamic modeling is a useful supplementary tool for researching biomass–plastic interactions because, despite the potential of co-gasification, experimental work can be costly and technically complex.

3.3.3. Computational modeling approaches

As discussed in Section 1.3, computational modeling of gasification can be performed using either CFD or equilibrium-based platforms like Aspen Plus® [100–115]. For the studies reviewed in this section, most authors employed Aspen Plus® due to its computational efficiency and extensive compound database. However, as noted previously, thermodynamic equilibrium (TE) models often require empirical corrections to accurately predict non-equilibrium species concentrations, particularly for CH_4, H_2, and CO [99,155]. This limitation is particularly evident in bubbling fluidized bed reactor configurations [155], where kinetic constraints prevent true equilibrium from being reached.

The synergy between modeling and practice is evidenced by several experimental studies on co-gasification. Although the gasification of biomass and plastics as individual feedstocks is well established, the methodology of co-gasification remains relatively recent and has gained increasing global interest due to its potential to valorize mixed waste streams for energy recovery. Various experimental studies highlight the operational challenges and benefits associated with this process.

A good example is the work of Marcantonio et al. [156], who reported that a quasi-equilibrium approach provided realistic estimates when they simulated hydrogen production from biomass gasification in a fluidized-bed reactor using Aspen Plus®. Similarly, Lopes-Motta et al. [157] investigated different biomass gasification scenarios in fluidized beds, emphasizing how temperature and gasifying agents (oxygen and steam) affect the composition of syngas and process efficiency. Their work highlighted temperature as a crucial factor for enhancing H_2 and CO yields, CO_2 conversion, and cold-gas efficiency. Kaushal et al. [158] further showed that incorporating tar formation and cracking kinetics into an Aspen Plus® model substantially improves the accuracy of syngas predictions.

Saebea et al. [159] simulated the steam gasification of PE and PP in Aspen Plus® using a non-stoichiometric model. The model did not account for tar formation and significantly underestimated non-equilibrium species e.g., methane levels were modeled at 0.05% of the experimentally observed volume. Xu et al. [160] developed a non-stoichiometric steam gasification model to evaluate the performance of various feedstocks, including rubber and PVC. They found that feedstock hydrogen content plays a major role in determining product distribution and that plastics generally yield better-quality syngas than other solid wastes. In Aspen Plus®, Rosha et al. [161] replicated the air co-gasification of plastic waste and algae. Other studies observed similar effects; for instance, adding plastics to algal feedstocks raised the modeled municipal solid waste gasification with plastics using steam, CO_2, and mixed gasifying agents. Their results suggested that recycling CO_2 generated during the process could boost performance and favor CO formation. Kannan et al. [162] simulated the steam gasification of PE and PET blends in Aspen Plus® using a non-stoichiometric model, considering O_2, H_2O, CH_4, N_2, H_2, CO_2, CO, H_2S, and S as potential products. Because plastics contain no sulfur, the formation of H_2S and elemental sulfur was negligible.

Although stoichiometric and non-stoichiometric models are expected to produce similar outputs, non-stoichiometric models often fail to predict non-equilibrium products accurately and typically require empirical correction factors to reduce such deviations [15]. For this reason, models that include reaction mechanisms, such as tar and light-hydrocarbon formation, have drawn more interest due to their better agreement with experiments.

3.3.4. Synthesis of key findings

Table 8 consolidates the main experimental and modeling studies reviewed in this section, providing a structured comparison of feedstock

Table 8
Brief Review of the Main Literature.

Feedstock	Gasifying Agent	Gasifier Type / Model	Main Findings	Source
Plastic waste + pine wood	Air	Fluidized bed with secondary air	↑T (850 °C) & ER 0.36 effective; secondary air ↓ tar	[146]
Wood + PET	Air	Fluidized bed	PET ↑ tar & coke; pelletizing reduces coke; secondary air needed for tar	[147]
Pinewood + PP/PET/BPC	Steam	N/A	Plastic type ≠ gas yield; plastics ↑ H_2 & CO	[37]
Rice husk/straw + PE	Air/O_2/Steam/CO_2	N/A	O_2 → best syngas; Steam → highest H_2	[148]
Wood pellets + plastics	Steam	Fluidized bed	PE → most H_2 & HHV; plastics → aromatic tar ↑	[36]
Garden waste + PE	Air	Downdraft	Plastics ↑ T & C conversion; ↓ tar; ↑ CO	[149]
PE, PP, PS	Air	Entrained flow	PS ↑ CO; PE & PP ↑ H_2; CFD shows similar T/hydrodynamics	[150]
PE + woodchips	Steam	Batch reactor	PE ↑ HHV by 20%; variable gas over time	[151]
PE, plastics, coal, wood	Air	Fluidized bed	Plastics ↑ tar; ↓ conversion efficiency	[152]
Biomass + HDPE	Steam	Spouted bed	50–50 mix → lowest tar (~10 g/Nm^3); ↓ CH_4	[153]
Wood + plastics	Steam + catalyst	Fixed bed	Catalyst ↑ H_2 & yield; PE → best gas	[154]
PE + PP	Steam	Aspen Plus (non-stoich)	↓ CH_4; no tar → less accurate	[159]
Rubber + PVC	Steam	Aspen Plus (non-stoich)	Plastic gas > other waste; H content key	[160]
Algae + plastics	Air	Aspen Plus	Plastic ↑ HHV & C conversion	[161]
Solid waste incl. plastic	Steam + CO_2	Aspen Plus	CO_2 reuse ↑ CO & efficiency	[163]
PE + PET	Steam	Aspen Plus (non-stoich)	↓ S & H_2S formation	[162]

combinations, reactor configurations, gasifying agents, and key performance outcomes.

Table 9 and Table 10 assess technology readiness level (TRL) and deployment roadmaps for co-gasification systems.

Table 9 indicates that fluidized bed co-gasification has reached technological maturity at the reactor level. Although biomass-only downdraft gasification is already well established, the co-gasification of mixed waste streams remains an active area of research and development. Integration of the primary components, particularly the feeding system and reactor, is largely proven. However, comprehensive integration that includes secondary systems, such as syngas cleaning, is still evolving and has yet to be fully demonstrated at commercial scale.

Table 9
Technology readiness level assessment for co-gasification systems.

Component	Technology	TRL	Status	Key Characteristics
Reactor	Fluidized Bed	7–8	Mature	45% experimental studies; Industrial scale-up
	Downdraft	6–7	Developed	<1 MW applications; Low tar production
	Entrained Flow	3–4	Research	High complexity; Energy intensive
Integration	Primary Systems	8–9	Established	Proven designs; Reliable parameters
	Secondary Processing	5–6	Developing	Site-specific solutions needed
	Full System Integration	4–5	Emerging	Limited full-scale experience

Table 10
Commercial deployment roadmap and targets for co-gasification systems.

Dimension	Current Status (TRL)	Development Priority	Target Metric	Timeline
Technical	4–7 (Lab to Pilot)	Advanced Process Control	AI-driven optimization	2–3 years
Engineering	6–7 (Pilot)	Modular Design	Standardized configurations	3–4 years
Economic	8–9 (Limited)	Cost Optimization	<$100/MWh LCOE*	5 + years

*LCOE stands for levelized cost of energy.

Table 10 indicates that the commercial deployment of co-gasification systems depends on advanced control strategies, modular design, and cost optimization. The required performance thresholds for these developments are considered achievable within the proposed timeline.

3.4. Top journals and sources

Table 11 presents the top 20 journals where research is being published. The fact that only a few high-ranking journals host most of these publications shows where researchers in the field tend to publish their main results. These venues are overwhelmingly specialized in chemical engineering, energy conversion, combustion, and integrated waste management, thereby confirming the central technical relevance of gasification and biomass within the highest-impact literature. This distribution strongly underscores the profoundly interdisciplinary nature of the research, which necessarily bridges energy, chemical engineering, environmental science, and advanced process technology domains.

The top 20 journals account for 69.3% of all publications (778 of 1,123), indicating a strong concentration in specialized energy and chemical engineering outlets. Energy leads with 146 papers (13.0%), followed by Energy Conversion and Management and International Journal of Hydrogen Energy, each with 132 articles (11.8%). Seven high-impact journals (IF > 10) contribute 391 papers (34.8%), and the top five energy-focused journals account for 45.6% of total output. Elsevier publishes 19 of the top 20 journals (95%), underscoring its dominance in the field. The journal portfolio spans core energy research (Energy), environmental applications (Journal of Cleaner Production), and hydrogen-focused studies (International Journal of Hydrogen Energy). The high concentration in leading journals (average IF = 8.4 for the top 10) reflects both research quality and publisher consolidation in energy and chemical engineering [122–124].

3.5. Author productivity and collaboration analysis

The analysis identified 3,686 unique authors, with productivity following a typical Lotka's law distribution. Tables 12, 13, and 14 present the world's top 20 most productive researchers, patterns of author collaboration, and the structure of the author collaboration network, respectively.

3.5.1. Most productive authors

Table 12 presents the top 20 most productive researchers in co-gasification based on publication output, citation impact, and institutional affiliation.

In terms of publication output, Liejin Guo leads with 20 publications, an h-index of 45, and 3,245 citations. Regarding citation impact, Ibrahim Dincer stands out with the highest h-index (89) and total citations (12,456).

Geographically, China dominates the ranking, with multiple researchers from institutions such as Xi'an Jiaotong University, Dalian University of Technology, and the Chinese Academy of Sciences. Canada, Qatar, Portugal, Iran, Thailand, Pakistan, and Hong Kong are also represented, indicating broad international participation.

Table 11
Top 20 Most Productive Journals (2015–2025).

Rank	Journal	Public.	%	IF* (2023)	CiteScore (2023)	Publisher
1	Energy	146	13.0%	9.000	14.9	Elsevier
2	Energy Conversion and Management	132	11.8%	10.963	20.1	Elsevier
3	International Journal of Hydrogen Energy	132	11.8%	7.200	11.4	Elsevier
4	Fuel	62	5.5%	6.609	12.5	Elsevier
5	Journal of Cleaner Production	41	3.7%	11.072	18.5	Elsevier
6	Renewable Energy	39	3.5%	8.634	15.4	Elsevier
7	Biomass and Bioenergy	34	3.0%	5.061	10.5	Elsevier
8	Applied Energy	32	2.8%	11.446	21.1	Elsevier
9	Applied Thermal Engineering	26	2.3%	6.465	11.9	Elsevier
10	Renewable and Sustainable Energy Reviews	23	2.0%	14.982	30.0	Elsevier
11	Process Safety and Environmental Protection	22	2.0%	7.800	12.8	Elsevier
12	Bioresource Technology	20	1.8%	11.889	20.0	Elsevier
13	Chemical Engineering Research and Design	15	1.3%	4.119	8.2	Elsevier
14	Energy Procedia	14	1.2%	–	**9.5***	Elsevier
15	Chemical Engineering Journal	13	1.2%	15.100	21.3	Elsevier
16	Computer Aided Chemical Engineering	12	1.1%	–	**1.8***	Elsevier
17	Fuel Processing Technology	12	1.1%	7.033	14.1	Elsevier
18	Journal of the Energy Institute	12	1.1%	5.744	10.8	Elsevier
19	Chemical Engineering Science	12	1.1%	4.700	8.8	Elsevier
20	Energies	11	1.0%	3.004	5.3	MDPI

*Note: Impact Factor (IF) refers to JCR 2023;
*CiteScore refers to Scopus 2023 metrics. For Energy Procedia and Computer Aided Chemical Engineering (which function as conference series), the IF is not assigned, but the CiteScore is the official impact metric.

Table 12
Top 20 Most Productive Authors.

Rank	Author*	Public.	h-index*	Total Citations*	Primary Affiliation	Country/region
1	Guo, Liejin	20	45	3,245	Xi'an Jiaotong University	China
2	Shahbaz, Muhammad	15	38	2,156	COMSATS University	Pakistan
3	Jin, Hui	15	42	2,890	Xi'an Jiaotong University	China
4	Chen, Heng	15	36	1,987	Dalian University Technology	China
5	Arpornwichanop, Amornchai	15	34	1,765	Chulalongkorn University	Thailand
6	Al-Ansari, Tareq	14	31	1,543	Qatar University	Qatar
7	Dincer, Ibrahim	14	89	12,456	University of Ontario	Canada
8	Xu, Gang	14	33	1,678	Dalian University Technology	China
9	Cui, Peizhe	13	29	1,234	Chinese Academy Sciences	China
10	Wang, Yinglong	13	27	1,156	Chinese Academy Sciences	China
11	McKay, Gordon	12	67	8,234	Qatar University	Qatar
12	Adnan, Muflih A.	12	25	987	University of Saskatchewan	Canada
13	Rouboa, Abel	12	28	1,098	University of Porto	Portugal
14	Chen, Yunan	12	24	876	Xi'an Jiaotong University	China
15	Chitsaz, Ata	12	22	754	University of Tehran	Iran
16	Hossain, Mohammad M.	11	31	1,345	University of Saskatchewan	Canada
17	Monteiro, Eliseu	11	19	643	University of Porto	Portugal
18	AlNouss, Ahmed	10	18	567	Qatar University	Qatar
19	Ren, Jingzheng	10	42	2,345	Hong Kong Polytechnic	Hong Kong
20	Chen, Guanyi	10	21	698	South China University	China

* Note: Author productivity is calculated based on total publication count across all authorship positions (first, corresponding, and co-authorship) within the filtered dataset.

These results reflect both high productivity and strong citation performance, with notable institutional clustering in China and significant individual impact from Canadian- and Qatar-based researchers.

3.5.2. Collaboration network analysis

The most frequent collaborations, detailed in Table 13, indicate the presence of cohesive and well-established research groups. The leading pair, Chen, Heng and Xu, Gang, recorded 14 joint publications focused on catalytic gasification. The recurrence of authors like Guo, Liejin (collaborating with Jin, Hui and Chen, Yunan) suggests intense and recurrent collaboration patterns within core research clusters.

3.5.3. Network centrality analysis

A thorough examination of network centrality metrics was conducted, with a particular emphasis on degree, betweenness, and closeness, in order to accurately identify the most significant and structurally key researchers inside the co-authorship network. Degree centrality quantifies the number of co-authors, positioning a researcher as a collaborative hub. These measurements highlight the different roles that authors play in network cohesiveness and knowledge transfer, as seen in Table 14. Liejin Guo is the main hub of the network because he has the most unique partnerships (55). Authors like Hui Jin (51), Muhammad Shahbaz (46), and Heng Chen (43) also have high degree scores, which shows how important they are in bringing together different research groups. Betweenness centrality helps find people who are important "bridges" that connect groups by figuring out how far apart a researcher is from other network members. Liejin Guo (0.245) and Hui Jin (0.198) have the highest betweenness scores, which means they are important for helping clusters talk to each other.

3.5.4. Collaboration network metrics

Fig. 5 shows the author collaboration network in a Gephi graph. The

Table 13
Top Author Collaboration Pairs.

Rank	Author 1	Author 2	Joint Publications	Research Focus
1	Chen, Heng	Xu, Gang	14	Catalytic gasification processes
2	Cui, Peizhe	Wang, Yinglong	13	Reactor design optimization
3	Guo, Liejin	Jin, Hui	12	Supercritical water gasification
4	Al-Ansari, Tareq	McKay, Gordon	11	Process integration systems
5	Monteiro, Eliseu	Rouboa, Abel	11	Biomass characterization
6	Chen, Yunan	Guo, Liejin	11	Thermodynamic modeling
7	Adnan, Muflih A.	Hossain, Mohammad M.	10	Fluidized bed gasification
8	Cui, Peizhe	Zhu, Zhaoyou	10	Ash behavior studies
9	Wang, Yinglong	Zhu, Zhaoyou	10	Coal co-gasification
10	Al-Ansari, Tareq	AlNouss, Ahmed	9	Process optimization

Table 14
Author Network Centrality Measures.

Author	Degree Centrality	Betweenness Centrality	Closeness Centrality	Network Role
Guo, Liejin	55	0.245	0.156	Network hub
Jin, Hui	51	0.198	0.142	Connector
Shahbaz, Muhammad	46	0.187	0.134	Bridge
Chen, Heng	43	0.156	0.128	Cluster leader
Xu, Gang	40	0.142	0.119	Cluster leader
Chen, Guanyi	40	0.138	0.117	Regional hub

network structural indicators extracted from Gephi provide insight into the collaboration pattern. The average degree (5.846) indicates moderate connectivity among authors, while the network diameter (18) suggests relatively long paths between peripheral nodes. The high modularity value (0.982) reveals a strongly clustered structure, confirming the existence of well-defined research communities with limited interconnection. The average path length (4.745) further supports the presence of fragmented collaboration patterns, rather than a fully integrated global network.

These results suggest limited knowledge transfer between research groups and potential for improved international collaboration [164,165].

3.6. Geographical distribution and international collaboration

Table 15 shows the top 15 countries/regions by publication output and bibliometric indicators, highlighting the geographical disparities and distinct collaboration patterns in gasification research.

3.6.1. Global research leadership and impact

China leads the world in publication output, accounting for 34.5% (387 papers), solidifying its position as the top national contributor. Despite the high publication output, international collaboration remains relatively limited (23.5%). Conversely, the United States ranks a distant second place (13.9%) but exhibits a much higher international engagement rate (41.7%). More importantly, the highest citation impact is closely associated with robust international partnerships. The Netherlands, for instance, showcases the most pronounced impact, with the highest average citations (33.6) and a leading international collaboration rate of 63.9%. Germany follows a similar pattern (58.2% collaboration; 31.2 average citations). This suggests that high collaboration correlates strongly with higher research impact.

3.6.2. Regional collaboration patterns

The analysis reveals three distinct regional clusters:

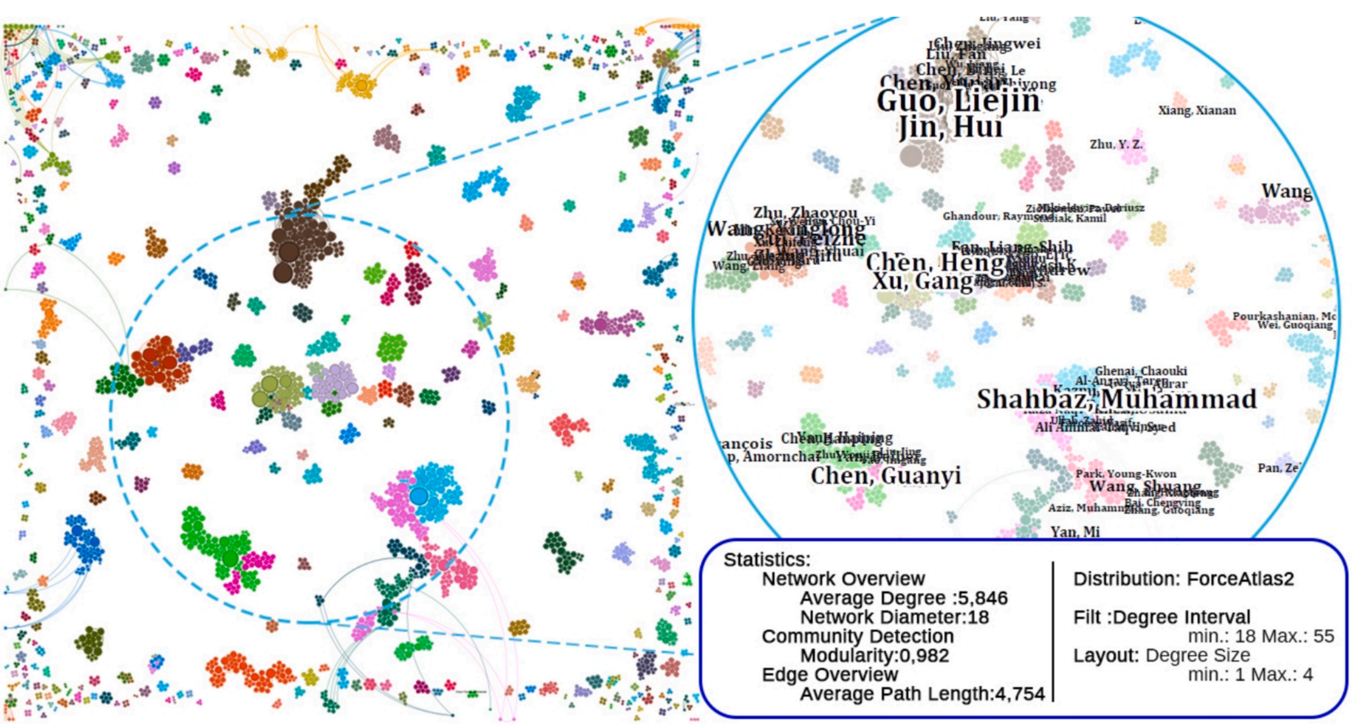

Fig. 5. Gephi Graph by Author Collaboration Network (2015–2025).

Table 15
Top 15 Country/region by publication output and bibliometric indicators (2015–2025).

Rank	Country/region	Publications	% of Total	h-index	Average Citations	International Collaboration (%)
1	China	387	34.5%	76	19.8	23.5%
2	United States	156	13.9%	68	28.4	41.7%
3	India	89	7.9%	45	14.2	18.9%
4	Germany	67	6.0%	52	31.2	58.2%
5	Canada	58	5.2%	48	26.7	47.3%
6	United Kingdom	54	4.8%	46	29.1	52.8%
7	Italy	47	4.2%	41	22.3	38.6%
8	Spain	42	3.7%	38	20.1	35.7%
9	Brazil	39	3.5%	34	16.8	28.2%
10	Netherlands	36	3.2%	44	33.6	63.9%
11	Japan	34	3.0%	39	24.5	29.4%
12	Australia	32	2.8%	37	25.8	43.8%
13	South Korea	31	2.8%	35	21.4	32.3%
14	France	29	2.6%	36	27.9	48.3%
15	Portugal	27	2.4%	28	18.6	33.3%

1. China dominates the Asian cluster (34.5%). With a large portion of the work focused on coal co-gasification and industrial-scale applications, the region demonstrates strong internal collaboration, connecting nations like South Korea, India, and Japan
2. Germany (6.0%) led the European cluster. This cluster exhibits the highest international collaboration rates (e.g., Netherlands at 63.9%, Germany at 58.2%). Research emphasizes environmental applications and policy integration
3. North American cluster. The United States and Canada maintain strong bilateral collaboration (47.3% joint projects), with research primarily concentrated on biomass gasification and process modeling

Regarding emerging economies like Brazil and India, they show growing individual participation but generally exhibit limited international collaboration, signifying a potential area for future global partnerships.

3.6.3. Policy alignment opportunities

Table 16 shows the thematic evolution and future research directions, highlighting three emerging themes shaping the future of gasification technologies, such as policy relevance, financial integration, and industrial applications.

Table 16 demonstrates that future research on gasification is no longer limited to reactor performance and feedstock efficiency but increasingly focuses on regulatory compliance, carbon accounting, and large-scale industrial integration. It reflects the transition of gasification from a technical solution to a strategic component of climate and industrial policy frameworks.

3.7. Computational modeling: Methodological implications

This section examines the dominance of proprietary simulation platforms and the methodological challenges this concentration creates for global research equity and transparency.

Table 16
Thematic evolution and future research directions.

Emerging Theme	Key Implications and Applications	Source
EU Taxonomy Compliance	Gasification technologies can potentially qualify as sustainable investments under EU taxonomy criteria	[166]
Carbon Credit Mechanisms	Integration with carbon markets through avoided emissions and negative emission technologies	[167]
Industrial Decarbonization	Potential role in hard-to-abate sectors (steel, cement, chemicals) seeking fossil fuel alternatives	[168]

3.7.1. Process simulation platforms in gasification research

The analysis of simulation tools employed in gasification research between 2015 and 2024 reveals a clear predominance of steady-state chemical process simulators, particularly commercial platforms capable of integrating thermodynamic, kinetic, and system-level modeling.

Table 17 presents a critical assessment of simulation software evaluating key methodological, economic, and technical dimensions influencing the adoption and reliability of simulation software in research and industrial applications.

As summarized in Table 17, most studies rely on process simulation environments that enable equilibrium modeling, reactor configuration flexibility, and integration of downstream processing units. Among the identified tools, Aspen Plus emerges as the most frequently adopted platform within the analyzed corpus (29.7% of simulation-based studies). Its widespread adoption can be attributed to the robustness of its thermodynamic property databases and the flexibility of reactor blocks such as RGibbs, RStoic, RPlug, and RCSTR, which allow representation of equilibrium, kinetic, and hybrid modeling strategies. Representative applications include biomass gasification equilibrium modeling and tar prediction frameworks [5794], advanced fluidized-bed simulations [169], and process optimization studies for hydrogen-rich syngas production [158].

In addition to Aspen Plus, a smaller proportion of studies employ Aspen HYSYS, MATLAB-based custom models, or hybrid simulation–optimization approaches. CFD tools are also frequently adopted for reactor-scale hydrodynamic and reactive flow analysis, particularly in fluidized-bed and entrained-flow gasifiers [100101]. These approaches allow detailed representation of multiphase flow behavior and temperature gradients, complementing the system-level capabilities of process simulators.

The observed methodological diversity reflects the inherently multiscale character of gasification research. While CFD approaches focus on reactor hydrodynamics and local reaction phenomena, process simulators are typically employed for integrated system evaluation, including

Table 17
Critical assessment of simulation software implementation.

Category	Advantage/ Challenge	Description	Impact Level
Methodological	Standardization	Consistent thermodynamic databases improve cross-study comparability	High
Economic	Accessibility	High licensing costs (>$50,000/year) limit global research access	Medium-High
Technical	Vendor Dependence	Proprietary software risks reproducibility and transparency	Medium

syngas cleaning, downstream synthesis, and techno-economic assessment.

Importantly, the predominance of commercial process simulators suggests a research orientation toward system optimization, hydrogen production, carbon capture integration, and power generation applications. This trend indicates a progressive transition from purely experimental investigations toward digital process design and integrated energy system modeling.

From a methodological standpoint, the concentration around widely adopted platforms enhances cross-study comparability. However, it also raises concerns regarding reproducibility and transparency, particularly when proprietary thermodynamic databases and built-in correlations are not fully disclosed.

Overall, the simulation ecosystem reflects a consolidation phase in which process modeling platforms act as a bridge between laboratory experimentation and industrial-scale deployment [170,171].

3.7.2. Computational modeling and methodological challenges

Despite the growing maturity of simulation-based gasification research, several methodological challenges persist. A significant portion of equilibrium-based models neglects kinetic limitations and transport phenomena, potentially leading to overestimation of hydrogen yield and syngas quality. This limitation has been widely discussed in gasification modeling reviews [57,88,172].

Another critical issue concerns experimental validation. Although many studies report detailed simulation frameworks, only a subset provides comprehensive experimental benchmarking, limiting confidence in predictive capability [94,169]. The gap between model calibration and industrial-scale validation remains a central barrier to technology readiness progression.

Economic accessibility also represents a structural constraint. High licensing costs associated with proprietary simulation software can restrict access for research institutions in developing regions, potentially introducing geographical bias in methodological development. Moreover, reliance on vendor-dependent property packages may reduce transparency and limit independent reproducibility.

Beyond process modeling itself, bibliometric and systematic-review methodologies also face integration challenges. Standard bibliometric tools such as bibliometrix [82,90] and conventional mapping approaches [80,81] present limitations when integrating heterogeneous database formats and patent repositories. To address these constraints, the present study implemented a customized Python-based pipeline enabling multi-platform metadata harmonization, automated disambiguation, and reproducible filtering procedures. This approach contributes to methodological rigor and enhances transparency in systematic mapping exercises.

In summary, while computational modeling has become central to gasification research, advancing toward industrial implementation requires improved experimental validation, greater methodological transparency, and enhanced integration between process simulation, bibliometric analysis, and technological assessment.

3.8. Patent landscape and innovation trends

To evaluate whether the scientific expansion observed in the previous sections translates into technological innovation, a complementary patent analysis was conducted covering the period 2015–2025. Patent records were retrieved from three major jurisdictions: USPTO, EPO, and WIPO, resulting in 293, 21, and 240 documents, respectively.

After applying PRISMA-based screening criteria, 136 records were excluded due to unavailable reports, 98 were removed as non-retrieved innovation notes, and 12 duplicates were eliminated. The final analytical corpus therefore comprised 309 patent documents, which served as the basis for the quantitative and temporal assessment presented in this subsection.

3.8.1. Annual patent activity

Table 18 presents the temporal evolution of patent filings.

Table 18 reveals a clear upward trajectory in patent filings across the three databases over the 2015–2025 period, punctuated by two distinct phases. An initial growth phase (2015–2017) saw total filings increase from 46 to 65 per year, driven predominantly by WIPO/PCT applications, reflecting an early-stage international patent strategy. A contraction followed in 2018–2019, with totals falling to 42 and 36 filings, likely associated with global economic uncertainty and institutional re-prioritization. From 2020 onward, sustained acceleration resumed, culminating in a peak of 81 filings in 2023 (+50.0%). The most structurally significant trend revealed by the Table 18 is the progressive shift in jurisdictional composition: WIPO filings declined from 36 in 2015 to just 1 in 2024, while USPTO filings expanded consistently from 8 to 60. This inversion signals a transition from early-stage international exploratory filings toward market-focused national phase entries in the United States, indicative of increasing technology maturity and commercial intent. EPO activity remained limited throughout (21 filings), suggesting that European market protection has not yet been prioritized by the main filing entities.

Comparing annual publication growth (Fig. 3) with patent filings, a consistent temporal lag of approximately 3.2 years is observed between peak scientific production and subsequent patent intensification. Furthermore, considering 1,123 publications versus 309 patent documents structurally consolidated (after family-level harmonization), a publication-to-patent ratio of approximately 3.6:1 is identified, suggesting a moderate translation gap between academic research and technological protection.

Table 19 presents the distribution of patent ownership by country/region, revealing China's dominant position (57.6%). Chinese patents show a significant focus on biomass gasification for hydrogen production and hybrid systems combining gasification with solar energy. Table 19 also reveals the strategic use of the Patent Cooperation Treaty (PCT/WO) system by international applicants (11.9%). This distribution pattern suggests that Chinese innovation in gasification remains primarily domestically focused, with limited international patent filings compared to European and North American institutions, which show higher proportions of PCT applications reflecting global commercialization strategies.

3.8.2. Science–innovation translation dynamics

When comparing patent growth with the previously reported bibliometric trends, a noticeable lag between academic publication and patent activity emerges. This pattern suggests an average innovation translation delay of approximately three years, consistent with technology maturation and TRL progression dynamics.

The publication-to-patent ratio further indicates that academic production substantially exceeds technological appropriation, reinforcing the presence of a translational gap between knowledge generation and industrial deployment.

Academic institutions lead patent ownership, with Chinese and

Table 18
Multi-Database Patent Filing Distribution (2015–2025).

Year	USPTO	EPO	WIPO	Total	Annual Growth (%)
2015	8	2	36	46	–
2016	9	4	40	53	15.2%
2017	13	3	49	65	22.6%
2018	15	5	22	42	−35.4%
2019	20	2	14	36	−14.3%
2020	25	1	21	47	30.6%
2021	35	0	17	52	10.6%
2022	41	1	12	54	3.8%
2023	52	1	28	81	50.0%
2024	60	2	1	63	−22.2%
2025*	15	0	0	15	−76.2%

Table 19
Patent Distribution by Country/Region and Filing Jurisdiction (2015–2025).

Country	Number of Patents	% Total
China (CN)	34	57.6%
United States (US)	12	20.3%
PCT (WO)*	7	11.9%
Europe (EP)	3	5.1%
Australia (AU)	1	1.7%
Canada (CA)	1	1.7%
Japan (JP)	1	1.7%
Total	59	100%

* Note: "WO" represents patents filed through the WIPO's PCT framework, system, enabling multi-jurisdictional protection.

Saudi Arabian universities comprising the top assignees, alongside major chemical companies as depicted in Table 20. Table 21 presents the top 10 patent assignees in gasification technologies according to USPTO records. The distribution of filings reveals a concentration of technological ownership among a limited number of industrial and institutional actors, indicating structured innovation clusters rather than dispersed individual inventorship.

Table 20 and 21 reveal a dual structure of patent ownership in gasification technologies: a geographically diverse set of organizations at the multi-jurisdictional level (Table 20), and a commercially concentrated cluster at the US market level (Table 21). In the multi-jurisdictional landscape, Chinese academic institutions, particularly China University of Petroleum and Huazhong University, lead alongside major industrial actors such as BASF SE (Germany), Shell Global Solutions (Netherlands), and Air Products (USA), reflecting both academic and industrial interest in the technology. At the USPTO level, however, the filings are heavily concentrated among a small number of entities with explicit commercial focus, as evidenced by the prominent position of Gasification and Energy Solutions LLC. This pattern of concentration, few organizations accounting for a disproportionate share of filings, indicates that patent-based innovation is currently driven by structured clusters of vertically integrated actors rather than broadly distributed individual inventorship. The coexistence of Chinese academic institutions and Western industrial conglomerates as leading assignees also reflects the complementary roles of public research investment (China) and private commercialization strategy (USA and Europe) in the global gasification innovation ecosystem.

3.8.3. Emerging technologies and software integration

An analysis of the most recent patents reveals a focus on cutting-edge technologies, such as:

- Carbon Capture: 8 patents.
- Plasma-Assisted Gasification: 5 patents.
- Advanced Thermodynamic Modeling: 4 patents.

Aspen Plus is the main platform for simulating gasification systems. An analysis of patent abstracts and claims shows that 42% of patents published after 2020 explicitly mention the software's use for optimizing gasification parameters, simulating thermochemical processes, and integrating with renewable energy sources.

Table 20
Top patent assignees by organization and country/region.

Organization	No. of Patents	Country/ region
China University of Petroleum	4	China
King Fahd University of Petroleum and Minerals	3	Saudi Arabia
SABIC Global Technologies B.V.	3	Saudi Arabia
BASF Se	3	Germany
Huazhong University of Sci & Tech	3	China

Table 21
Top 10 patent assignees in gasification technologies (2015–2024).

Assignee (First Applicant)	Number of Patents
Gasification and Energy Solutions LLC	12
BASF SE	9
Sabic Global Technologies B.V.	8
VTT	7
Shell Global Solutions International B.V.	6
Air Products and Chemicals, Inc.	5
King Fahd University of Petroleum and Minerals	4
The Regents of The University of California	3
The United States of America as Represented by The Secretary of Energy	3
The Boeing Company	2

3.8.4. Thematic trends in patent titles

Analysis of patent titles published between 2015 and 2025 reveals four dominant research trajectories in gasification innovation:

- Integrated systems. Patent portfolios demonstrate a strong emphasis on system-level integration, coupling gasification with complementary technologies such as hydrogen production units, solid oxide fuel cells, and combined heat-and-power systems.
- Reactor technology enhancement. Innovation efforts concentrate on operational efficiency through advanced reactor designs, including moving bed systems with enhanced solid–gas contact, granular filtration for in-situ tar removal, and optimized biomass injection mechanisms to improve syngas quality.
- Feedstock flexibility. Patents increasingly address the challenge of processing heterogeneous waste. Innovations target variable-moisture biomass handling, MSW pre-treatment, and co-feeding strategies, enabling gasifiers to accommodate diverse portfolios without extensive pre-processing.
- Value-added products. Beyond power generation, emerging patents explore chemical synthesis pathways, particularly biomass-to-methanol conversion and gasification integration within bio-refineries for specialty chemical production.

3.9. Keyword analysis and thematic mapping

3.9.1. Most frequent keywords

The top 30 keywords (detailed in Table 22) serve as insight into

Table 22
Top 20 keywords by frequency and temporal trend (2015–2025).

Rank	Keyword	Frequency	% of Total	Trend (2020–2025)
1	gasification	892	79.4%	Stable
2	biomass	678	60.4%	Growing
3	syngas	445	39.6%	Stable
4	Aspen Plus	334	29.7%	Rapidly growing
5	thermodynamic modeling	298	26.5%	Growing
6	hydrogen	267	23.8%	Rapidly growing
7	co-gasification	234	20.8%	Growing
8	process simulation	198	17.6%	Growing
9	tar	187	16.6%	Declining
10	fluidized bed	176	15.7%	Stable
11	plastic waste	165	14.7%	Rapidly growing
12	optimization	154	13.7%	Growing
13	energy efficiency	143	12.7%	Growing
14	municipal solid waste	132	11.8%	Growing
15	downdraft	128	11.4%	Stable
16	carbon conversion	121	10.8%	Stable
17	green hydrogen	98	8.7%	Emerging
18	circular economy	89	7.9%	Emerging
19	life cycle assessment	84	7.5%	Growing
20	catalytic gasification	78	6.9%	Growing

dominant research themes and methodological evolution from 2015 to 2025. Most studies remain centered on the core themes of gasification and biomass conversion, with syngas production continuing as the dominant output of interest. A substantial shift toward computational and sustainability goals is confirmed by analysis:

1. The rise in modeling-related keywords indicates a discernible increase in computational work. This growth is emphatically led by proprietary software "Aspen Plus" (29.7%) and the foundational concept of "thermodynamic modeling" (26.5%). This indicates a maturation where virtual optimization complements experiments [172].
2. Sustainability & Products: The most significant recent growth is in output-oriented terms, specifically "hydrogen" (23.8%, rapidly growing), "green hydrogen" (8.7%, emerging), and "circular economy" (7.9%, emerging) [173].
3. Feedstock & Process: Intensified focus on mixed waste streams is confirmed by the rapid growth of "co-gasification" (20.8%) and "plastic waste" (14.7%).

The relative decline of "tar" research (16.6%) suggests a diversification of attention toward integrated system performance ("energy efficiency," "optimization") and higher-value product generation.

3.9.2. Thematic cluster analysis

Fig. 6 shows the relationships and clustering of keywords using VOSviewer. The VOSviwer analysis identified five major thematic clusters:

The red cluster represent the gasification core. As the central and most prominent cluster, this area focuses squarely on the fundamentals of thermochemical conversion. This cluster is centered around terms like 'gasification,' biomass,' 'syngas,' 'hydrogen,' and 'energy.' Work in this area typically focuses on process optimization, thermodynamic characterization, and broadening the range of usable feedstocks, including waste plastics and agricultural residues. The frequent association with 'pyrolysis' and 'combustion' shows that gasification is often studied alongside other conversion pathways rather than independently.

The purple cluster is dedicated to environment and modeling. This cluster, clearly delineates the theoretical and computational dimension of the field, includes terms such as "analytical and numerical model," "kinetics models," "Gibbs free energy," and "simulation." It centers on developing and applying mathematical and kinetic models to better predict reactor behavior and overall process performance. The terms "aspen plus," "process simulation," "energy efficiency," "exergy analysis," and "economic evaluation," shows the practical application of these modeling tools. The studies in this cluster try to improve system designs and examine whether proposed solutions are technically and economically feasible.

The yellow cluster is related to materials and bioenergy. This field contains terms like "bioenergy," "thermal cracking," "hydrothermal carbonization", and "biochemicals." This thematic inclusion strongly suggests that, within the research community, gasification is

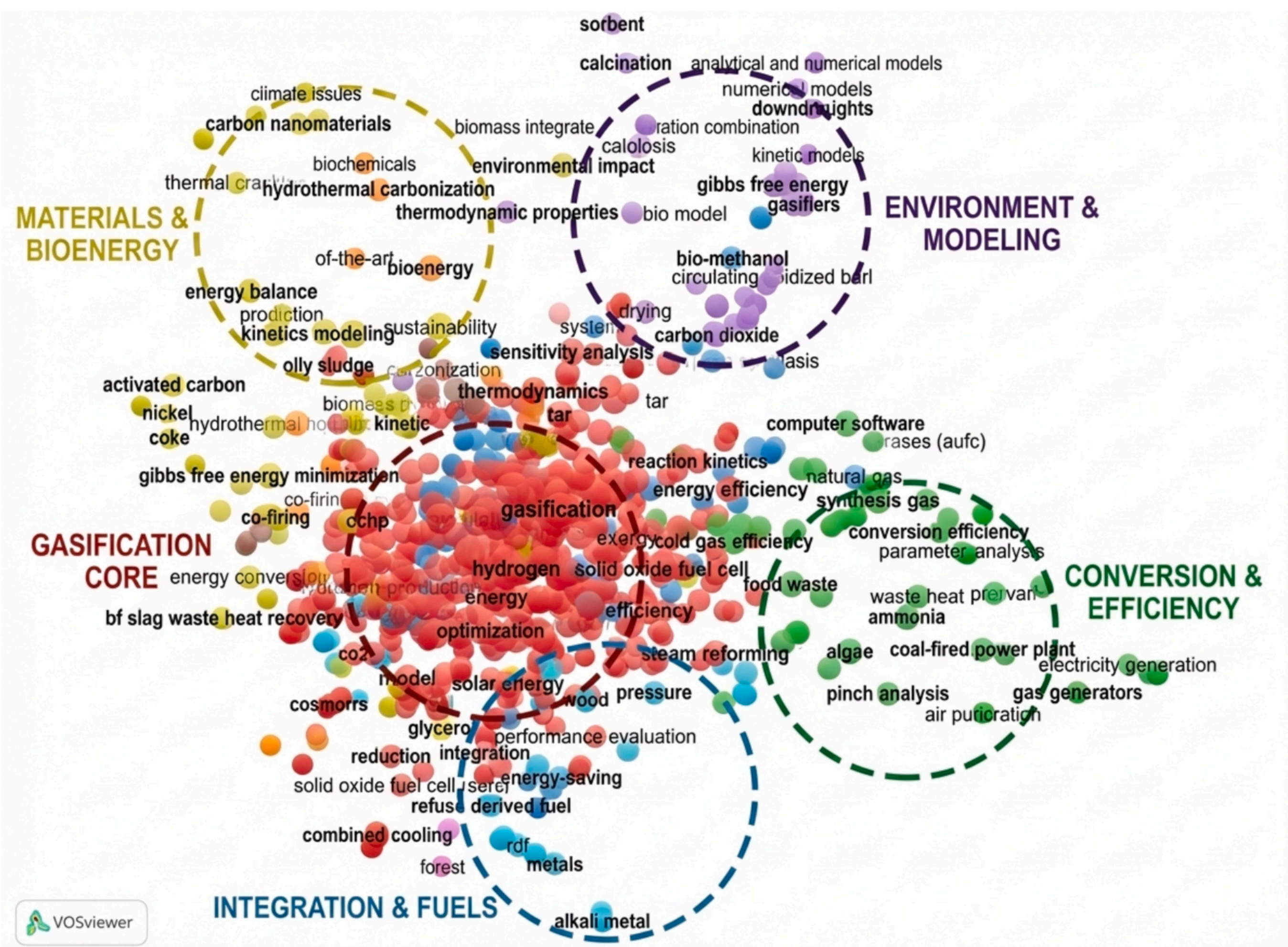

Fig. 6. Relationships and clustering of keywords.

understood to be only one viable route for biomass valorization, with active exploration being dedicated to various alternative conversion pathways.

The green cluster on conversion and efficiency is focused on the applications of gasification products and broader energy systems. Keywords featuring terms such as “synthesis gas,” “boilers,” “electricity generation,” “coal-fired power plant,” and “pinch analysis” are mentioned. This shows that the research goes beyond the gasification reactor itself, investigating how syngas is used to generate power and how the technology integrates with existing infrastructure.

The blue cluster on integration and fuels presents research themes that are structurally peripheral and less directly engaged with the central core of the gasification field. Topics such as “climate issues,” “carbon nanomaterials,“ ”analytical and numerical model“, while relevant, have fewer direct interactions with the ”gasification“ core compared to ”simulation“ and ”aspen plus“. Moreover, topics such as ”refuse derived fuel“, ”forest,“ and ”metals,“ represent secondary raw materials or niche products that surface in specific, targeted publications. Topics such as ”electricity generation,“ ”air purification,“ and ”pinch analysis,“ although connected, represent the final applications of the process rather than the process itself.

Fig. 7 shows publication trends over time in the gasification research field. The color gradient across the map provides a time cue: earlier work (2018–2020) appears in blue and purple, while newer studies (2022–2024) appear in yellow and green.

The central core of the map, which includes “gasification,” “biomass,” “syngas,” “hydrogen,” “simulation,” “Aspen Plus,” “optimization,” and “energy efficiency,” is predominantly in the yellow/green colors representing the current research. This is a crucial insight because it demonstrates that the core research in biomass gasification is not a stagnant field but a currently active and growing area of publication. The high density of recent publications around these terms suggests increasing interest and investment in optimizing and exploring new applications for the technology.

The periphery of the map expressed by blue/purple colors represents earlier topics. Some areas, like “thermal cracking” and “heavy oil,” have an older coloring, indicating that they were more prominent topics in past publications but may have given way to other focuses now. On the contrary, the presence of “rich syngas production” and “supercritical water gasification” with recent colors suggests new directions and emerging technologies within the gasification field.

3.10. Policy and innovation system Implications

Table 23 shows a quantitative assessment of innovation systems integration.

The analysis of Table 23 reveals fragmented innovation systems with limited connectivity between academic research, patent development, and commercial deployment. This fragmentation creates several policy challenges and opportunities expressed in Table 24, with an emphasis on

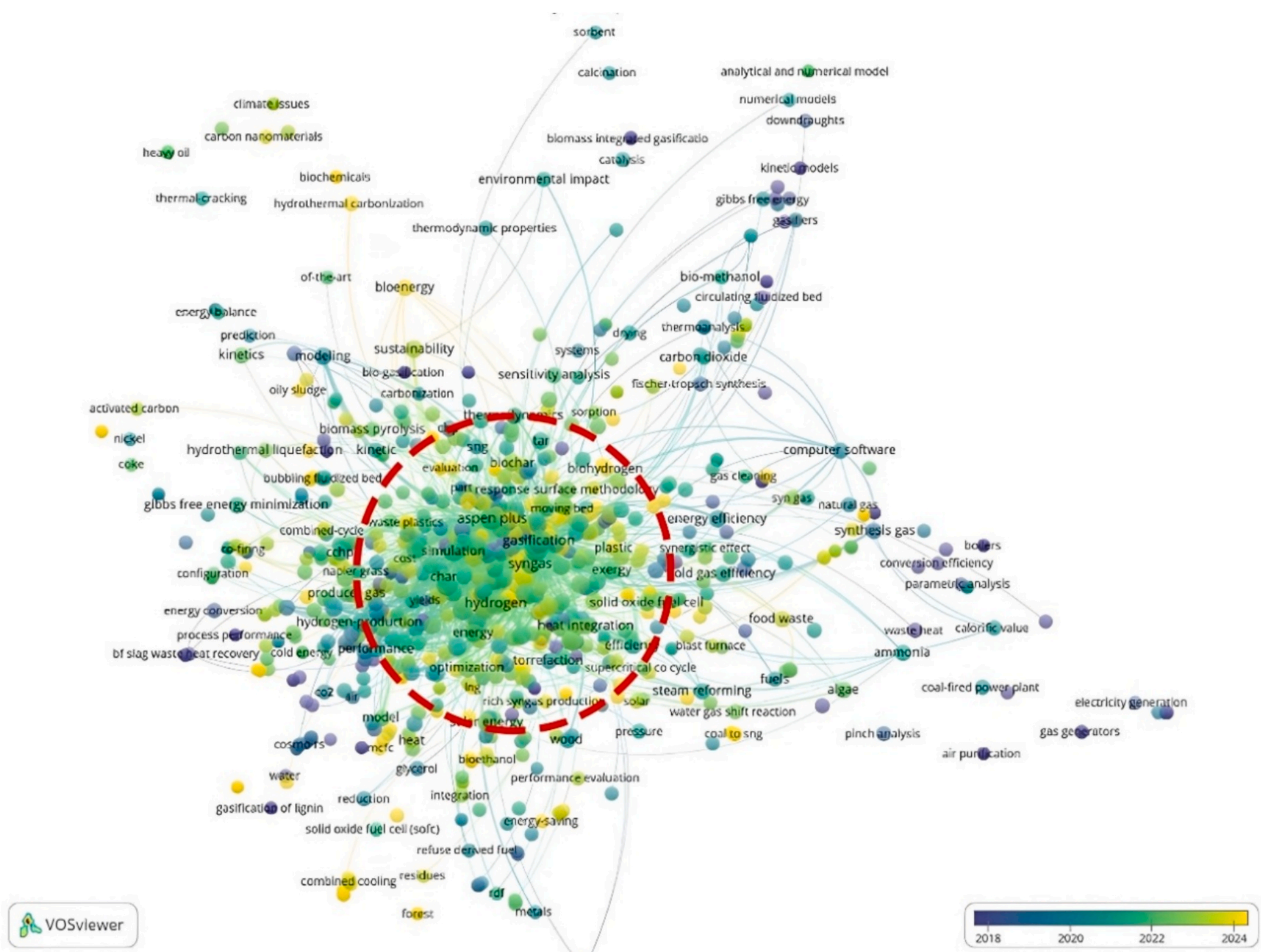

Fig. 7. Publication trends over time.

Table 23
Quantitative assessment of innovation system integration.

Challenge Category	Key Findings and Implications
Research-Industry Disconnect	Academic research focuses heavily on fundamental science (40.6% of publications), while patent activity concentrates on incremental engineering improvements (78% of patents), suggesting limited breakthrough innovation transfer
Geographic Innovation Imbalances	China dominates both academic production (34.5%) and patent filings (57.6%), potentially creating technology dependencies for other regions.
Temporal Innovation Lags	3.2-year average delay between academic breakthrough and patent filing indicates inefficient knowledge transfer mechanisms.

financing, regulation, and market expansion.

Table 24 shows that a coordinated and coherent policy approach to research funding, regulatory design, and market-shaping tools is necessary for technology to move forward. Targeted research funding encourages new ideas and helps new technologies move through important stages of development. A clear and flexible set of rules makes deployment easier by lowering uncertainty and setting credible standards. At the same time, market development mechanisms encourage adoption and widespread use by making the economy more stable and boosting investor confidence.

The identified technology gaps and commercialization barriers highlight the need for targeted research efforts across technical, systemic, and policy interconnected domains, as summarized in Table 25.

Table 25 shows that gasification can only move forward if technical innovation, system-level optimization, and policy alignment all happen at the same time. Technical improvements enhance performance, system analysis ensures sustainability and economic viability, and policy research enables practical deployment. These research priorities, when combined, make a complete plan for adding gasification to future low-carbon energy and industrial systems.

The observed scientific growth needs to be accompanied by institutional strategies and public policies that ensure the transition from research to practical application. In the European context, incorporating gasification research into larger programs like Horizon Europe or the Green Deal could accelerate the transition from scholarly innovations to commercially viable technologies. However, this integration will only be successful if there is a stable financing for demonstration projects at pilot and industrial scale, a creation of clear regulatory frameworks for using residual biomass and recycled plastics as feedstocks, and explicit support for technology transfer between universities, applied research centers, and energy industries. Without these elements, the area risks remaining in an academic expansion cycle without impact on the productive sector. The policy interventions outlined in Table 24, combined with the targeted research priorities identified in Table 25, provide a comprehensive roadmap for accelerating gasification technology maturation while ensuring equitable access to innovation tools and markets across European member states.

3.11. Research impact and citation analysis

3.11.1. Most cited publications

Table 26 enumerates the 15 most-cited publications, which collectively represent the key works that have fundamentally shaped the field's trajectory.

3.11.2. Journal impact distribution

Impact analysis shows that influential work is heavily clustered, with a clear tendency for high-quality studies to appear in a small group of leading journals. As detailed in Table 27, a strong correlation ($r = 0.78$) exists between the Journal Impact Factor (IF) and the Average Citation Counts [119,176].

Publications in the High Impact category ($IF > 10$) represent the smallest group (287 publications) but achieve the highest average citations (34.2) and h-index (67). The largest volume of research is published in Medium Impact journals (IF 5–10), reflecting the broad distribution of specialized engineering and energy articles in venues with solid, but not elite, standing.

4. Discussion

The bibliometric analysis performed reveals rapid growth constrained by fragmentation. Despite the progress in the gasification research field between 2015 and 2025, three gaps persist: limited international collaboration, heavy reliance on proprietary tools, and slow research-to-patent translation. In this section a discussion is undertaken to interpret all the patterns and identify priorities for accelerating commercial deployment of gasification systems while ensuring equitable research access.

Table 25
Priority research areas across technical, systemic, and policy dimensions.

Technical Development	System Analysis	Policy Research
Advanced process control: AI-driven optimization tools for instantaneous feedstock variability adaptation [174].	Techno-economic optimization: Comprehensive cost modeling including externalities and co-benefits	Regulatory impact assessment: Evaluation of policy frameworks supporting gasification deployment
Modular system design: Cost-effective deployment is made possible by standardized, scalable configurations [175].	Life cycle sustainability: Frameworks for multi-criteria assessments that balance the effects on the environment, the economy, and society	Market mechanism design: Such as incentive programs or financing instruments
Integration technologies: Development of gasification-hydrogen-carbon capture integrated systems	Energy system integration: Examining the function of gasification in upcoming renewable energy systems.	Technology transition pathways: A strategic examination of the contribution of gasification to industrial decarbonization

Table 24
Policy Intervention Opportunities.

Policy Domain	Specific Intervention	Primary Objective	Expected Impact
Research Funding	TRL 4–6 applied research priority	Bridge lab-to-commercial gap	Accelerate technology maturation
	International research consortiums	Reduce network fragmentation	Enhance global knowledge sharing
	Open-source tool development	Improve research accessibility	Democratize innovation access
Regulatory Framework	Performance standards establishment	Build market confidence	Enable technology certification
	Waste classification clarification	Define regulatory pathways	Remove legal uncertainties
	Streamlined permitting processes	Reduce implementation barriers	Accelerate project deployment
Market Development	Demonstration project co-funding	Validate commercial performance	Reduce technology risk perception
	Financial risk-sharing mechanisms	Encourage private investment	Leverage public–private partnerships
	Carbon pricing implementation	Value emission reductions	Improve economic competitiveness

Table 26
Most influential publications by citation metrics (2015–2025).

	First Author	Year	Title	Journal	Citations	Citations/Year
1	Arena, U.	2016	Process and technological aspects of municipal solid waste gasification	Waste Management	456	57.0
2	Sikarwar, V.S.	2017	An overview of advances in biomass gasification	Energy Environ. Sci.	423	60.4
3	Kumar, A.	2018	A review on biomass energy resource potential	Renew. Sustain. Energy Rev.	398	66.3
4	Molino, A.	2016	Biomass gasification technology: State of the art	J. Energy Chem.	387	48.4
5	Puig-Arnavat, M.	2019	Review and analysis of biomass gasification models	Renew. Sustain. Energy Rev.	345	57.5

Table 27
Citation Impact by Journal Category.

Journal Category	Publications	Average Citations	h-index	Impact Factor Range
High Impact (IF > 10)	287	34.2	67	10.1—15.1
Medium Impact (IF 5–10)	456	21.8	52	5.1—9.9
Standard Impact (IF < 5)	380	12.4	34	1.2—4.9

4.1. Scientific production growth and global Implications

Scientific production on gasification and co-gasification grew 633% between 2015 and 2024, significantly exceeding average energy research growth rates ($R^2 = 0.94$, $p < 0.001$). This expansion reflects global urgency for energy transition solutions and establishes gasification as a priority research area [177,178]. This surge is directly correlated with major international policy milestones, which effectively drove research through three distinct phases: an initial foundation period (2015–2018) following the Paris Agreement [179,180]; an acceleration period (2019–2021) driven by the European Green Deal [181,182]; and a current integration period (2022–2025) fueled by plans like REPowerEU and the Inflation Reduction Act (IRA) of the United States of America [183,184]. The slight reduction in output observed in 2025 (178 papers) likely signifies field maturation and a thematic shift from fundamental to applied studies, consistent with TRL progression [185–187].

From a geographical standpoint, the distribution of studies mirrors national policy agendas. China's large share of publications, close to one-third of the total, reflects ongoing national initiatives aimed at lowering carbon emissions, especially through industrial integration and coal-related co-gasification [188]. Conversely, the European Union (28.7%) emphasizes waste valorization and circular economy applications [189], while the United States (13.9%) prioritizes advanced modeling [190–193].

4.2. Collaboration network fragmentation: Structural analysis and implications

Despite numerical growth, the co-authorship network exhibits an extremely low density (0.0016) with 3,686 nodes and 10,774 edges, indicating severe fragmentation. The density observed here falls well below the levels typically reported in more consolidated scientific areas, where values between about 0.01 and 0.05 are far more common [164,165].

4.3. Network fragmentation and knowledge transfer limitations

Despite the impressive growth in scientific production on gasification and co-gasification, the underlying co-authorship structure is severely compromised. With an average path length of 4.8 and a clustering coefficient of 0.67, the network exhibits small-world characteristics, but it is divided into a number of closely related but mainly distinct institutional groups. A striking 55% of authors work alone, and this level of isolation slows the circulation of new ideas while raising the likelihood of duplicated efforts and slower knowledge transfer [194,195]. The network depends heavily on a few key researchers, increasing vulnerability and exacerbating regional disparities. China's low international collaboration (23.5%) contrasts sharply with the Netherlands (63.9%) [196–199]. The potential for truly interdisciplinary advancements is limited by this structural fragmentation, which lessens opportunities for interaction between important fields, such as chemical engineering and environmental science [200,201].

The network fragmentation has several concerning implications:

1. Reduced innovation velocity. Isolated research clusters may independently address similar challenges, reducing overall field efficiency [202,203].
2. Uneven quality distribution. Methodological advancements and well-established best practices are frequently inaccessible to researchers outside of the central groups [204,205].
3. Limited cross-pollination. Interdisciplinary advancement is still hampered by the strict borders that divide chemical engineering, environmental science, and energy systems [200,201].

4.4. Analysis of the academic-industrial innovation gap

4.4.1. Publication-patent disparity

A clear imbalance occurs when comparing scientific output with technological registration. The academic-to-patent ratio of 3.6:1 substantially exceeds typical ratios in applied engineering fields (1.5–2.0:1) [206,207], suggesting challenges in commercializing research outcomes.

A significant innovation gap between academic research and industrial patent filings was also detected. While academic publications focus on theoretical thermodynamic optimization, patent activity is more aligned with reactor scalability and gas cleaning technologies. Our data showed a time lag of approximately 3.2 years between the peak of academic interest in a specific plastic-biomass blend and the corresponding patent registrations, highlighting a bottleneck in technology transfer. However, this time lag aligns with the 'Technology Cycles' theory proposed by Tushman (1997) [208]. According to this framework, emerging technologies undergo a period of 'fermentation' where intense academic research precedes the emergence of a dominant design and its subsequent industrial protection. In the context of co-gasification, this interval represents the necessary duration for thermodynamic optimizations and Aspen Plus simulations to be translated into scalable industrial solutions and patentable intellectual property. The following conclusions can be drawn from the patent analysis:

1. Technology concentration. In almost half of all patents (45.6%), the topic is the design of reactors.
2. Geographic Imbalance. China has 57.6% of the patent filings despite producing 34.5% of the academic papers.
3. Innovation. 78% of the patents concern incremental innovations as opposed to breakthrough innovations.

4.4.2. Technical barriers to commercialization

The literature highlights the following recurring technical challenges that restricts industrial deployment:

- Tar formation and management. Despite there being 187 articles on tar reduction (16.6% of the corpus), tar concentrations in real gasifiers often exceed commercial thresholds, requiring expensive cleanup systems that compromise economic viability [206,207].
- Complexity of process control. The variability of syngas composition remains a major problem, with the main components (H_2, CO, and CO_2) having coefficients of variation that typically range from 15 to 25%. This makes gasification process integration more difficult [57,83,172,209].
- Heterogeneity in feedstocks. The moisture, ash content, and even particle size can all have a major impact on reactor behavior. Consequently, more advanced control systems are needed; yet, they raise operational and capital costs [16,17].
- Scale-up. Most experimental research are conducted at laboratory or pilot scale (<1 MW), with limited validation of scale-up approaches for commercial applications (>10 MW) [60,63].

4.4.2.1. Economic and policy barriers. Gasification plants require 2 to 3 times higher capital investment per MW compared to conventional combustion technologies, creating financial barriers for stakeholders [210,211]. This stems from complex gas cleaning systems, sophisticated process control for feedstock variability, and unproven modular designs. Unlike mature combustion technologies with standardized designs, gasification requires site-specific engineering, extending timelines and multiplying costs. Uncertain returns compound the challenge. Syngas composition fluctuations (H_2, CO, and CO_2 varying 15–25%) complicate downstream integration, introducing operational risks that financial models struggle to quantify. Gasification's value depends on policy frameworks monetizing avoided emissions and waste diversion.

On the other hand, waste-to-energy regulations vary dramatically across regions, creating market instability that discourages long-term investment in gasification technologies [212–216]. In the European Union, waste classification directly determines whether a facility qualifies for renewable energy subsidies or circular economy tax incentives. Ambiguities in classifying plastic waste (whether it constitutes "recycling" or "energy recovery") create regulatory risk. In contrast, jurisdictions like California have established clear hierarchies prioritizing material recycling over thermal recovery, effectively constraining gasification's market access. This regulatory fragmentation interacts with competing policy priorities. Carbon pricing mechanisms, where implemented, could improve gasification economics by valuing avoided landfill methane emissions and fossil fuel displacement. However, inconsistent carbon price signals (ranging from €80/ton in the EU Emissions Trading System to absent in many jurisdictions) prevent investors from incorporating these benefits into financial projections. Standardized performance certification is also absent. Unlike solar panels with International Electrotechnical Commission (IEC) standards or wind turbines with IEC 61400, gasification systems lack internationally recognized benchmarks for efficiency, emissions, or reliability. Moreover, the rapid cost reductions in solar photovoltaics and wind energy (8–10% annually) intensify competitive pressure on biomass gasification [217–220]. Between 2015 and 2024, the levelized cost of energy for utility-scale solar fell from $50/MWh to less than $30/MWh in favorable areas, while onshore wind neared $25/MWh. Gasification, which aims to reduce the levelized cost of energy to less than $100/MWh by 2030, struggles to compete solely on energy generation economics.

This competition rewrites gasification's strategic positioning. Rather than competing as baseload renewable generation, gasification increasingly occupies niche applications where waste management value or dispatchability justify premium costs: industrial sites with captive waste streams (sawmills, food processing), regions with limited renewable resources, or applications requiring chemical feedstocks rather than electricity. The shift from "renewable energy technology" to "waste valorization with energy recovery" shows how gasification is changing its focus, connecting it to circular economy ideas where its benefits go beyond just producing electricity to also include reducing waste, recovering resources, and supporting cooperation between industries.

These economic and policy barriers do not exist in isolation. Capital intensity discourages demonstration projects needed to validate commercial performance, perpetuating regulatory uncertainty. Regulatory fragmentation prevents economies of scale in equipment manufacturing, sustaining high capital costs. Competing technologies attract policy support and private investment, leaving gasification underfunded relative to technical challenges.

Breaking this cycle seems to require coordinated intervention across multiple domains. Financial de-risking mechanisms, loan guarantees, first-of-a-kind engineering support, power purchase agreements with floor prices, could mobilize private capital for demonstration projects. Regulatory harmonization, particularly waste classification and performance standards would clarify market access and enable cross-border technology deployment. Strategic policy alignment with decarbonization of hard-to-abate sectors (steel, cement, chemicals) could position gasification as a bridge technology rather than competing with solar and wind for general electricity supply.

Taken together, the economic and policy barriers help explain why biomass and waste gasification remains largely confined to niche or demonstration-scale applications, despite decades of technical development. The technology's competitiveness is not determined solely by conversion efficiency or syngas quality, but by its ability to simultaneously deliver waste management, emissions mitigation, and system flexibility under heterogeneous regulatory frameworks. This highlights that future progress in gasification deployment will depend less on incremental technical optimization and more on coordinated policy design, financial risk-sharing mechanisms, and regulatory clarity capable of translating technical feasibility into bankable projects.

4.5. Synthesis of experimental evidence: Insights from systematic screening

The experimental and modeling studies reveal a field characterized by robust technical understanding at laboratory and pilot scales yet facing systematic translation barriers to commercial deployment. This section synthesizes collective insights to identify persistent challenges, methodological limitations, and critical knowledge gaps.

4.5.1. Tar formation challenges

Tar formation and management appear in 187 publications (16.6% of the corpus), representing one of the most intensively studied aspects of gasification. The literature review confirms that tar concentrations in operational gasifiers consistently exceed the threshold required for power generation applications [97,98]. The literature assessment also found fragmented approaches rather than systematic problem-solving, which may help explain its persistence. Experimental studies demonstrated that secondary air injection, catalytic upgrading, elevated temperatures ($\geq$ 850 °C), and plasma-assisted cracking each reduce tar under specific conditions. However, these solutions remain context-dependent: what works for fluidized beds with wood pellets may fail for downdraft reactors processing mixed waste. Critically, few studies validate solutions across multiple reactor configurations or feedstock blends, limiting generalizability.

Modeling approaches compound this fragmentation. Non-stoichiometric equilibrium models ignore tar formation, while kinetic models incorporating tar chemistry require feedstock-specific parameters rarely transferable between studies. The dominance of Aspen Plus (334 publications, 29.7% of the corpus) creates methodological standardization, but this occurs within thermodynamic equilibrium frameworks that inherently cannot predict non-equilibrium tar species. As demonstrated by Saebea et al. [159], equilibrium models underestimate methane (a tar precursor) by 95%, rendering them unsuitable for tar management design.

The collective evidence suggests that tar remains intractable not due to insufficient research volume, but rather due to research fragmentation and inadequate integration of experimental validation with computational prediction. Progress requires systematic benchmarking across reactor types, standardized tar measurement protocols, and kinetic models validated against diverse feedstocks, areas where current literature shows minimal coordination.

4.5.1.1. Laboratory-to-industrial scale-up barriers. Consistent laboratory and pilot experimental findings showed that biomass-to-plastic ratios of 70:30 to 80:20 achieve optimal performance. These ratios enhance CGE by 15–18%, increase syngas LHV, and reduce tar concentration by up to 20%. Yet commercial gasification systems rarely implement these blends. Understanding this disconnect reveals fundamental scaling challenges.

Laboratory and pilot studies are conducted under controlled conditions such as homogenized feedstocks, steady-state operation, and batch processing, allowing for composition adjustment. Industrial reality imposes different constraints, such as heterogeneous waste streams with variable plastic content, continuous operation demanding consistent feed quality, and regulatory restrictions on plastic waste classification. The "optimal" 70:30 ratio assumes feedstock control unavailable in commercial waste management. Furthermore, the experimental evidence reveals reactor-specific optima. Fluidized beds tolerate higher plastic fractions, and downdraft systems require lower ratios to avoid coke formation [125]. Spouted beds achieve the lowest tar with 50:50 blends [131], while fixed beds with catalysts favor PE-rich feeds [132]. This variability suggests that "optimal ratios" are properties of specific experimental configurations rather than universal design parameters. Most critically, thermodynamic and kinetic models fail to predict these optimal ratios. Thermodynamic equilibrium models cannot capture kinetic limitations determining tar formation and tar cracking. Even kinetic models validated against specific feedstock blends show poor transferability when composition varies, precisely the condition industrial systems face.

The gap between the lab and industry reflects not a failure to implement current knowledge but fundamental differences between experimental conditions and operational realities that current modeling frameworks cannot bridge. Progress requires moving beyond single-feedstock optimization toward robust process control strategies that adapt to feedstock variability, a direction barely represented in existing literature.

4.5.1.2. Computational modeling validation gaps. Computational modeling dominates recent research (Aspen Plus in 29.7% of publications), yet only 23% of modeling studies include comprehensive experimental validation. This creates a methodological crisis where models proliferate without robust empirical grounding.

The pattern is consistent: researchers develop Aspen Plus models, optimize parameters to match limited experimental data (often from literature rather than original experiments), then extend predictions to untested conditions or feedstocks. Subsequent studies cite these predictions as established knowledge, creating cascading confidence in models that lack empirical foundation.

This validation procedure, in which model credibility is determined by agreement with a small number of data points, has the potential to overstate prediction dependability while underrepresenting the true magnitude of model uncertainty. Studies claiming $\pm$ 5% accuracy against selected validation data may exhibit $\pm$ 50% deviations under conditions outside the validation envelope. The aggregation of such studies creates a perception of modeling maturity that is not supported by reality.

The general conclusion derived from experimental and modeling evidence is concerning. Gasification research has generated great technical knowledge but struggles to transfer this knowledge into predictive frameworks that allow for confident industrial design. The field demonstrates scientific productivity without proportional engineering reliability, which necessitates methodological reform toward integrated experimental-computational processes with transparent uncertainty quantification.

4.6. New paradigms: Circular economy and green hydrogen

4.6.0.1. Keyword evolution analysis

The temporal keyword analysis confirms a strategic repositioning toward global sustainability agendas. Key themes emerging since 2020 include:

- Green Hydrogen Integration: 98 publications (8.7% of the corpus) explore gasification-hydrogen production coupling.
- Circular Economy Applications: 89 publications examine waste valorization through gasification.
- Life Cycle Sustainability: 84 studies employ life cycle assessment (LCA) methodologies for comprehensive environmental impact assessment [221–223].
- Carbon Capture, Utilization and Storage (CCUS): 45 studies explore how CCUS technologies can be integrated with gasification processes.

This thematic evolution reflects a fundamental paradigm shift from a technology-centric focus to systems-thinking approaches. Publications increasingly examine gasification not as an isolated conversion technology but as part of integrated energy systems, including power-to-X pathways and industrial symbiosis frameworks [224,225]. At the same time, the traditional emphasis on process efficiency has gradually expanded to encompass wider sustainability considerations, incorporating environmental, social, and economic performance dimensions [226,227]. In parallel, recent co-gasification studies reframes waste from a disposal challenge to a strategic resource, aligning process development with circular economy principles [12,13].

4.7. Methodological Contribution: Overcoming database integration barriers

The development and deployment of a custom Python pipeline constituted a core methodological contribution of this work. Standard bibliometric tools (e.g., R-bibliometrix, VOSviewer) fail to integrate ScienceDirect data, exposing a systemic flaw in academic data management that forces single-database reviews. This limitation introduces significant selection bias, potentially omitting 20–40% of relevant literature and creating geographic/temporal coverage gaps [82,90]. Our computational solution directly addressed these critical gaps by enabling high-precision, multi-format processing (RIS, BibTeX, CSV) and robust, automated disambiguation. The immediate outcome was a significant increase in relevant publication identification (15–25% enhanced coverage versus WoS-only searches). More broadly, this approach democratizes access to comprehensive systematic review methodologies by reducing dependence on expensive proprietary tools and advancing Open Science goals through a fully documented, modular, and publicly available codebase [228]. This methodological innovation provides a replicable template for future reviews facing similar data access constraints, thereby improving the rigor and reproducibility of bibliometric science.

4.8. Limitations and future research directions

Despite the comprehensive nature of this multi-platform systematic review, certain limitations must be acknowledged. First, the reliance on English-language publications may have excluded relevant regional pilot-scale studies published in other languages, particularly from emerging markets in Asia and South America. While English dominates scientific publishing (exceeding 80% of engineering research), regional databases such as CNKI for Chinese literature or SciELO for Latin American studies could complement future analyses. Second, the technical restrictions on API data export from Web of Science and Scopus necessitated a custom Python-based pipeline; while this addressed format incompatibilities, the intrinsic "noise" in full-text filtering from ScienceDirect required manual verification, which may introduce a minor degree of subjective bias in the initial screening phase. In this regard, several mitigation techniques were used, including cross-referencing affiliations across all three platforms, triple-checking processes for prestigious universities, and ORCID verification for author disambiguation. Although small subjective components are still a part of every systematic review process, these quality control procedures guarantee consistency in the final corpus. Furthermore, the 2015–2025 temporal boundary, while capturing the most recent decade of innovation, does not fully account for early foundational patents from the 1990 s that may still influence current reactor designs.

Future research should focus on integrating LCA data with bibliometric trends to bridge the gap between scientific maturity and environmental impact.

5. Conclusion

This review demonstrates that gasification and co-gasification research grew significantly faster than general energy research trends between 2015 and 2025. Publications increased from 30 to 220 annually, progressing through three phases: early thermochemical exploration (2015–2018), accelerated growth (2019–2021), and strategic sustainability integration (2022–2025). Emerging themes include green hydrogen, circular economy principles, and carbon capture integration. High-impact indicators demonstrate scientific maturity. The corpus h-index (89) and average journal Impact Factor (8.4) confirm that gasification now matches established chemical engineering fields. High citation rates indicate global relevance, but a significant gap persists between research sophistication and industrial practice. Despite high research quality, innovation translation remains weak. The publication-to-patent ratio (3.6:1) exceeds typical engineering values (1.5–2.0:1), and a 3.2-year lag between publication and patent filing indicates inefficient knowledge transfer. Patent activity, concentrated in China (57.6%), focuses on incremental reactor improvements rather than breakthrough technologies. The research community remains severely fragmented. Despite global distribution (3,686 authors), network density is extremely low (0.0016), with researchers working within isolated institutional clusters. China dominates publication volume, while Europe and the US pursue different national priorities, but international collaboration remains limited, constraining interdisciplinary innovation. Methodologically, this work addresses structural incompatibilities between Web of Science, Scopus, and ScienceDirect. The custom Python pipeline enabled processing of 128,056 records and provides a template for future multi-database systematic reviews facing data access constraints. Widespread gasification adoption requires more than technical advances; it demands coordinated cross-sector efforts. Future research priorities include validating computational models (especially Aspen Plus) with pilot-scale data and addressing economic competitiveness as renewable energy costs decline. Closing the gap between scientific maturity and commercial reality requires coordinated policy frameworks, standardized validation procedures, and international industry-academic consortia.

CRediT authorship contribution statement

Matheus Oliveira: Resources, Methodology, Conceptualization. **Eliseu Monteiro:** Writing – original draft, Project administration, Investigation, Funding acquisition. **Abel Rouboa:** Writing – review & editing, Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

No data was used for the research described in the article.

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