



# BIBLIOMETRIC STUDY OF THE GREEN AMMONIA ECONOMY (2010–2025)

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## ABSTRACT

*This study presents a comprehensive bibliometric analysis of the green ammonia economy, aiming to map its evolution, structure, and thematic trends from 2010 to 2025. Green ammonia is emerging as a key solution for hydrogen storage and carbon-free fuel in decarbonizing hard-to-abate sectors. The analysis uses a dataset of 2,520 peer-reviewed articles and reviews sourced from the Scopus database, employing R-Studio and VOSviewer for quantitative analysis of publication trends, citation impact, international collaborations, and keyword co-occurrence. The results reveal significant growth in research output, particularly after 2020, driven by global interest in low-carbon energy solutions. Geographically, China leads in publication volume, while the United Kingdom and the United States are central hubs for international research collaborations. Thematic analysis identifies four main clusters: core chemistry and electrochemical conversion, combustion science, techno-economic analysis, and engine applications. The field has transitioned from foundational studies to applied research and policy-oriented analysis. The study emphasizes the need for further interdisciplinary collaboration, particularly in socio-economic and policy research, to address the remaining challenges of commercial deployment and systemic integration of green ammonia technologies.*

## 1 INTRODUCTION

The global energy sector is undergoing a significant transformation driven by the urgent need to address climate change and meet carbon neutrality goals by mid-century (Anekwe et al., 2025; Evro et al., 2024). In this context, green hydrogen has emerged as one of the most promising solutions due to its status as a clean, carbon-free energy carrier (Kurien & Mittal, 2022). However, challenges associated with its storage

and transportation over long distances, such as low volumetric density and the need for liquefaction at extremely low temperatures or high-pressure conditions, continue to hinder its widespread adoption (Anekwe et al., 2025; Negro et al., 2023).

To address these challenges, ammonia (NH<sub>3</sub>), specifically "green ammonia," has emerged as a strategic and efficient hydrogen-carrier (Kurien & Mittal, 2022; Valera Medina et al., 2025).

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Ammonia boasts a significantly higher volumetric energy density compared to liquid hydrogen, in addition to being easily liquefied, stored, and transported using existing global infrastructure, which helps reduce initial investment costs (Boretti, 2024b). Moreover, ammonia can be directly used as a carbon-free fuel in sectors that are difficult to electrify, such as maritime shipping, power generation, and heavy-duty transportation, positioning it as a key player in the future hydrogen economy (Ishaq & Crawford, 2024).

Despite its promising potential, the direct use of ammonia as a fuel faces significant challenges, including its less-than-ideal combustion properties, such as low flame speed, ignition difficulty, and narrow flammability limits (Doosti et al., 2025; Zhang et al., 2025).

Its combustion can release harmful emissions, including nitrogen oxides (NO<sub>x</sub>), nitrous oxide (N<sub>2</sub>O)—a potent greenhouse gas—and unburned ammonia ('ammonia slip'), highlighting the need for advanced combustion technologies and treatment systems (Mashruk et al., 2024; Valera Medina et al., 2025).

In recent years, the green ammonia economy has witnessed remarkable advancements, particularly due to the increasing global focus on sustainable energy solutions. This surge in interest has been matched by a corresponding rise in research and development, with significant improvements in ammonia production technologies using renewable energy sources such as solar and wind power (Boretti, 2024a). Additionally, the progress in ammonia cracking technologies for onsite hydrogen production is a key factor enhancing ammonia's role as a low-carbon fuel for the future (Prodkornburee et al., 2025). Furthermore, innovations in ammonia combustion and catalysis technologies are improving its efficiency and reducing harmful emissions, further enhancing its economic and environmental viability (Mashruk et al., 2024; Saif & Mokheimer, 2025).

As the research surrounding green ammonia continues to evolve, it is increasingly important for policymakers, researchers, and industrial stakeholders to understand the dynamics of this field. Given the growing body of work in this area, it is crucial to explore the development of green ammonia research and identify key themes, challenges, and opportunities that lie ahead. The

following questions encapsulate the primary issues that this research aims to address:

What has been the development of research in the field of green ammonia over recent years (2010–2025)?

- How has the substantial growth in research been influenced by the Paris Agreement on Climate Change?
- What are the main themes that researchers have focused on in this field?
- How is research on green ammonia distributed across different disciplines (e.g., energy, engineering, chemistry)?
- Is there interdisciplinary overlap, and how does this affect the progression of the field?
- What areas require further research and development?
- What bibliometric patterns reflect the impact of green ammonia research on policy and economics?
- How do economic and technological studies on green ammonia influence its strategic integration into the energy markets?

By examining these aspects, this study endeavors to provide a comprehensive analysis of the green ammonia economy, highlighting the future trajectory of this promising technology and the factors that drive its development.

## 2 MATERIALS AND METHODS

### 2.1 Search methodology

This bibliometric study aimed to map the evolution, structure, and thematic frontiers of research on the green ammonia economy. The Scopus database was selected for its comprehensive coverage of peer-reviewed publications across energy systems, environmental sciences, chemical engineering, and policy research.

A concept-driven keyword strategy was initially applied, encompassing terms related to technical pathways (e.g., ammonia fuel, power-to-ammonia) and economic dimensions (e.g., green ammonia economy, techno-economic analysis, LCOA). The complete Boolean query and filtering steps are detailed in Table 1, ensuring transparency and reproducibility.

The initial search retrieved 3,374 records. After applying filters for publication year (2010–2025),

document type (articles and reviews), and language (English), a final dataset of 2,520 documents was obtained. This time frame spans both the formative years of ammonia energy research and the post-2015 growth period following the Paris Agreement, which catalyzed global interest in low-carbon energy vectors.

This selection strategy prioritizes peer-reviewed research (n = 2,449) and review articles (n = 305), excluding conference papers, book chapters, and grey literature to ensure methodological rigor and citation consistency.

*Table 1. Search Criteria and Bibliometric Summary for Green Ammonia Economy Research*

	Criteria	Details	N° of Documents
<b>Search Criteria</b>	<b>Search Equation</b>	Keywords related to green ammonia technologies, economics, energy use, and value chains (see full query below)	3,374
	<b>Year Range</b>	From 2010 to 2025 (as of 21 October 2025)	3,243
	<b>Document Type</b>	Only Articles and Reviews (Articles = 2,449; Reviews = 305)	2,754
	<b>Language</b>	English only	2,520
	<b>Final Search Query</b>	TITLE-ABS-KEY ("green ammonia" OR "renewable ammonia" OR "ammonia energy" OR "ammonia fuel" OR "NH3 fuel" OR "power-to-ammonia" OR "ammonia cracking" OR "ammonia combustion" OR "ammonia as energy carrier") OR TITLE-ABS-KEY("green ammonia economy" OR "economics of green ammonia" OR "techno-economic analysis of green ammonia" OR "green ammonia market" OR "ammonia value chain" OR "LCOA" OR "ammonia trade") AND (LIMIT-TO(DOCTYPE,"ar") OR LIMIT-TO (DOCTYPE,"re")) AND (LIMIT-TO (LANGUAGE,"English")) AND PUBYEAR > 2010 AND PUBYEAR < 2026	2,520
	<b>Subject Area Distribution</b>	Energy (1,896); Engineering (1,320); Chemical Engineering (1,172); Chemistry (1,045); Environmental Science (694); Physics & Astronomy (660); Materials Science (414); Mathematics (241); Computer Science (125); Biochemistry & Molecular Biology (86); Business & Management (63); Earth Sciences (49); Social Sciences (44); Multidisciplinary (33); Agriculture & Biology (32); Medicine (26); Economics & Finance (16); Decision Sciences (6); Pharmacology & Toxicology (5); Neuroscience (5); Immunology (5); Veterinary (1); Nursing (1); Dentistry (1)	
<b>Bibliometric Indicators</b>	<b>Metric</b>	Sources (Journals)	441.0
		Average years from publication	1.75
		Average citations per documents	32.29
		Total Documents,	2520.0
		Total Unique Authors	5836.0
		Author Appearances (Total)	14032.0
		Single-authored Documents	57.0
		Multi-authored Documents	2463.0
		Authors of Single-authored Documents	52.0
		Authors of Multi-authored Documents	5803.0
		Documents per Author	0.43
		Authors per Document	5.57
		Co-Authors per Document	4.57
	Collaboration Index	2.36	

Table 1 summarizes the search strategy, subject area distribution, and core bibliometric indicators derived from the final dataset. These descriptive metrics, while informative, are further analyzed and interpreted in the following sections.

## 2.2 Data sources and analytical tools

To process and analyze the bibliographic dataset, a dual-platform methodology was employed, utilizing R-Studio and VOSviewer to ensure methodological rigor and reproducibility.

R-Studio (version 2024.09.1+394), combined with the bibliometric package, was used to perform advanced bibliometric analyses. These included descriptive statistics, citation burst detection, co-authorship networks, source impact metrics, and thematic evolution mapping — offering a quantitative foundation for identifying influential authors, journals, and research trends.

VOSviewer (version 1.6.20) was applied to construct keyword co-occurrence networks, segmented by three strategic time periods. These visualizations revealed the conceptual structure of the field and traced how research themes have shifted — from early studies on ammonia production pathways to its emerging role in sustainable and decarbonized energy systems.

Together, these tools enabled a high-resolution mapping of the green ammonia research landscape, combining longitudinal, structural, and thematic perspectives.

## 2.3 Methodological considerations

Despite its methodological rigor, this bibliometric study has limitations. The exclusive use of the Scopus database may omit publications indexed elsewhere. Additionally, the English-only filter introduces potential linguistic bias, and the exclusion of non-peer-reviewed materials may overlook certain emerging insights. However, cross-validation between Python and R outputs was performed to ensure analytical consistency and data reliability.

# 3 RESULTS

## 3.1 Descriptive Bibliometric Analysis

A foundational step in bibliometric assessment involves understanding the structural

characteristics of the retrieved literature. This includes analyzing the overall volume of publications, subject area distribution, authorship patterns, and citation performance. Such descriptive indicators provide crucial insights into the maturity, interdisciplinarity, and scholarly engagement of a research field.

The bibliometric overview of the final dataset (Table 1) reveals several key characteristics of the green ammonia research landscape. A total of 2,520 peer-reviewed documents were identified, published between 2010 and 2025, reflecting a substantial and steadily growing body of knowledge. The field demonstrates a strong interdisciplinary profile, with dominant contributions from Energy ( $n = 1,896$ ), Engineering (1,320), Chemical Engineering (1,172), and Chemistry (1,045). These subject areas underscore the technological and applied orientation of the domain.

The collaboration index of 2.36 and the average of 5.57 authors per document indicate a high degree of research collaboration, consistent with patterns observed in complex, cross-sectoral fields such as energy systems and environmental technologies. The low number of single-authored papers ( $n = 57$ ), compared to multi-authored publications ( $n = 2,463$ ), further reinforces this trend.

In terms of authorship dynamics, the dataset comprises 5,836 unique authors and 14,032 author appearances, yielding an average of 0.43 documents per author. This suggests a distributed contributor base rather than concentration among a small group of prolific researchers. The average of 32.29 citations per document points to a moderate to high scholarly impact, highlighting the field's increasing relevance within both academic and policy arenas.

Despite the broad disciplinary spread, certain fields remain underrepresented. These include Economics ( $n = 16$ ), Social Sciences ( $n = 44$ ), and Business and Management ( $n = 63$ ), indicating potential gaps in the integration of economic modelling, policy frameworks, and market analysis within green ammonia research. These underexplored areas may offer promising directions for future interdisciplinary collaboration, especially as the field moves from technological feasibility toward commercial deployment.

Figure 1 illustrates the evolution of research output and citation activity related to the green ammonia economy from 2010 to 2025. The data reveal a clear trajectory of exponential growth,

particularly over the last five years, reflecting a shift from conceptual exploration to mainstream academic and policy interest.

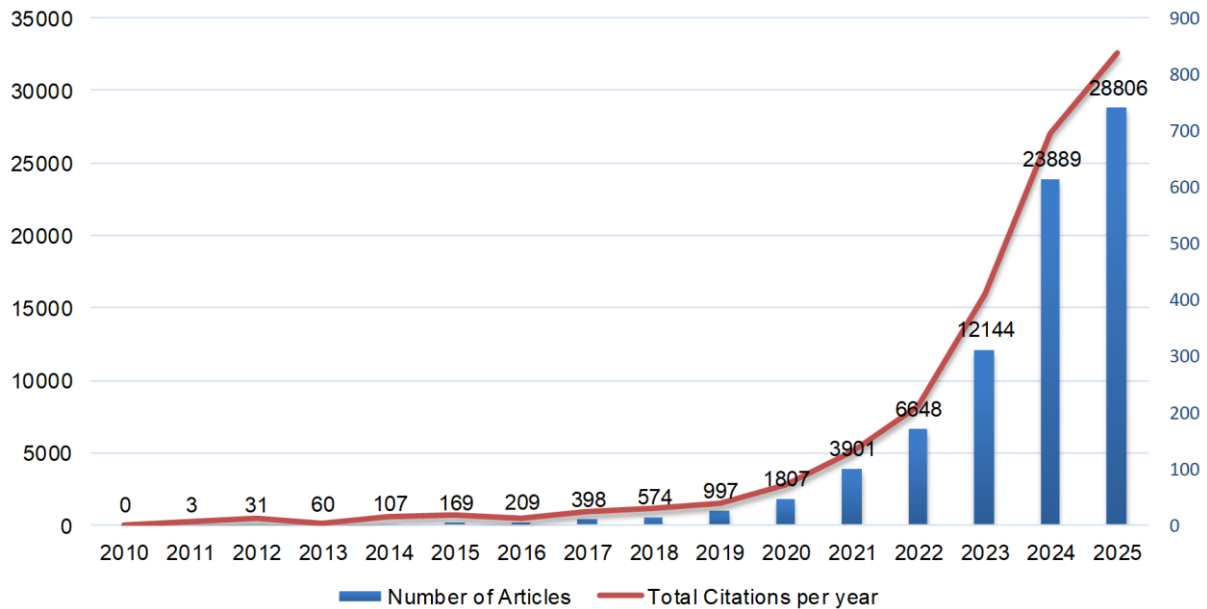
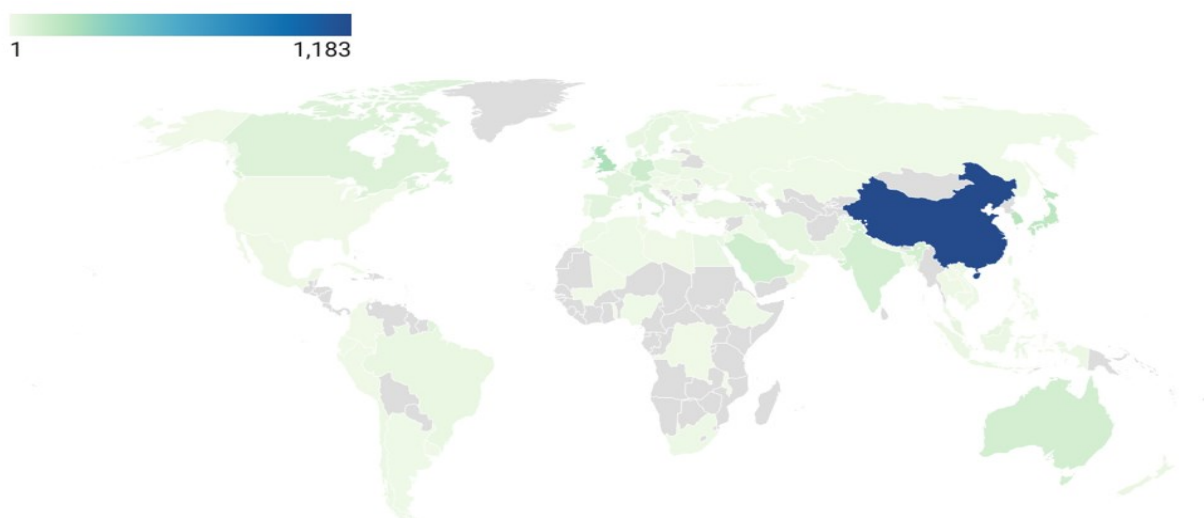


Figure 1. Documents Published and Citations Received on the Green Ammonia Economy Over the Years (Data Until October 2025).

**Note:** The 2025 data were retrieved in October 2025 and may continue to evolve.

Between 2010 and 2015, the field remained in its nascent stage, with very limited output (only 18 articles in 2015) and modest citations (169). This early phase was characterized by foundational studies exploring the technical feasibility of green ammonia in energy systems (Marçano et al., 2024)

From 2016 to 2020, research activity gradually increased, growing from 12 articles in 2016 to 71 in 2020. Citations during this period also rose steadily, reaching 1,807 in 2020. This stage reflects growing academic interest as green ammonia began to be recognized as a potential vector in decarbonization pathways



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Figure 2. Global Geographical Distribution of Scientific Publications on the Green Ammonia Economy

A significant turning point occurred after 2020. Publications increased rapidly from 132 in 2021 to 837 in 2025, while citations escalated from 3,901 in 2021 to 28,806 in 2025. Notably, 2024 and 2025 alone accounted for more than 50% of the total citations in the dataset. This surge can be attributed to multiple factors, including increased public and private investment in hydrogen-derived fuels, national and international roadmaps for ammonia deployment, and its emerging role in hard-to-abate sectors such as maritime transport (IRENA, 2023; Marçano et al., 2024). Despite the slight temporal lag typically seen between publication and citation accumulation, 2025 already shows the highest annual citation count (28,806), indicating exceptional scholarly and perhaps industrial attention.

These findings confirm that the green ammonia economy has rapidly evolved from a fringe

research topic into a central pillar of the global energy transition discourse. (Marçano et al., 2024)

The geographical distribution of publications on green ammonia highlights a concentration of research activity in technologically advanced nations. China leads significantly with 1,183 documents, followed by the United States (247), the United Kingdom (222), Japan (167), and South Korea (180). Strong contributions from European countries such as Germany, Italy, and the Netherlands, alongside emerging players like Saudi Arabia, Australia, and India, reflect both policy-driven and market-oriented research agendas. In contrast, limited output from regions in Africa, Latin America, and Southeast Asia indicates ongoing disparities in research infrastructure and funding access, despite the global relevance of green ammonia.

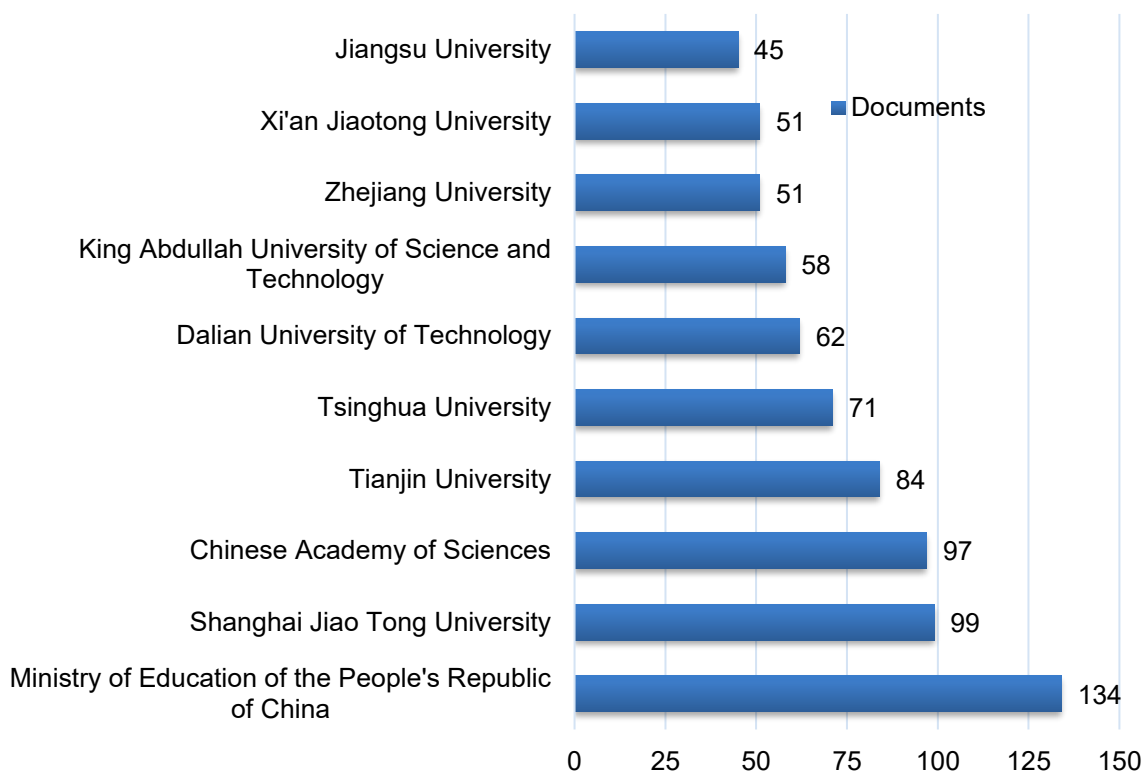


Figure 3. Top 10 Most Productive Institutions in Green Ammonia Economy Research

Figure 3 highlights the top ten most productive institutions in the field of green ammonia research. The data reveal an overwhelming dominance by Chinese institutions, which occupy nine out of the ten leading positions. At the forefront is the Ministry of Education of the People's Republic of China, contributing 134 documents—an indicator not of a single institution, but rather a coordinated national effort, reflecting a strategic prioritization of

this research area at the governmental level. Following closely are prestigious Chinese universities and research bodies such as Shanghai Jiao Tong University (99 documents) and the Chinese Academy of Sciences (97), demonstrating the concentration of scholarly output within China's leading academic centers. The only non-Chinese institution in this group is King Abdullah University of Science and

Technology (KAUST) from Saudi Arabia, ranking seventh with 58 publications. KAUST's presence underscores not only its strong research capacity but also Saudi Arabia's strategic investment in hydrogen and green ammonia technologies as part of a broader vision to diversify its post-oil economy.

Table 2. *Leading Authors in the Green Ammonia Economy*

Rank	Author	N° Doc	Total Citation	H-index
1	Valera-Medina, A.	32	2,203	17
2	Long, W.	32	896	16
3	Dincer, I.	27	1,882	20
4	Wei, H.	21	699	12
5	Siddiqui, O.	19	722	13
6	Dong, P.	19	542	11
7	Tian, J.	18	570	11
8	Guibert, T.F.	17	741	11
9	Lu, X.	17	299	8
10	Wang, Z.	17	414	11
11	Meng, X.	17	343	8

Table 2 identifies key contributors to green ammonia research. Valera-Medina, A. and Dincer, I. stand out as the most influential scholars—

combining high productivity (32 and 27 documents, respectively) with exceptional citation metrics (2,203 and 1,882 citations; h-indices of 17 and 20). Long, W. matches Valera-Medina in output but has a lower citation count, indicating a potentially narrower or more recent research focus.

Other core authors, including Siddiqui and Guibert, display strong citation performance despite fewer publications, reflecting high per-paper impact. A broader group of active contributors (e.g., Wei, H., Dong, P., Wang, Z.) sustains the field's growth, with stable h-indices (11–12) and steady output.

Overall, leadership in the field is defined not only by volume but by consistent scholarly influence, marking a well-developed and mature research community.

The Sankey diagram offers a panoramic visualization of the interconnected landscape of green ammonia research, illustrating the dynamic relationships between institutions (left), first authors (center), and indexed keywords (right). The thickness of the flows represents the volume of publications, allowing for immediate identification of the most influential contributors and research themes.

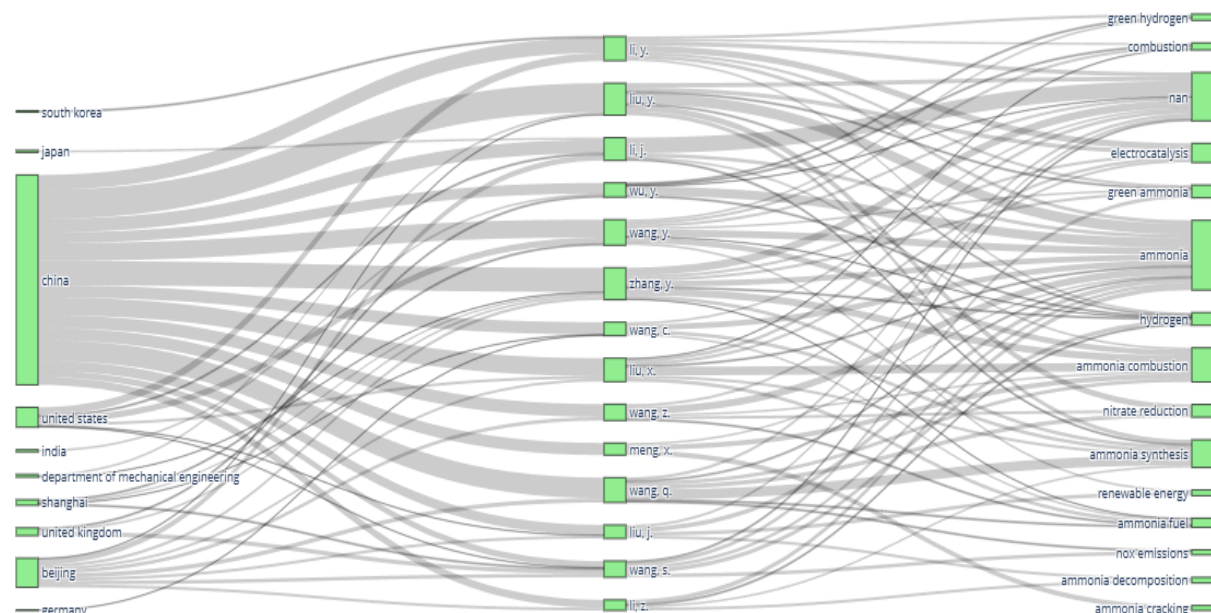


Figure 4. *Three-field Plot of Institutions, Authors, and Keywords*

A clear and overwhelming dominance by China is observed, both in terms of institutional affiliations and prolific authorship. The largest flow originates from Chinese institutions, particularly those linked to leading researchers such as Wang, Y. and Liu,

Y., and converges on high-frequency keywords like ammonia combustion, electrocatalysis, and green ammonia.

This suggests that China not only leads in research volume but also drives key thematic developments within the field.

Other notable contributors include institutions and authors from the United States, Japan, South Korea, and the United Kingdom, albeit with smaller flows. These highlight important but more specialized or regionally focused research clusters.

Crucially, the diagram reveals direct linkages between specific researchers and their topical specializations. For instance, authors affiliated

with South Korea and Japan appear to be strongly connected to hydrogen production and solid oxide fuel cells, suggesting a geographical clustering of thematic expertise.

The thematic flows on the right confirm the field's central research axes, reinforcing earlier co-occurrence and cluster analyses. Keywords such as hydrogen, ammonia, combustion, and catalysts dominate, reflecting sustained academic focus on ammonia's dual role as a fuel and hydrogen carrier, as well as its relevance in sustainable energy systems.

Table 3. Top Ten Journals Publishing Documents on the Green Ammonia Economy

Rank	Journal Title	N° of Publications	Citations	H-Index	Cite Score	SJR	SNIP	Year Start
1	International Journal of Hydrogen Energy	291	10,680	53	13.3	1.685	1.777	2010
2	Fuel	225	8,225	47	16.5	1.614	1.739	2010
3	Energy	110	2,241	27	7.3	0.713	1.739	2019
4	Combustion and Flame	94	2,899	27	10.9	2.015	1.871	2012
5	Energies	80	2,044	24	7.3	0.713	1.027	2019
6	Energy Conversion and Management	73	3,504	27	19.8	2.659	2.261	2019
7	Proceedings of the Combustion Institute	62	4,548	24	8.6	1.524	1.524	2017
8	Chemical Engineering Journal	58	1,402	18	/	0.125	/	2021
9	Energy and Fuels	49	748	15	9.5	1.124	1.145	2018
10	Applied Energy	48	3,495	25	20.1	2.902	2.512	2014
<b>TOTAL</b>		<b>1,090 (43.25%)</b>						

Note: The 2025 data were retrieved in October and may continue to evolve

Table 3 presents a comprehensive view of publication activity in the green ammonia economy, showcasing both productivity and scholarly impact. The International Journal of Hydrogen Energy and Fuel clearly dominates in terms of publication volume. International Journal of Hydrogen Energy leads with 291 articles, representing the largest share of the total output, followed by Fuel with 225 articles. Together, these journals contribute to 43.25% of the total publications in the field, highlighting their dominance as primary venues for publishing research on green ammonia. This suggests a

concentration of research in a small number of high-output journals, which serve as the main dissemination platforms for work in this area.

On the other hand, while Energy Conversion and Management and Applied Energy publish fewer articles (73 and 48, respectively), they stand out in terms of impact. These journals boast high CiteScores of approximately 20 and are among the highest in the field. Their SJR (SCImago Journal Rank) and SNIP (Source Normalized Impact per Paper) scores also surpass those of the more prolific journals. This indicates that while these journals may not be published as frequently,

the articles they do publish are of strong influence, as evidenced by their substantial citation counts. These journals, therefore, represent the "elite" within the field, where quality and prestige are more significant than publication volume.

Combustion and Flame and Proceedings of the Combustion Institute emerge as highly influential journals in the combustion sector, though they are more specialized. Combustion and Flame has an SJR index of 2.015, positioning it at the forefront of combustion-related research. Remarkably, Proceedings of the Combustion Institute has achieved 4,548 citations from just 62 articles, resulting in the highest average citations per article in the list. This exceptional performance highlights the journal's significant impact, despite its smaller volume of publications. These journals publish pivotal research in their specific niche within the green ammonia economy.

Additionally, the relatively new Chemical Engineering Journal began publishing in 2021 and, as expected, does not yet have calculated CiteScore or SNIP values. Its publication count (17

articles) reflects its early stages in contributing to green ammonia research. In contrast, broader journals such as Energy and Energies, while publishing a substantial number of articles, have lower SJR and CiteScore values compared to more specialized journals. This suggests that while these broader journals contribute to the literature, they are not as tightly focused on green ammonia as other journals in the list.

This analysis suggests that while the International Journal of Hydrogen Energy and Fuel dominate in terms of volume, journals like Energy Conversion and Management and Applied Energy lead in terms of the quality and impact of their articles. Specialized journals such as Combustion and Flame continue to be instrumental in advancing specific areas of research, such as combustion science within the green ammonia field. The data also highlights the emergence of newer journals like Chemical Engineering Journal, which may increase its influence in future years as more data becomes available.

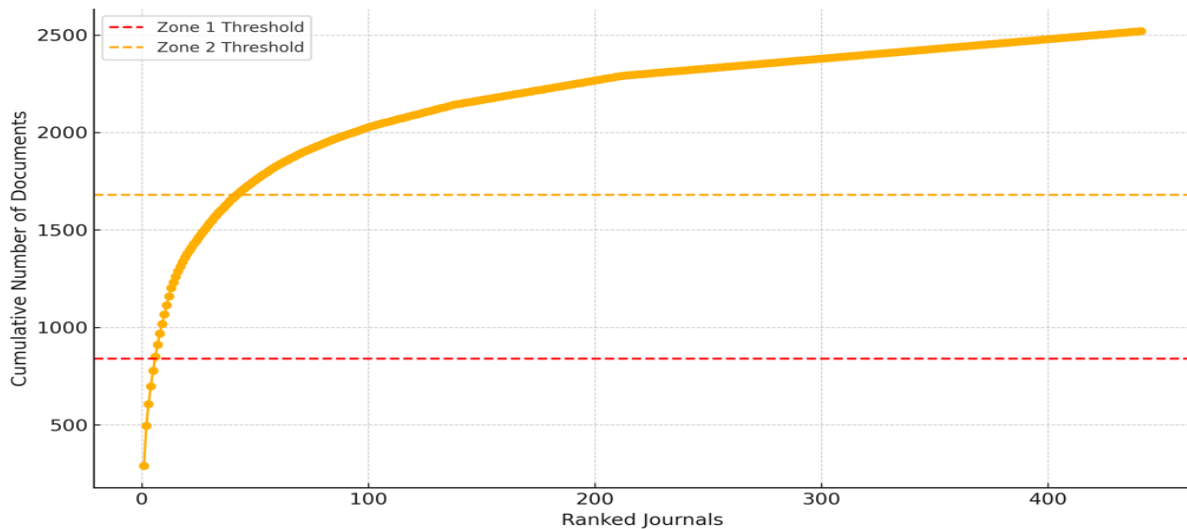


Figure 5. Bradford's Law: Distribution of Publications by Source

Figure 5 presents Bradford's Law of Scattering distribution for publications in the green ammonia economy domain. The graph plots cumulative document counts against ranked journals, offering insight into the concentration and dispersion of scholarly output.

As illustrated, the curve can be segmented into three distinct zones of approximately equal volume (~850 documents each), revealing a typical Bradfordian distribution pattern:

Zone 1 (Core Zone): The first ~850 documents are concentrated in a small set of high-yield journals (around 20–25). These represent the core journals in this field, characterized by their thematic specialization and consistent output on green ammonia topics. The steep gradient in this segment reflects the high productivity of each journal.

Zone 2 (Peripheral Zone): The next third of documents is distributed over a larger group of journals, indicating broader but less frequent





Figure 7. Temporal Evolution of the Top 20 Author Keywords (2010–2025)

**Cluster 1 (Red):** Core chemistry, materials, and electrochemical conversion

Prominent keywords include “direct ammonia fuel cells”, “catalyst”, “ammonia synthesis”, “electrochemical oxidation”, “solid oxide fuel cells” (SOFC), “nitrogen reduction”, and “nano-catalyst”. This cluster spans three interlinked axes: (i) electrochemical conversion technologies, evidencing the diversification of fuel-cell architectures (DAFC, SOFC, alkaline) and investigations into electrodes, electrolyte, and power-density optimization; (ii) advanced materials and catalysis science, focused on nano-structured and single-atom catalysts using transition-metal systems and addressing stability issues; and (iii) sustainable ammonia synthesis pathways, notably electrochemical ammonia synthesis and nitrate-reduction approaches, as alternatives to the conventional Haber–Bosch process. In essence, this cluster represents the molecular-scale research frontier that underpins both green ammonia production and utilization.

**Cluster 2 (Green):** Fundamental combustion science and fluid-chemical dynamics

Key terms such as “combustion”, “kinetics”, “flame”, “nitrogen oxides”, “chemical kinetic model”, “hydrogen”, and “simulation” characterize this cluster. It encompasses (i) flame dynamics and combustion physics, informed by CFD and large-eddy simulation of laminar vs turbulent burning behavior; (ii) chemical-kinetic modelling of reaction pathways and pollutant formation (particularly NO<sub>x</sub>); and (iii) co-firing and fuel-blending strategies (ammonia–hydrogen, ammonia–methane) to improve ignition and flame stability. This cluster, therefore, provides the foundational science required for practical implementation. Such aspects are likely addressed in other clusters.

**Cluster 3 (Blue):** Strategic systems, economics, and energy-policy integration

Highlighted keywords include “green ammonia”, “decarbonization”, “techno-economic analysis”, “renewable energy”, “hydrogen economy”, “costs”,

and “life-cycle assessment”. This cluster explores (i) environmental motivation and sustainability frameworks (LCA, carbon footprint); (ii) economic viability and market integration (cost–benefit, value-chain, supply-chain analyses); and (iii) energy-systems integration and the role of ammonia in the hydrogen economy (power-to-ammonia, hydrogen carrier). It effectively bridges technological innovation with policy, market, and system-level considerations.

**Cluster 4 (Yellow):** *Engine applications, performance, and emissions control*

With keywords such as “diesel engines”, “dual-fuel engine”, “engine performance”, “emission characteristics”, “ammonia-diesel”, “thermal efficiency”, and “ammonia slip”, this cluster focuses on the applied engineering of ammonia in internal-combustion engines. Its three axes are (i) engine technologies and dual-fuel modes; (ii) performance and efficiency metrics; and (iii) emissions management (NO<sub>x</sub> control, ammonia slip, after-treatment devices such as selective catalytic reduction). Thus, it represents the translation of foundational science into system-level engineering for deployment.

Viewed together, these clusters reflect the field’s dual trajectory of specialization and expansion. The progression, from foundational combustion science (Cluster 2) and electrochemical materials (Cluster 1) toward system applications (Cluster 4) and strategic integration (Cluster 3), underscores a mature and multi-dimensional research landscape. Emerging themes such as “green ammonia” and advanced catalysis signal shifting priorities from proof-of-concept to environmental and market relevance. Additionally, the overlap between clusters—visible in shared keywords and thematic bridges—points to an increasingly interdisciplinary domain, where chemistry, engineering, economics, and policy converge.

### 3.3 Collaboration Networks and Source Analysis

The analysis of international collaboration in green ammonia research presents a complex and hierarchical global landscape, providing valuable insights into both the productivity of countries and the strength of their research ties. This evaluation highlights key players, collaboration patterns, and

emerging research trends, with a particular focus on the role of both major contributors and emerging hubs in shaping the future of the field.

The international co-authorship network, visualized in Figure 9, reveals a research landscape dominated by China (1,183 documents), which leads not only in publication volume but also holds the highest total link strength (410). This positions China as the primary driver of research in this domain, contributing significantly to both the quantity of output and centrality in the global collaboration network.



Figure 9. International Co-Authorship Network in Green Ammonia Economy Research.

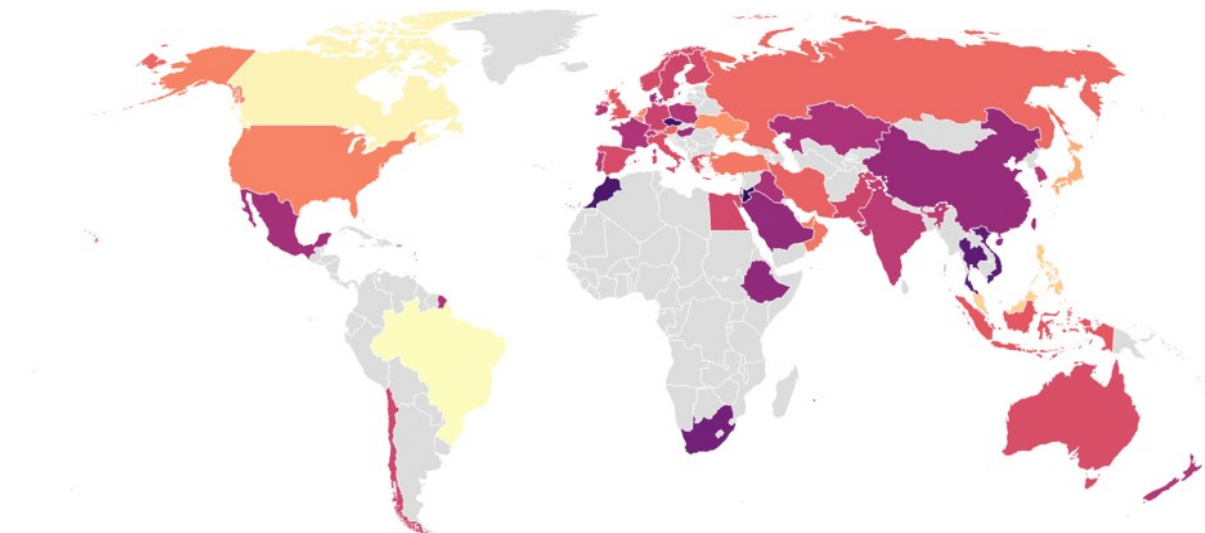
The United Kingdom (222 documents) and the United States (247 documents), while producing fewer publications than China, play critical roles as collaborative hubs. The UK, with a total link strength of 224, is particularly significant in fostering international collaboration, with research being highly interconnected across borders. Similarly, the US, with a link strength of 204, connects multiple research networks, underlining its importance in facilitating global collaboration.

East Asian countries, such as South Korea (180 documents) and Japan (167 documents), remain significant contributors to green ammonia research. However, their link strength values (95 and 93, respectively) suggest that their collaborations are more regionally focused, highlighting a robust local network within East

Asia. These countries are key players in technological advancements related to green ammonia, particularly within the region.

Emerging hubs like Saudi Arabia (107 documents), Australia (98 documents), and others are making noteworthy contributions. Saudi Arabia, with a link strength of 123, which exceeds its publication count, stands out. This indicates that Saudi Arabia is rapidly positioning itself as a key global research partner, helping to connect the Middle East with broader international networks.

Countries such as Qatar (6 documents) appear more isolated, with a total link strength of 0,



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*Figure 10. Geographical Expansion and Emerging Players in Green Ammonia Research*

As shown in Figure 10, geographical green ammonia research has shown significant expansion, with new players emerging alongside traditional leaders. Early contributors like Brazil, Canada, and Malaysia, with relatively early publication years (2021.23, 2021.33, and 2021.7, respectively), were among the first to engage deeply with green ammonia technologies, laying the foundation for its development within the global sustainability framework.

More recently, countries such as Jordan (2024.8), the Czech Republic (2024.6), and Morocco (2024.5) have entered the field, reflecting a broader global interest and the increasing

momentum in green ammonia research. While Qatar contributes to research output, it has yet to integrate into the broader global network of green ammonia research.

Conversely, countries like Canada (64 documents) and Finland (11 documents) demonstrate high levels of impact despite publishing fewer papers. Canada, with 4,055 citations (63.35 average citations per document), and Finland, with an average citation rate of 63.45 per document, showcase exceptional research quality. Their smaller publication output does not diminish their significant intellectual contributions to the field.

China has been a dominant force in green ammonia research and continues to lead the field. Its average publication year of 2023.8 indicates that its surge in research productivity is a recent phenomenon, driven by significant strategic investments in green ammonia technologies. This reflects China's increasing centrality in the global network of green ammonia research.

Table 4. Analysis of International Collaboration Clusters by Key Bibliometric Indicators.

Country	Documents	Citations	Total Link Strength	Avg. Pub. Year	Avg. Citations
<b>Cluster 1</b>					
<b>United Kingdom</b>	222	11204	224	2022.98	50.47
<b>Germany</b>	112	3267	117	2023.29	29.17
<b>Italy</b>	83	2735	74	2023.13	32.95
<b>Netherlands</b>	47	2163	64	2022.53	46.02
<b>France</b>	53	1923	60	2023.57	36.28
<b>Canada</b>	64	4055	43	2021.33	63.36
<b>Egypt</b>	24	794	36	2023.21	33.08
<b>United Arab Emirates</b>	19	1130	34	2022.63	59.47
<b>Belgium</b>	32	1736	26	2022.56	54.25
<b>Brazil</b>	22	730	20	2021.23	33.18
<b>Greece</b>	12	242	18	2023.08	20.17
<b>Turkey</b>	33	976	17	2022.64	29.58
<b>Portugal</b>	16	749	14	2023.50	46.81
<b>Morocco</b>	10	77	5	2024.50	7.70
<b>Cluster2</b>					
<b>South Korea</b>	180	4605	95	2023.46	25.58
<b>Spain</b>	50	1246	39	2023.16	24.92
<b>Pakistan</b>	24	644	38	2023.25	26.83
<b>Iran</b>	34	720	18	2022.88	21.18
<b>Chile</b>	13	722	13	2023.23	55.54
<b>Ireland</b>	10	247	16	2023.50	24.70
<b>Iraq</b>	5	142	12	2023.60	28.40
<b>Mexico</b>	6	139	8	2023.67	23.17
<b>Russian Federation</b>	5	164	8	2022.80	32.80
<b>Finland</b>	11	698	4	2023.18	63.45
<b>Cluster 3</b>					
<b>Saudi Arabia</b>	107	2514	123	2023.82	23.50
<b>India</b>	92	2780	88	2023.43	30.22
<b>Malaysia</b>	30	1386	40	2021.70	46.20
<b>Taiwan</b>	25	333	37	2023.68	13.32
<b>Viet Nam</b>	9	193	27	2024.33	21.44
<b>Thailand</b>	6	29	11	2024.33	4.83
<b>Oman</b>	6	264	10	2022.67	44.00
<b>Ethiopia</b>	7	192	11	2023.86	27.43
<b>Philippines</b>	8	81	8	2021.75	10.13

Cluster 4					
<b>Singapore</b>	49	788	51	2024.16	16.08
<b>Sweden</b>	31	968	35	2023.26	31.23
<b>Denmark</b>	39	981	33	2023.72	25.15
<b>Switzerland</b>	25	721	31	2023.44	28.84
<b>New Zealand</b>	19	799	21	2023.53	42.05
<b>Hungary</b>	8	173	6	2023.75	21.63
<b>Austria</b>	7	48	6	2022.86	6.86
Cluster 5					
<b>Japan</b>	167	8837	93	2022.08	52.92
<b>Poland</b>	31	859	38	2023.52	27.71
<b>Norway</b>	28	1255	33	2023.18	44.82
<b>Indonesia</b>	15	719	18	2023.00	47.93
<b>South Africa</b>	8	58	3	2024.13	7.25
Cluster 6					
<b>China</b>	1183	28517	410	2023.80	24.11
<b>Australia</b>	98	4813	87	2023.12	49.11
<b>Hong Kong</b>	37	1226	46	2023.08	33.14
<b>Macao</b>	12	477	15	2023.92	39.75
Cluster 7					
<b>United States</b>	247	13557	204	2022.52	54.89
<b>Kazakhstan</b>	5	44	8	2023.60	8.80
<b>Ukraine</b>	11	82	9	2022.36	7.45
Cluster 8					
<b>Czech Republic</b>	10	68	16	2024.60	6.80
<b>Israel</b>	13	250	9	2023.85	19.23
<b>Jordan</b>	5	23	8	2024.80	4.60

The cluster analysis, detailed in Table 4, reveals that international collaboration is not random but structured into distinct research blocks, each with unique characteristics in terms of productivity, impact, and scientific focus.

Cluster 1, the largest and most interconnected group, represents a robust European-global network. It is anchored by the United Kingdom, which acts as a major collaborative hub (Total Link Strength = 224). This cluster also includes other European powerhouses like Germany, Italy, and France, and has strong transatlantic links to Canada. Notably, this cluster contains countries with some of the highest research impact, such as Canada (Avg. Citations = 63.36) and the United

Arab Emirates (Avg. Citations = 59.47), indicating that this network is a hub for high-quality, influential research.

In contrast, Cluster 6 is clearly the East Asian powerhouse cluster, dominated by China (1183 Documents, Total Link Strength is 410). This cluster, which also includes Australia and Hong Kong, is characterized by massive research output driven primarily by China's recent and extensive engagement in the field (Avg. Pub. Year for China is 2023.80).

Cluster 3 highlights an emerging and influential research network spanning South Asia and the Middle East. It is led by Saudi Arabia (Total Link Strength is 123) and India (Total Link Strength

is 88). The recent entry of countries like Vietnam and Thailand (Avg. Pub. Year  $\approx$  2024.33) into this cluster signals a dynamic expansion of research activity in this region. The older publication records of Malaysia (Avg. Pub. Year = 2021.70) suggest it was a foundational member of this bloc.

Other clusters represent smaller but significant networks. Cluster 7 is notable for being anchored by the United States, another major global hub (Total Link Strength is 204), but with fewer direct partners in this specific visualization. Cluster 2 brings together a diverse group of countries, including South Korea and Spain, and importantly, Finland, which, despite having very low link strength (4), boasts the highest average citation rate in the entire network (63.45), marking it as a source of exceptionally high-impact research. Finally, Cluster 8 represents a group of highly specialized or newly emerging players like Israel and Jordan, with Jordan having the most recent average publication year (2024.80) in the dataset.

#### 4. CONCLUSIONS

This bibliometric study reveals the significant evolution, structure, and thematic frontiers of research on the green ammonia economy. The analysis of the Scopus database, covering publications from 2010 to 2025, highlights a sharp increase in research activity, especially post-Paris Agreement 2015. This surge can be attributed to the global shift towards low-carbon energy solutions, with green ammonia emerging as a viable energy carrier for sustainable development.

The study identifies two primary thematic dimensions that dominate the green ammonia research landscape: technical pathways and economic dimensions. On the technical side, there has been a substantial focus on ammonia fuel production technologies, such as power-to-ammonia, and their integration with renewable energy sources like wind and solar. These findings are consistent with the growing emphasis on developing ammonia as a clean hydrogen carrier. On the economic side, the techno-economic analysis of green ammonia, including metrics like the Levelized Cost of Ammonia (LCOA), remains a critical area of research as scholars aim to assess the commercial viability of ammonia-based energy systems.

A notable trend observed in this study is the increasing interdisciplinary nature of the research. While most publications were originally centered around chemical engineering and energy systems, a significant portion now emerges from environmental economics and policy research. This shift underscores the necessity of combining both technical and socio-economic perspectives to understand the full potential of green ammonia technologies and their role in global energy transitions.

The study also reveals challenges related to the direct use of ammonia as a fuel, particularly its combustion characteristics. As highlighted in previous research, ammonia faces significant challenges such as low flame speed, ignition difficulty, and a narrow flammability range, which limit its practical applications. Additionally, concerns regarding ammonia slip and harmful emissions like NO<sub>x</sub> and N<sub>2</sub>O were prevalent in the findings. These results emphasize the need for further technological development to optimize ammonia combustion processes and mitigate its environmental impact.

Geographically, the study identifies that leading contributors to green ammonia research are China, the United States, and the United Kingdom, with China standing out due to its strong governmental support for clean energy technologies. This aligns with the broader trend of strategic investments in low-carbon energy systems, particularly in countries that are heavily focused on reducing emissions from their industrial and transportation sectors. In contrast, regions like Africa and Latin America still face significant barriers, including a lack of research infrastructure, which hinders their participation in the development of green ammonia technologies.

The results also indicate a growing focus on sectors such as maritime transport and heavy industry, which are among the largest carbon-emitting sectors globally. This trend reflects a shift from foundational studies to more practical applications of green ammonia, particularly in industries where traditional energy sources are difficult to replace. These findings suggest that future research should continue to explore the application of green ammonia in these sectors, where it could offer significant environmental benefits.

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