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# Towards Inherently Safer Dry Reforming for Carbon Capture: Trends, Gaps, and Insights

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## ABSTRACT

Dry reforming of methane (DRM) is considered a promising technology to produce syngas since it offers possibilities for carbon dioxide ($CO_2$) conversion, sustainable generation of hydrogen, and environmentally friendly production. However, the efficiency of the current process, its sustainability, and its scalability remain critical considerations despite the numerous scientific developments in the field. Process safety needs special attention while addressing the problem of carbon deposition, catalyst deactivation and other hazards associated with DRM at the industrial level and operational risks, to ensure the practicality and reliability of large-scale applications. This study aims to evaluate global research trends at the intersection of DRM and process safety through a bibliometric analysis. In total, 1,036 research papers collected from the Scopus database within the timeframe of 1997-2024 were used in this study via a multi-phase process of material collection and analysed using bibliometric techniques, including publication trend analysis, country and author productivity assessment, collaboration network analysis, and keyword co-occurrence mapping. The results show a significant increase in research activity after 2017. Among the productive countries and authors, China and the USA are considered the key drivers and contributors to the topic. Four major safety-related themes have been defined as follows: safety in syngas production, carbon formation and catalyst deactivation, catalyst stability and anti-poisoning capabilities, and process intensification with innovative reactor design. These results indicate that safety issues are becoming more integrated into the DRM research field, especially through studies relating to operational stability, performance of reactors, and mitigating hazards.

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This paper attempts to provide a systematic analysis of emerging safety themes, identify current research gaps, and propose future directions involving inherently safer design, predictive safety monitoring, and pilot-scale validation. The outcomes may support researchers and industry practitioners in developing safer and more reliable DRM technologies for large-scale implementation.

*Keywords:* Bibliometric analysis, carbon capture and utilisation (CCU), catalyst, dry reforming, sustainable syngas safety

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## INTRODUCTION

The increased demand for energy has altered the landscape due to industrialisation for years (Tanksale et al., 2010). Additionally, energy demand is expected to continue increasing despite the current low oil prices. Methane ($CH_4$) and Carbon Dioxide ($CO_2$) are the most abundant greenhouse gases and are believed to be the major contributors to climate change challenges (Ampomah et al., 2024). The emission of greenhouse gases leads to a surge in global temperatures, which is the leading factor in most ecological and environmental challenges. Therefore, it is paramount that greenhouse gases are reduced and utilised to maintain the balance required for the sustenance of the earth through various energy conversions. The primary components of greenhouse gases are $CO_2$ and $CH_4$. The production of $CO_2$ will come from the combustion of fossil fuels. At the same time, methane emissions can arise from various sources, including coal mining, biogas fermentation ecosystems, paddy fields, and manganese-rich constructed wetlands (Liu et al., 2023; Tucker et al., 2021).

According to the United States Environmental Protection Agency, in 2011, about one-third of all $CH_4$ emissions in the United States came from $CH_4$ production at landfills. Landfill gas is approximately 40-45% $CH_4$ and 55-60% $CO_2$ by volume (Abdullah et al., 2017). Methane dry reforming (DRM) typically occurs at high temperatures, as it is an endothermic process. Methane is the major component of natural gas. Most natural gas reservoirs are located far from industrial zones and are typically produced offshore. Accordingly, technical and financial considerations regarding the transportation of this valuable commodity from offshore locations to prospective consumers have resulted in massive flaring of natural gas worldwide (Lunsford, 2000). In response to the challenges posed by global climate change and the need for sustainable energy sources, Carbon dioxide Capture and Storage (CCS) has been implemented globally to reduce carbon dioxide emissions. DRM has received considerable attention due to its efficiency in converting $CH_4$ and $CO_2$ into syngas, which consists of hydrogen ($H_2$) and carbon monoxide (CO). The produced syngas from DRM has an optimal $H_2$/CO ratio of approximately 1, which is considered ideal for Fischer-Tropsch (F-T) synthesis of methanol, ammonia, and other chemical products (Bachmann et al., 2023; He et al., 2020).

DRM has attracted considerable interest in recent years due to its environmental and economic benefits, including $CO_2$ utilisation and syngas production. Its application in industry has grown rapidly, mainly due to improvements in catalyst design and reactor technology (Shi et al., 2020). The risk factors related to high temperatures, irregular pressure, flammable vapours, and potential catalyst deactivation are strongly manifested in the DRM. Therefore, with the advancement and widespread implementation of DRM technologies worldwide, safety requirements and design guidelines have been gradually developed for the systems (Chen et al., 2022; Gobbo et al., 2018). These requirements and guidelines support the safe operation and reliability

The additional hazards encountered during the operation and maintenance of the DRM process are summarised in Table 1. Therefore, to prevent a few accidents from occurring, safety performance in the design and operational phases of the DRM system should be comprehensively analysed (Amelse & Behrens, 2021). International safety standards and guidelines, including those developed by the International Organisation for Standardisation (ISO) and other regulatory bodies, outline safety requirements for high-temperature chemical reactors, which include DRM processes. Recently, DRM has gained significant attention due to its environmental and economic merits, including $CO_2$ utilisation and syngas production (Oyama et al., 2012). Additionally, the industrial utilisation of DRM has been developing rapidly, primarily through improvements in catalyst design and reactor engineering. A significant amount of work related to the safety aspects associated with DRM catalysts, reactor configuration, operating conditions, and process integration strategies has emerged in the literature (Soleimani & Lehner, 2022). Although several excellent reviews exist on safety-related DRM (Noor et al., 2013). A macroscopic overview of the knowledge map in this area is still lacking.

The research questions were developed after a preliminary review of the DRM literature, which revealed that most studies mainly focused on catalyst activity, syngas production efficiency and $CO_2$ conversion performance, while systematic discussion on process safety and inherent safety remains limited (Hussien et al., 2022; Sandoval-Diaz et al., 2022; Usman et al., 2015). Existing bibliographic studies also focus on catalytic thermodynamic aspects, without explicitly linking research developments to industrial safety considerations and safety engineering frameworks. As a result, this study aims to identify the main research themes in DRM and evaluate how these topics contribute to understanding safety in the design, operation and integration of catalysts, reactors and processes.

To address the gaps in the current understanding of dry reforming of methane, this study is conducting the following research questions: (1) What are the main research groups and trends in DRM, particularly in terms of catalyst design, reactor performance and process safety? (2) How can the insights of the literature inform the considerations of process safety, including risks such as carbon deposition, catalyst deactivation, hotspot formation, and thermal runaway? Based on these questions, the study explores whether safety-related research themes can be systematically identified and interpreted through bibliometric mapping. Bibliometric analysis using VOSviewer allows for the identification of research clusters that can then be linked to specific safety-related aspects. For example, catalyst design groups inform strategies for preventing coking and sintering, while reactor design groups highlight the importance of temperature and pressure management. Process integration clusters provide insight into the adoption of inherent safety principles and standards. This approach strengthens the conceptual framework of research by linking knowledge trends to practical safety frameworks, highlighting areas for future research and industrial applications.

Although a quantitative risk ranking was beyond the scope of this bibliometric study, the identified hazards can be qualitatively prioritised based on their frequency of occurrence in the literature and potential impact on DRM operation. The most critical hazards, such as carbon monoxide release, hotspot formation, reactor overpressure, and carbon deposition, are considered due to their association with toxic exposure, thermal instability, equipment damage, and process disruption (Pawar et al., 2017). Catalyst deactivation and sulphur poisoning are generally regarded as secondary hazards.

Table 1
*Common hazards during the expected lifetime of dry reforming*

| No. | Hazard Type | Hazard Situation |
|---|---|---|
| 1 | Mechanical Hazard | Reactor vessel failure due to prolonged exposure to high pressure and material fatigue.<br>Catalyst bed collapse caused by uneven gas distribution and mechanical stress.<br>Blockage in reactor tubes due to excessive carbon deposition, leading to increased pressure drop. |
| 2 | High-Temperature Hazard | Localised overheating (hotspots) caused by uneven heat distribution in the catalyst bed.<br>Thermal stress cracking of reactor walls during rapid heating or cooling cycles.<br>Thermal runaway reaction due to uncontrolled methane feed rate. |
| 3 | Explosion and Flammability Hazard | Formation of an explosive methane-air mixture due to leaks in the reactor system.<br>Accumulation of unburned methane in the reactor during startup. |
| 4 | Toxic Gas Hazard | Accidental release of CO due to a leak in the reactor seal.<br>Incomplete methane conversion, causing high CO emissions.<br>Operator exposure to toxic gases during catalyst replacement. |
| 5 | Corrosion and Erosion Hazard | Reactor wall thinning caused by prolonged exposure to high-temperature $CO_2$.<br>Catalyst support degradation reduces structural integrity.<br>Corrosion-induced leakage in heat exchangers or reactor tubes. |

*Note.* Adapted from (Chen et al., 2022; Lunsford, 2000; Miao et al., 2021; Oyama et al., 2012)

However, prolonged catalyst degradation can contribute indirectly to process safety concerns via process instability and increased carbon accumulation. Corrosion and material degradation remain important long-term integrity issues, particularly under high-temperature operating conditions (Durán et al., 2023).

Bibliometrics is the cross-cutting science of quantitative analysis of all knowledge carriers utilising mathematics and statistics. A comprehensive body of knowledge can be generated using bibliometrics that integrates mathematics, statistics, and bibliography and focuses on quantification (Merigó et al., 2019). In recent years, bibliometrics has been extensively employed to analyse and visually demonstrate the state, structure, hotspots, and research trends in specific fields (Osarogiagbon et al., 2021). A few researchers have conducted bibliometric studies in the field of dry reforming. Alhassan et al. (2022) performed a bibliometric analysis of dry reforming of methane for hydrogen production based on Web of Science (WoS) data. They set up the effect of certain parameters on the DRM reaction. A bibliometric study on biogas reforming for the synthesis of sustainable aviation fuel, providing a statistical overview of the literature on nickel catalyst reforming and the thermodynamic influences of temperature, pressure, and the $H_2O/CH_4$ ratio (Duarte et al., 2024; Li et al., 2020).

Although previous systematic research has contributed to valuable insights into catalyst development, hydrogen production, thermodynamic optimisation and sustainable fuel synthesis in DRM, it generally lacks a clear discussion of process safety and inherent safety considerations (Ávila-Neto et al., 2009). Unlike previous bibliographic analyses, this study focuses specifically on safety-related aspects of DRM, including catalyst deactivation, carbon deposition, thermal stability of reactors, toxic gas formation and operational risks. Furthermore, this study expands previous bibliometric approaches by linking identified research groups to established safety engineering frameworks and inherent safety principles, which provides practical implications for the safe implementation of industrial DRM. To the best of the authors' knowledge, based on searches conducted in the Scopus database using combinations of the keywords 'dry reforming of methane', 'bibliometric analysis', 'scientometric analysis', 'safety' and 'process safety', no previous bibliometric study examining DRM from a process safety perspective was identified.

## METHODOLOGY

Bibliometric analyses were carried out to identify research trends, collaborative networks, and thematic clusters in the field of dry reforming of methane. VOSviewer was used to construct and visualise co-authorship, keyword co-occurrence, and citation networks. The tool is suitable for analysing large-scale datasets from databases such as Scopus and Web of Science, as it generates graphical maps showing research clusters, linking strengths, and emerging topics (van Eck & Waltman, 2010). Analysis followed standard library procedures, including data extraction using relevant keywords, data cleaning to unify author and institution names, network construction based on co-occurrence and reference relationships, cluster identification using the VOSviewer cluster algorithm, and visualisation of networks to highlight dominant research themes, emerging trends, and knowledge gaps. Bibliometric mapping using VOSviewer is widely recognised as a rigorous method for exploring scientific fields and supporting empirical literature reviews

The research identified the search terms for retrieving articles through a systematic screening process. The research began with gathering articles from the Scopus database through focused online searches. The query string was refined by incorporating a broad range of safety-related terms associated with dry reforming of methane. To improve search coverage, the query string incorporated a wide range of process safety and operational risk terms in addition to “dry reforming”. These included hazard identification, risk assessment, process control, emergency shutdown systems, thermal runaway, hotspot formation, gas leakage, toxic emissions, catalyst deactivation, sulphur poisoning, and inherently safer design concepts. This strategy was intended to capture publications addressing safety-related DRM issues even when the term “safety” was not explicitly stated. The complete search string employed in this study is presented in Table 2.

1,506 articles were identified using the search string "dry reforming" and safety terms in the title and abstract fields across various document types, including journal articles, conference articles, and book chapters, from 1996 to 2024. Afterwards, the exclusion criteria were used to filter out duplicate papers, non-English language papers, and papers outside the defined scope, and hence, the number of papers was reduced to 1,036 journal articles, as shown in Table 3. Lastly, the filtering process included specific themes related to dry reforming safety, such as syngas production, carbon management, catalytic stability, poisoning resistance, and process intensification.

Table 2
*Search string*

| |
|---|
| TITLE-ABS ( "Process safety" OR "Hazard identification" OR "HAZID" OR "Risk assessment" OR "Emergency shutdown system*" OR "Process control" OR "Inherent safe*" OR "Inherent* safe*" OR "inherent* safet* design*" OR "chemical route selection" OR "process design" OR "synthesis route" OR "ISD" OR “Carbon deposit*” OR "Material degradation" OR "High* temperature corrosion*" OR "Reactor design*" OR "Catalyst poison*" OR "Heat distribution" OR "Thermal runaway*" OR "Hotspot formation" OR "Temperature control*" OR "Thermal stress*" OR "Gas leak*" OR "CO exposure" OR "Toxic* emission*" OR "Flammable gas*" OR "catalyst deactivation" OR "sulfur poison*" ) AND ( "dry reforming*" OR "dry reforming of methane" OR "dry reforming methane" ) AND PUBYEAR > 1995 AND PUBYEAR < 2025 AND ( LIMIT-TO ( DOCTYPE, "ar" ) ) AND ( LIMIT-TO ( SRCTYPE, "j" ) ) AND ( LIMIT-TO ( LANGUAGE, "English" ) ) |

*Note.* Search query performed in Scopus (accessed December 2024). Filters applied: journal articles, English language, publication years 1996 to 2024

Table 3
*Refinement process*

| Stage | Description | Records |
|---|---|---|
| Initial Retrieval | Scopus search using DRM and safety-related keywords | 1,506 |
| Database Filtering | Publication year (1997–2024), English language, journal articles | 1,094 |
| Screening | Removal of duplicate and non-relevant publications | 1,036 |
| Final Dataset | Records included in the bibliometric analysis | 1,036 |

Therefore, the three-stage filtering process ensures a systematic and comprehensive analysis of bibliometrics on dry reforming safety-related topics, as illustrated in Figure 1. Hence, a total of 1036 articles were identified through the final search string. The refinement process was used in the bibliometric analysis. Consequently, a total of 1036 articles were sourced from 81 countries/regions, 2,302 organisations, 239 sources, and 4,671 authors. Scopus was selected as the preferred database for this study because it provides broad coverage of journals in engineering, energy, catalysis, and process safety. This database also provides standardised bibliographic data suitable for use with VOSviewer software. Scopus has been widely used in bibliometrics due to its broad database coverage and citation indexing (Lam et al., 2023; Pranckutė, 2021). Nevertheless, it is acknowledged that the inclusion of other databases, such as Web of Science, Engineering Village, or Dimensions, may result in variations in publication counts, citation metrics, and collaboration networks due to differences in database coverage and indexing practices.

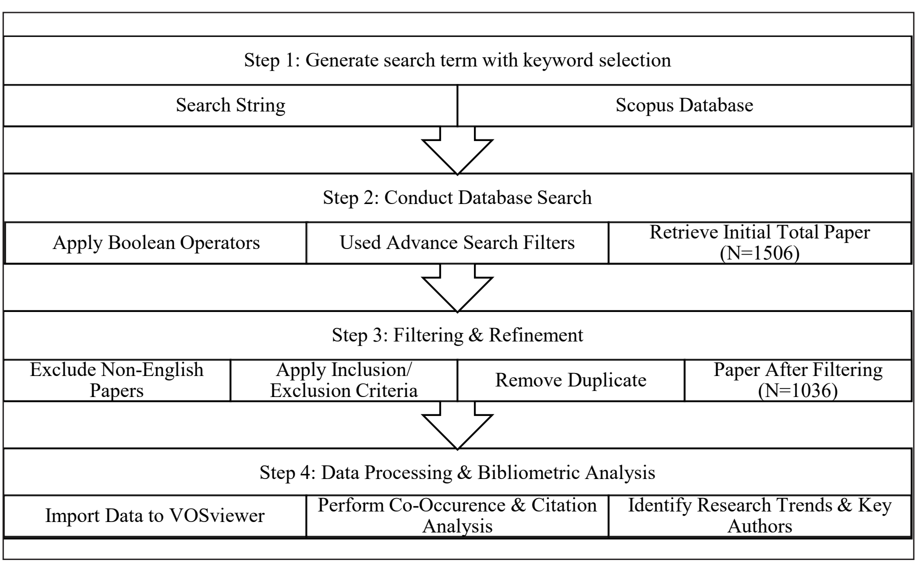


*Figure 1*. Search strategy and data refinement process for bibliometric analysis of safety-related DRM literature

## RESULT AND DISCUSSION

### Annual Publication Trend

The rapid growth of science and technology has significantly increased the volume of scientific knowledge. Scientific publication is crucial for disseminating knowledge. Hence, its evolution can indicate scientific improvement in many fields (Collivignarelli et al., 2020). The first published document in the reforming field was issued by Mleczko et al. (1997) from Germany, who proposed the reformer-combustor for $CO_2$ reforming of methane to achieve high yield and energy efficiency in synthesis gas production in 1997. In 2024, the total number of publications concerning dry reforming safety-related reached a historical peak of 170. Annual trends, cumulative data, and trends in global and major country publications are shown in Figure 2.

Between 1998 and 2021, 25 years, research publications on dry reforming safety-related have increased noticeably. The central active countries are China, the United States, Spain, the United Kingdom, and South Korea. Before 2010, research in this field was evenly distributed among all countries. After 2017, the number of Chinese publications on dry reforming safety-related issues increased sharply compared to other countries. The significant increase in dry reforming publications from China since 2017, as shown in Figure 2, is closely linked to the country's increased emphasis on utilising $CO_2$ and implementing low-carbon industrial transformation, as outlined in its national energy and climate strategies (Central Committee of the Communist Party of China, 2016). Dry reforming aligns well with these priorities by enabling the simultaneous conversion of syngas and $CO_2$, supported by increased government funding and strong institutional incentives for high-impact research results. Beginning in 2019, China has dominated publication output. There is a high prevalence of research institutions in China, which is related to the advancement of Chinese researchers and the volume of their publication output (Zhou & Leydesdorff, 2006; Zeng et al., 2020). Yet the increase in publications is mainly driven by the growth of research and by increasing interest in the field. It does not mean, however, that the impact of safety can be measured directly through publications.

Regarding the total number of publications per year, 2018 and 2022 saw the most significant increases compared to the previous year, with increases of 31% and 53%, respectively. Safety-related DRM research has not progressed at the same pace as catalyst and reactor development for industrial applications. Active and durable catalysts have been recently developed, and newly designed reactors have accelerated the commercialisation of dry reforming technologies. Recent advances in syngas production have been widely recognised as significant contributions to sustainable process development. Consequently, the number of publications related to safety in syngas production technologies has increased significantly since 2020.

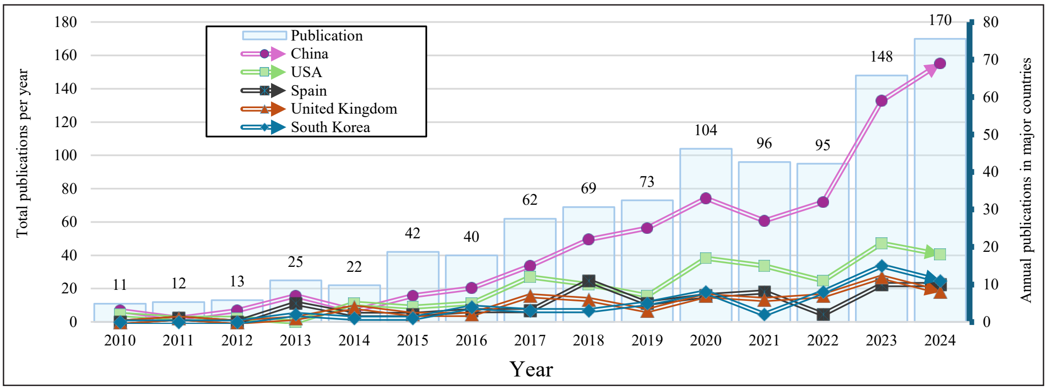


*Figure 2.* Annual trends in global and major country safety-related DRM publications

## Source Journal Analysis

An academic journal is a peer-reviewed publication. Academic journals are the means of disseminating information from intellectual research. Most cases comprise research papers, review articles, short communications, and book reviews 49. A search on Scopus yields 1,036 publications published in 239 journals. Table 4 summarises the top 15 source journals, ranking by the number of publications in dry reforming safety-related. International Journal of Hydrogen Energy (IJHE) leads by a mile with 110 article publications. Chemical Engineering Journal (CEJ) is the most recent in the above list, with an average publication year of 2021.32. The highest average citation is Applied Catalysis B: Environmental (ACBE) at 81.09. According to the result, in terms of the CiteScore 2024, there were 8 journals with an average CiteScore above 10. Although placed fifth in the list, ACBE secured the highest CiteScore at 37.3 compared to other journals. The journal with the lowest CiteScore was Industrial and Engineering Chemistry Research (6.5). This may be attributed to its specialised focus, which restricts its audience, or the presence of other journals in the field that garner greater attention and citations. The journal's scope may not consistently correspond with emerging high-impact research areas, potentially leading to a lower citation rate relative to more widely influential publications. The CJE has not been indexed in Scopus since 1993. Some researchers utilise CiteScore as a metric to assess the annual readership of a journal. CiteScore is vital to authors in their decision of where to publish. CiteScore is a substitute for the Clarivate Analytics Impact Factor, which measures a journal's impact from citation data within the Scopus database. While CiteScore is useful, it should not be used to decide on a journal. Considering all factors aside from the CiteScore, what matters is the journal's contribution towards reaching the right audience and advancing the discipline (Shaifudin et al., 2022).

Table 4

*The top 15 most productive journals on various research with their most cited articles from 1998 to 2024*

| Rank | Journal | NP | TP (%) | TC | CiteScore (2024) | APY | AC | Publisher |
|---|---|---|---|---|---|---|---|---|
| 1 | International Journal of Hydrogen Energy | 110 | 10.62 | 3030 | 12.8 | 2019.13 | 27.55 | Elsevier |
| 2 | Chemical Engineering Journal | 50 | 4.83 | 1139 | 19.6 | 2021.32 | 22.78 | Elsevier |
| 3 | Fuel | 42 | 4.05 | 1124 | 13.8 | 2020.52 | 26.76 | Elsevier |
| 4 | Industrial and Engineering Chemistry Research | 34 | 3.28 | 1031 | 6.5 | 2015.53 | 30.32 | American Chemical Society |
| 5 | Applied Catalysis B: Environmental | 33 | 3.19 | 2676 | 37.3 | 2017.24 | 81.09 | Elsevier |
| 6 | Applied Catalysis A: General | 31 | 2.99 | 1484 | 8.3 | 2015.52 | 47.87 | Elsevier |
| 7 | Catalysis Today | 30 | 2.90 | 1141 | 10.9 | 2019.47 | 38.03 | Elsevier |
| 8 | Catalysts | 29 | 2.80 | 2189 | 7.4 | 2020.48 | 11.03 | Multidisciplinary Digital Publishing Institute (MDPI) |
| 9 | Journal of CO2 Utilization | 25 | 2.41 | 894 | 14.7 | 2020.28 | 35.76 | Elsevier |
| 10 | Catalysis Science and Technology | 21 | 2.03 | 540 | 8.0 | 2018.81 | 25.71 | Royal Society of Chemistry |
| 11 | ACS Catalysis | 19 | 1.83 | 616 | 19.0 | 2020.75 | 38.50 | American Chemical Society |
| 12 | Chemical Engineering Science | 18 | 1.74 | 527 | 7.6 | 2017.06 | 29.28 | Scopus |
| 13 | Fuel Processing Technology | 17 | 1.64 | 430 | 16.6 | 2018.35 | 25.29 | Elsevier |
| 14 | Energy and Fuels | 16 | 1.54 | 321 | 9.3 | 2019.44 | 20.06 | American Chemical Society |
| 15 | Energy Conversion and Management | 14 | 1.35 | 532 | 19.0 | 2020.64 | 39.43 | Elsevier |

*Note.* NP: Number of publications; TP: Total publications; TC: Total citations; APY: Average publication year; AC: Average citations per document

## Quantitative Analysis of Productive Countries/Regions

A quantitative analysis of productive countries/regions can help researchers and institutions identify those with significant recent achievements in a particular research field. The geographical information of the corresponding authors in the 1036 publications shows that this safety-related DRM research is distributed in 81 countries/regions.

Table 5 lists the top 10 productive countries/regions, including the USA from North America, China, South Korea, India, Japan, and the United Arab Emirates from Asia, as well as the UK, Germany, Italy, and Spain from Europe. China produced a total of 322 publications, far more than any other country. This is credited to factors related to job titles and publications, government incentives, and the greater number of researchers. Spain has the largest AC of 47.12 and the most advanced APY of 2018.39, indicating the deepest research cumulation in dry reforming safety-related. This implies that the measures of publication productivity and research influence should be viewed independently. Even though China leads all other countries in the publication numbers concerning safety-related DRM research, using citation-based measures, there exist several countries that have relatively more research influence than their publications would imply. Consequently, publication productivity as well as citation-based measures need to be taken into consideration.

Table 5
*The top 10 countries and academic institutions that publish the most various publications*


| Rank | Country | Continent | Publications | SCP (%) | AC | APY | TLS | TPI | The Most Productive Academic Institution |
|---|---|---|---|---|---|---|---|---|---|
| 1 | China | Asia | 322 | 71.74 | 26.56 | 2020.39 | 88 | 40 | University of Chinese Academy of Sciences |
| 2 | United States | North America | 139 | 46.04 | 31.02 | 2018.96 | 74 | 14 | Texas A&M University |
| 3 | Spain | Europe | 74 | 45.95 | 47.12 | 2018.39 | 40 | 14 | Universidad De Zaragoza |
| 4 | United Kingdom | Europe | 71 | 19.72 | 35.18 | 2018.61 | 57 | 10 | Imperial College London |
| 5 | South Korea | Asia | 67 | 19.40 | 14.79 | 2019.93 | 25 | 7 | Hanyang University |

Table 5 (*continued*)

| Rank | Country | Continent | Publications | SCP (%) | AC | APY | TLS | TPI | The Most Productive Academic Institution |
|---|---|---|---|---|---|---|---|---|---|
| 6 | Germany | Europe | 59 | 37.29 | 30.97 | 2018.34 | 28 | 6 | Ruhr-University Bochum |
| 7 | United Arab Emirates | Asia | 54 | 16.67 | 20.63 | 2018.63 | 31 | 15 | King Saud University |
| 8 | Italy | Europe | 48 | 47.92 | 35.27 | 2018.63 | 20 | 7 | Sapienza Università di Roma |
| 9 | Japan | Asia | 48 | 54.17 | 21.23 | 2018.79 | 22 | 6 | Kyushu University |
| 10 | India | Asia | 44 | 63.64 | 25.41 | 2020.95 | 16 | 6 | Birla Institute of Technology and Science |

*Note.* SCP: Single country publication; AC: Average citation; APY: Average publication year; TLS: Total link strength; TPI: Total publication academic institution

The USA and Germany, supported by world-class research centres and secure funding initiatives, are the major drivers of the industry, demonstrating their passion for safety research and green energy. South Korea and Japan, leaders in innovation in fuel processing technology, have had consistent production capabilities, showcasing their passion for catalyst manufacturing and process safety improvements. On the other hand, new hotspots, such as India and the United Arab Emirates, have displayed increased activity by highlighting their focus on advanced research in sustainable hydrogen production and $CO_2$ utilisation. While China has the largest number of publications, Spain's citation-weighted rate indicates an increased scholarly contribution, potentially due to its strong connection with top European universities and industry leaders. These findings indicate that while China leads in research volume, countries such as Spain and Germany contribute significantly to the foundational and high-impact studies in this domain. The geographical distribution of research efforts underscores the need for fostering international collaboration to advance safety frameworks in dry reforming. Strengthening cross-border partnerships can enhance knowledge exchange, promote technology transfer, and ensure a more comprehensive understanding of safety challenges. Future research should focus on bridging the gap between high-output countries and high-impact research institutions to establish globally recognised safety standards for industrial-scale dry reforming applications.

## Authors and Their Cooperation Network

Knowledge maps based on the author-co-author network illustrate international co-authorship patterns, major research groups, and leading contributors to dry reform in the safety area. Based on the Scopus dataset, a total of 4,671 authors from 1,036 publications were identified and formed 108 distinct collaboration groups. These clusters are generated using VOSviewer, based on co-authorship links, where the size of nodes represents the output of the publication, and the strength of the links reflects the intensity of the collaboration. The significance of the cluster was evaluated using a combination of quantitative and structural criteria, including cluster size (in terms of author number), total link strength, and the presence of highly productive and well-connected primary authors. Although many clusters were identified, most of them were small, weakly linked groups, indicating fragmentary and topical research efforts.

As a result, two clusters were classified as important, characterised by substantially greater membership, stronger internal collaboration, and sustained research productivity. These two dominant clusters, referred to as clusters 1 and 2, led by Bilbao Javier and Muhler Martin as shown in Figure 3, represent the most established and influential research groups in dry safety reform. The large number of independent clusters also indicates the absence of a globally integrated research network in this area, which can be attributed to the diversity of the technology reform and the wide range of safety-related challenges encountered by different research teams.

The team in cluster 1, led by Bilbao Javier, primarily focuses on the experimental development and simulation-based optimisation of advanced catalysts for hydrogen and syngas production through various reforming processes, including DRM and steam reforming of bio-oil and biomass volatiles (Santamaria et al., 2020a; Santamaria et al., 2020b). Nickel (Ni) and Rhodium (Rh) are used for synthesising catalysts that are doped with various promoters, such as Cerium Oxide ($CeO_2$), Magnesium Oxide (MgO), Calcium (Ca), and Lanthanum Oxide ($La_2O_3$), and supported on Aluminium oxide ($Al_2O_3$), Silicon Dioxide ($SiO_2$), and FeCrAl-fibre materials. X-ray diffraction (XRD), scanning electron microscopy (SEM/TEM), BET surface area, and transverse phase polarisation (TPR/TPO) are employed as the sophisticated characterisation methods for the evaluation of the structural and chemical properties of the catalysts in single cluster 1 research (Dang et al., 2021; Ferrandon et al., 2022; Valecillos et al., 2024). It applies reaction kinetics, density functional theory, and computational fluid dynamics for the reaction process, heat and mass transfer, and process optimisation (Martinez-Hernandez et al., 2024). The models can estimate the performance impact by varying catalyst composition and reactor conditions, allowing for stable and efficient system design. Under controlled high-temperature environments, performance testing is conducted to quantify stability, catalytic activity, and coke resistance. Gas chromatography measures product gases, including water, carbon monoxide, and methane (Liu et al., 2023; Vicente et al., 2014).

Moreover, numerous research works focus on different methods involving biogas synthesis to diesel by Fischer-Tropsch catalysts, methanol synthesis from steel mill off-gases, and partial methane oxidation (Mhadeshwar et al., 2007; Jiang et al., 2023). This study utilises industrial exhaust, alternative fuels, and extended chemical production targets beyond syngas and hydrogen. Reactor level performance evaluation, analysing yields of products like syngas, diesel, or methanol, and catalytic lifetime at challenging feedstocks like biogas or steel mill gases. These publications strongly emphasise the integration of innovative, safer catalyst design with broad mechanistic investigations that address the challenge of sustainability and enhance energy and chemical production conversion processes (He et al., 2020).

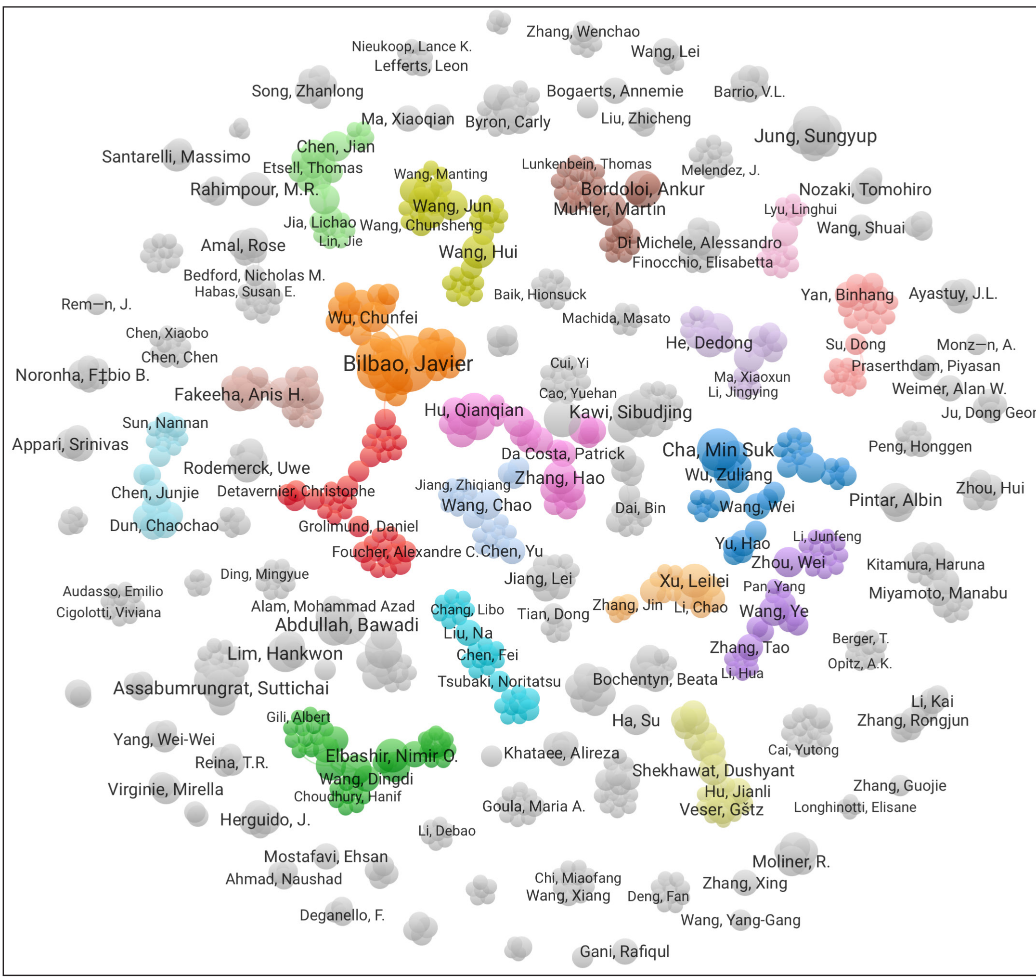


*Figure 3.* Overall author cooperation network of research on safety-related dry reforming

The second cluster, directed by Muhler Martin, exhibits notable similarities in its emphasis on developing new catalyst systems and comprehending their performance in high-temperature, energy-intensive processes. A key focus in these investigations is the development of high-performance catalysts that exhibit improved stability, activity, and resistance to deactivation. Catalytically active materials, such as Gadolinium-Ruthenium (Gd-Ru) nanoparticles on Zirconium-Cerium (Zr-Ce) nanorods, Nickel-based systems, and solution combustion-synthesised nanoalloys, are assessed for their performance under various operating conditions, including high temperatures and the presence of contaminants (Mette et al., 2016). Material design and nanostructure incorporation into support systems in alloys and modifications are vital aspects for maximising catalytic performance and stability at industrially feasible conditions (Das et al., 2021; Gazi et al., 2024). A second area is the application of in-situ and advanced characterisation techniques to investigate the activity of the catalyst in actual operating conditions. Particle dynamics and deactivation mechanisms, such as coke deposition, metal sintering, and poisoning by impurities, like steel mill off gases, are investigated using X-ray microscopy and spectroscopic techniques. (Beheshti Askari et al., 2020). In addition to researching cooperation patterns, clusters of authors identified have contributed to several important developments in safety-related DRM and scale-up, including enhancing catalyst stability, reducing carbon deposits, improving sulphur poisoning resistance, and optimising the design of reactors. These developments are important to reduce process instability, mitigate carbon-related operational problems, reduce hotspot formation, and improve the long-term reliability of industrial-scale DRM systems.

Table 6 shows the information on the top 10 authors with more than six publications. This table shows that three authors are from Spain, and one author is from the United Arab Emirates, South Korea, Malaysia, Singapore, Thailand, the United Kingdom, and Vietnam. While China leads in the total number of publications on the safety of dry reforming, it is remarkable that no Chinese authors feature among the top 10 most productive or highly cited authors. This may be due to several factors, not least of which is the popularity of long-list collaborations, in which Chinese researchers often take middle positions that limit individual recognition. This will lower the general citation impact of any researcher compared to the focus on specialised fields (Demeter et al., 2025). Citation metrics and journal visibility further extend this deficit, as many Chinese-authored articles were published in regional or lower-impact journals, which may lower their international reach and citation potential. These findings highlight a shortcoming of existing bibliometric studies, which often overlook the fine points of an author's contribution and the interaction among collaborators.

Table 6
*List of the most prolific authors related to the study*

| Rank | Author | Country | Total Publication | TC | AC | APY | TLS |
|---|---|---|---|---|---|---|---|
| 1 | Bilbao, Javier | Spain | 14 | 975 | 69.6 | 2018.8 | 54 |
| 2 | Gayubo, Ana G. | Spain | 8 | 646 | 80.8 | 2017.9 | 30 |
| 3 | Cha, Min Suk | United Arab Emirates | 8 | 215 | 26.9 | 2018.9 | 6 |
| 4 | Jung, Sungyup | South Korea | 7 | 82 | 11.7 | 2022.4 | 20 |
| 5 | Abdullah, Bawadi | Malaysia | 7 | 155 | 22.1 | 2021.4 | 15 |
| 6 | Kawi, Sibudjing | Singapore | 6 | 376 | 62.7 | 2020.7 | 22 |
| 7 | Remiro, Aingeru | Spain | 6 | 191 | 31.8 | 2020.2 | 22 |
| 8 | Assabumrungrat, Suttichai | Thailand | 6 | 146 | 24.3 | 2020.3 | 20 |
| 9 | Tu, Xin | United Kingdom | 6 | 407 | 67.8 | 2020.2 | 20 |
| 10 | Vo, Dai-Viet N. | Vietnam | 6 | 135 | 22.5 | 2021.2 | 20 |

*Note.* TC: Total citation; APY: Average publication year; AC: Average citation per document

Bibliometric analysis of leading authors in dry reforming and safety reveals that most highly cited works originate from Spain, with Javier Bilbao and Ana G. Gayubo as the leading contributors. First among them is Javier Bilbao, who has amassed an overall citation count of 975, emerging as a forceful researcher. He has a high average annual citation rate of 69.6 and is highly relevant and cited in the academic world. Thus, he has an academic influence spanning several years. Due to his consistently high citation rates, Bilbao is also recognised as a primary specialist in dry reforming research related to safety. Ana G. Gayubo from Spain ranks second, with 646 citations from 8 publications and excellent academic visibility. The research by Gayubo is from 2017 and represented one steady contribution to the field, presenting a critical part of the continuous investigation and mentioning the safety of dry reforming.

The data also reveal a significant representation from several countries. For instance, the UAE's Min Suk Cha and South Korea's Sungyup Jung, although having few publications, have contributed much to the field. Cha, on the other hand, with one publication and eight citations, exhibits a lesser impact in citation count yet shows promise for future research output. Sungyup Jung has made significant contributions over the last three years, as evidenced by seven publications and 82 citations, with an average publication year of 2022. His influence in the field is on the rise, as evidenced by his recent publications and citation data. International growth is enjoyed by Abdullah Bawadi of Malaysia, with seven publications and 155 citations, and Sibudjing Kawi of Singapore, with 6 publications and 376 citations.

The high citation counts for Kawi, combined with an average of 62.7 citations per year, underscore that his work is gaining increased momentum in the literature, especially in recent years, 2020 and 2021. Therefore, LS is part of this bibliometric research, which quantifies the network of co-authors and collaborations. High values of LS indicate that an author who is actively involved in the partnership for the diffusion and impact of their research can have a more significant impact. Ana G. Gayubo shows an LS of 30, which is very high, with a notable degree of multidisciplinary in several research projects she has participated in. Kawi has 22 TLS, which would disclose a collaboration strategy that extends the scope of his work. Other authors, such as Aingeru Remiro from Spain with 22 LS, Assabumrungrat from Thailand with 20 LS, and Xin Tu from the UK with 20 LS, are highly collaborative, which speaks in many instances to the prestige among scholars and the integration of their contributions within a broader academic community. These researchers, although somewhat fewer overall in citations or less in several publications, supplement this developing network of scholars in dry reformation and safety.

This bibliometric analysis highlights the leading role played by Spanish scholars Bilbao and Gayubo, as well as the increasing international contributions from primarily Southeast Asia and the Middle East. The steady rise in APY values for many authors, combined with their increasing total citations and LS, reflects an increased emphasis on dry reforming and safety in recent years, as young authors begin to be recognised. Safety in dry reforming represents an active domain of investigation. At the same time, it is undergoing continuous development and is characterised by robust international cooperation and a pronounced focus on the growing importance of this research in the years to come.

## Identification of Research Themes

Compared to previous library studies that focused primarily on catalyst development, hydrogen production and thermodynamic optimisation, this study emphasises the integration of process safety and inherent safety considerations into DRM research trends. This allows to interpret the identified research clusters from both a technological point of view and from the point of view of industrial safety and operational reliability. Keywords represent a basic summary of publications, and high-frequency keyword analysis is a common approach to identifying hot topics and themes in research areas (Lan et al., 2022). This paper analysed all keywords, including author keywords. Before analysis, singular and plural forms of words are reduced to the singular. Hence, "catalyst" and "catalysts" are reduced to "catalyst", and "kinetics" is reduced to "kinetic." Keywords with related terms are combined into one phrase each, as shown, for example, the words "DRM," "dry reforming," and "methane reforming" are combined into "dry reforming of methane."

The threshold value of keyword occurrence frequency was set to 5, and 134 keywords were identified. The sensitivity assessment was carried out using keyword occurrence thresholds of 3, 5, 7, 8 and 10. Lower thresholds create a larger number of low-frequency keywords, creating fragments and fewer interpreted groups. In contrast, higher thresholds reduced thematic coverage by excluding many relevant keywords associated with safety-related DRM research. The threshold of five occurrences was therefore chosen because it ensured the most balanced representation of the research landscape while maintaining the clarity and interpretability of clusters. The resulting network identified four clusters. Figure 4 illustrates the four identified clusters, labelled as Cluster 1 (red), Cluster 2 (green), Cluster 3 (blue), and Cluster 4 (orange). These four clusters contain 40, 27, 51, and 16 keywords, respectively, whose central keywords and the relevant LS are sorted in Table 7.

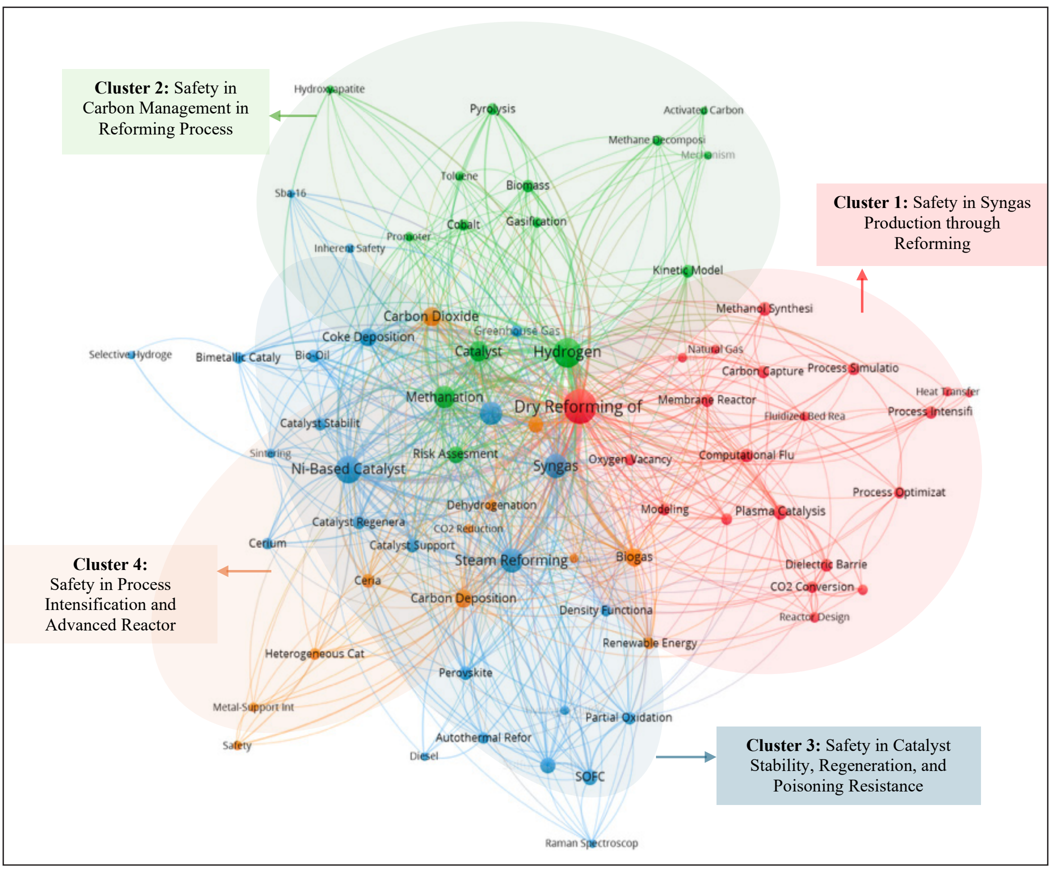


*Figure 4.* Distribution of co-occurrence network clusters for safety-related dry reforming publications keywords

Table 7
*Top 10 keywords in each co-occurrence network cluster according to total link strength in safety-related dry reforming publications*

| **Cluster 1: Safety in Syngas Production Through Reforming** | | **Cluster 2: Safety in Carbon Management in Reforming Process** | | **Cluster 3: Safety in Catalyst Stability, Regeneration, and Poisoning Resistance** | | **Cluster 4: Safety in Process Intensification and Advanced Reactor Design** | |
|---|---|---|---|---|---|---|---|
| Dry Reforming of Methane | 467 | Hydrogen | 298 | Ni-based Catalyst | 269 | Carbon Dioxide | 111 |
| Plasma Catalysis | 39 | Methanation | 152 | Syngas | 192 | Biogas | 99 |
| Dielectric Barrier Discharge | 31 | Catalyst | 103 | Steam Reforming | 191 | Carbon Deposition | 64 |
| Computational Fluid Dynamics | 26 | Risk Assessment | 61 | Catalyst Deactivation | 158 | Coke Resistance | 48 |
| Modelling | 26 | Cobalt | 37 | Coke Deposition | 96 | Ceria | 39 |
| Chemical Looping | 24 | Biomass | 30 | Sulphur Poisoning | 50 | Renewable Energy | 20 |
| Membrane Reactor | 24 | Promoter | 25 | Catalyst Regeneration | 49 | Dehydrogenation | 18 |
| CO2 Conversion | 20 | Pyrolysis | 25 | Bio-Oil | 39 | Heterogeneous Catalysis | 16 |
| Carbon Capture | 18 | Gasification | 22 | Catalyst Support | 39 | Safety | 11 |
| Fluidised Bed Reactor | 18 | Kinetic Model | 22 | Perovskite | 38 | Ethylene | 10 |

The bibliometric analysis resulted in several distinct research clusters in dry reforming of methane (DRM) that can be systematically mapped to safety-relevant aspects, thereby clarifying their practical implications for inherently safer process design. These clusters extend beyond descriptive research trends and demonstrate direct relevance to industrial safety standards, reactor design, and catalyst management strategies. In particular, the catalyst-related clusters are closely associated with risks of catalyst deactivation, sintering, and carbon deposition. Reactor-oriented clusters emphasise temperature management, heat removal, and pressure control, while clusters related to process integration and operation align with established safety engineering frameworks such as ISO 45001, API 521, and conventional HAZID/HAZOP methodologies. Table 8 summarises the explicit mapping between bibliometric clusters, corresponding safety principles, and their operational implications, illustrating how bibliometric insights can be translated into actionable guidance for safer DRM systems.

Table 8
*Mapping of bibliometric clusters to safety themes, dominant hazards, and relevant safety engineering frameworks*

| Cluster | Theme | Dominant Research Topics | Safety Issues Identified | Representative Safety Framework |
|---|---|---|---|---|
| Cluster 1 | Safety in Syngas Production Through Reforming | Reactor performance, catalyst activity, syngas generation | Hotspots, thermal instability, and CO handling | HAZOP/ Process Safety Management |
| Cluster 2 | Safety of Carbon Management in Reforming | Carbon deposition, catalyst deactivation | Reactor blockage, pressure rise, loss of flow distribution | HAZID |
| Cluster 3 | Safety of Catalyst Stability and Regeneration | Coking, sulphur poisoning, catalyst regeneration | Process instability, regeneration hazards | HAZOP |
| Cluster 4 | Safety in Process Intensification and Advanced Reactor Design | Advanced reactors, heat transfer enhancement | Overpressure, thermal stress, and equipment integrity | API 521 |

*Note.* Adapted from (Hendershot, 2012; Omran et al., 2020; Usman et al., 2015)

The four clusters are categorised into four themes according to the publications where these keywords are found and related to the safety of dry reforming. Cluster 1 theme is "Safety in Syngas Production through Reforming", and it addresses the optimisation of the reforming process, catalysis, and reactor design for safe and efficient syngas production (Cherif et al., 2022). It also addresses several safety aspects, including reactor stability and catalyst performance, as well as environmental concerns (Zhao et al., 2024; Li et al., 2019). Cluster 1 emphasises $CO_2$ recycling and the ecological aspects of methanol production. Safety and environmental analyses are incorporated into syngas production processes through modelling, simulation, and optimisation, which are essential for safe and efficient catalytic reactions in reforming (Gyanwali et al., 2023; Saqline et al., 2021).

Cluster 2 is on the Safety of Carbon Management in the Reforming Process. This leads to a focus on carbon deposition and catalyst deactivation. Various studies have identified the stability of the catalyst and prevention of carbon deposition as key safety issues in the catalytic reforming process (Kim et al., 2024). Many studies have focused on methane and hydrogen production through various catalytic techniques that optimise reaction protection and process efficiency (Durán et al., 2023; Hondo et al., 2023; Valle et al., 2013)). Multiple reviews are available that assess the environmental and economic aspects of catalytic processes, often including safety analyses of the manufacturing systems. (Liu et al., 2023). The research in this cluster also focuses on catalyst deactivation and carbon deposition, which are two of the most persistent challenges in DRM systems (Boscherini et al., 2023).

In addition to reducing catalytic performance, excessive carbon accumulation may lead to reactor blockages, increased pressure dropped and formation of local hotspots, which may affect equipment integrity and process stability (Dannesboe et al., 2020). As a result, strategies aimed at mitigated formation of coke and catalyst deactivation not only improve process efficiency but also contribute to safer and more reliable DRM operations.

Cluster 3 is on the Safety of Catalyst Stability, Regeneration, and Poisoning Resistance. The stability, deactivation mechanism, and performance optimisation of various catalysts in several reforming and hydrogenation processes have been investigated. This work presents and discusses the following challenges, such as coking problems, sulphur poisoning, and catalyst regeneration, which are essential challenges that must be considered while developing long-term stability and safety for catalytic reforming processes. Some articles dwell on deactivation mechanisms, such as sulphur poisoning and coke formation, and restoration methods or ways of preventing losses in catalysts' activity (Naidu et al., 2022; Li et al., 2021). Featured is the stability of the catalyst in reforming and hydrogenation processes for effectiveness and safety during operations, which is the subject of many papers. (Li et al., 2021; Shao et al., 2023). Various works investigate ways to decrease coke formation, a critical problem for maintaining catalyst activity in dry reforming processes. (Manavi & Liu, 2023). In addition to causing problems related to catalysts, sulphur poisoning and catalyst degradation could also lead to process instability and deviation from normal operating conditions (Yuan et al., 2023; Li et al., 2024). Effective catalyst regeneration and poisoning resistance, therefore, play an important role not only in maintaining catalyst activity and longevity but also in supporting the safe and stable operation of DRM systems (Pham Minh et al., 2021).

Cluster 4 focuses on Safety in Process Intensification and Advanced Reactor Design. Process intensification, advanced reactor design, and optimisation of catalysts are repeatedly mentioned throughout the studies to improve operational safety and minimise the risk. Research on core-shell nanostructured catalysts, perovskite-modified catalysts, and strong metal-support interactions suggests the development of advanced reactors and catalysts that can perform effectively and safely at high temperatures and pressures (Ahmad et al., 2022, Duma et al., 2024; Yang et al., 2022). A trickle bed reactor and porous crystalline catalysts ensure better heat and mass transfer and reduce potential hazards. A few quantitative risk assessment literature reviews focus on process safety and the strategy for amine-based $CO_2$ capture, related to mitigating risks in industrial-scale operations (Aliyu, 2024). Some findings from chemical kinetic modelling in related studies suggest its role in forecasting and mitigating probable hazardous reactions to enhance reactor design safety (Kanayama et al., 2024). Compared to other technologies, this theme is more advanced. These four themes were categorised into the circle of the co-occurrence matrix based on safety-related DRM research that could give clarity among researchers unfamiliar with the area and external investors about the research framework.

Some identified research clusters also demonstrate the relevance of designing DRM systems using an intrinsically safer design principle (ISD). Catalyst optimisation studies help to develop substitution and moderation strategies by allowing lower temperature operation and reducing carbon deposition trends. Process intensification and advanced reactor configurations support the principle of simplification and minimisation, reducing equipment inventory, improving heat transfer efficiency and reducing operational instability. In addition, hazards classification methods, DRM process risk mapping and inherent safety indicators can provide a systematic approach to assessing operational risks related to reactor temperature, pressure changes, toxic gas formation and catalytic degradation. These approaches are still relatively little explored in the DRM literature and are important directions for future research aimed at safety as shown in Table 8.

Identified bibliographic clusters can be interpreted in a broader context of process safety management and inherently safer design (ISD). In this study, research themes were mapped to safety frameworks based on the dominant keywords identified in Table 6 and the dominant research themes discussed in representative publications associated with each cluster. For example, keywords such as carbon deposition, catalyst deactivation, sulphur poisoning and risk assessment were used to determine the link between specific clusters and related safety considerations. The principles of inherently safer design refer to strategies to reduce risks at the source through minimisation, substitution, moderation and simplification. Support frameworks such as HAZID and HAZOP facilitate the systematic identification and assessment of hazards during the operation and expansion of DRM, while API 521 provides guidelines for thermal protection systems (Jafarian et al., 2023). Therefore, these frameworks are discussed as a relevant safety perspective for interpreting DRM research trends, rather than the methodology explicitly applied to each analysed publication.

The application of inherently safer design (ISD) principles in DRM systems can be achieved through several practical approaches. Minimisation may be achieved by reducing combustible gas inventory in the process, while substitution can involve using coke-resistant catalysts to reduce carbon deposition and catalyst degradation (Athar et al., 2022). Moderation may be achieved through improved temperature-control strategies to limit hotspot formation and thermal stress, whereas simplification can be promoted through reactor designs with improved heat distribution and reduced operational complexity (Hendershot, 2012). Collectively, these measures contribute to safer and more reliable DRM operation while supporting process efficiency and equipment integrity.

## Evolution of Keywords

Various elements can reflect the development of a field, and keywords are key elements that indicate the evolution of research hotspots and scale within a field over time (Tan et al., 2021). This evolution shows that “catalyst” has the highest frequency in all the years in this safety-related DRM research from 2013 to 2024, with the highest frequencies in 2023 and 2024, at 75 and 113, respectively. The keywords “hydrogen” and “methanation” rank second over the past 10 years, with the highest number, 74, recorded in 2024. “Ni-Based Catalyst” occurs most frequently in 2023 and 2024, with 30 and 47 occurrences, respectively. This is because most of the publications in 2023 (Dong et al., 2023; Wajahat ul Hasnain et al., 2023) and 2024 (Li et al., 2024; Lin et al., 2024) focus on the safety of catalyst stability, regeneration, and poisoning resistance in the dry reforming process. Safety is an immediate concern for the development of dry reforming processes. The terms "catalyst deactivation" and "coke deposition" track over time, along with the "risk assessment", reflect much of the present work being directed at resolving issues in catalyst stability and longevity concerns, as well as possible process safety. This tendency is characterised by a growing awareness of the risk assessment in dry reforming, particularly its operational reliability, environmental impact, and compensation options. Nevertheless, the integration of systems thinking into assessment approaches remains insignificant, illustrating the need for increased scientific study that examines issues of safety in conjunction with catalytic functionality. Furthermore, despite a greater focus on catalyst stability, there is a critical dearth of studies that comprehensively examine the risk factors affecting the overall dry reforming process, such as feedstock variability and reactor performance during transient conditions. Extensive system-wide studies of issues such as reactor heat removal, pressure control, and emergency shutdown systems should be included in process safety investigations alongside the catalysts' lifetime. Although DRM is an endothermic reaction, it operates at very high temperatures, and uneven heat supply can lead to local hot spots or cold spots, which can accelerate undesirable side reactions, carbon deposits, or catalyst sintering. These thermal gradients also impose mechanical constraints on the reactor, increasing the risk of secondary escape reactions and making heat removal and distribution a critical safety consideration. No work has been done to investigate the use of safety design to minimise unwanted side reactions and runaway reactions. Real-time monitoring and predictive analysis are likely to minimise major safety hazards, but most research employs traditional, conventional risk assessment methods.

Despite being commonly regarded as an eco-friendly process for $CO_2$ utilisation, dry reforming yields undesirable byproducts, such as carbon monoxide and higher hydrocarbons. Those generate extra concern about environmental issues. If improperly managed, these byproducts may lead to equipment fouling, increased maintenance needs, and potentially harmful emissions. Future studies can investigate new process control technologies, including AI-driven safety monitoring systems, machine learning-based failure prediction, and adaptive reactor systems that can dynamically adapt to various operating scenarios (Osarogiagbon et al., 2021). Among the essential concerns is the limited number of research works on large-scale industrial applications of dry reforming under realistic operation conditions.

Many works emphasise the importance of small-scale experiments, which can be inadequate in addressing the safety issues of industrial applications. Scaling up dry reforming from small to industrial scale requires intensive hazard evaluation, lifecycle safety estimation, and pilot-scale demonstration for verifying the efficacy of safety measures under actual operating conditions (Bachmann et al., 2023). Resolving these deficiencies will make dry reforming a long-term, sustainable, and industrially feasible process. Future research should prioritise catalyst performance and place significant emphasis on comprehensive safety evaluations, encompassing fundamental safety concepts, advanced risk assessment techniques, and real-time monitoring technologies, to maximise both process safety and efficiency. By applying a multidisciplinary framework that incorporates chemical engineering, safety science, and data technologies, researchers and industry stakeholders can advocate for a more secure and robust application of dry reforming in industrial hydrogen and syngas production.

## CONCLUSION

This study provides a comprehensive bibliometric overview of safety-related themes within the dry reforming of methane (DRM) research landscape. In general, it demonstrates that active challenges to industrialisation concern the catalysts' deactivation, carbon deposition, and process stability. The primary safety concerns remain related to operations at high temperatures, the integrity of the reactors, and the hazards associated with carbon formation. Researchers focus on catalyst design, reactor optimisation, and process control strategies as the most important domains for improving performance and ensuring safety. This knowledge gap needs to be addressed to pave the way for the safer industrial application of dry reforming. Future studies should develop risk assessment models for dry reforming processes that systematically outline all possible hazards. Principles of safety in catalyst and reactor design should focus on minimising the risks associated with high-temperature operation and material degradation. Therefore, future work should investigate critical operational risks such as catalyst deactivation, coke formation, and thermal runaway to develop a more robust process with high stability for long-term performance. Safety-driven approaches can be combined to enhance the reliability and sustainability of dry-reforming technologies. Such efforts should include measurable process indicators relevant for DRM operation, including reactor temperature gradients for hotspot detection, pressure drop as an indicator of carbon deposits and blockages, carbon monoxide concentrations for toxic gas monitoring, loss of catalyst activity and coke growth trends as indicators of catalyst degradation and long-term operating stability. The integration of these variables with predictive analysis can improve early warning of hazards and support safer industrial DRM operations. Although the current study is based mainly on Scopus-indexed peer-reviewed academic publications, future safety assessments of DRM systems may benefit from the inclusion of complementary sources such as pilot studies, industrial reports, patents, and process safety incident databases. These sources can provide additional insights into operational challenges, equipment reliability, scale-up considerations and safety incidents in the real world that are not always recorded in academic literature. Integration of scientific and industrial evidence can therefore strengthen future safety-related DRM assessments and support safer commercialisation pathways.

Within the coming five years, research related to the safety of DRMs needs to go beyond just being conducted using bibliometrics to the extent of being verified at a pilot scale and ultimately applied industrially. Some aspects to which research attention needs to be devoted include establishing DRM hazard databases that are standardised, validating safety indicators for pilot-scale operation, installing predictive safety monitoring systems and incorporating inherently safer design concepts in reactor scaling up. Stronger collaboration between academia and industry will also be essential to translate research findings into reliable and commercially viable DRM technologies.

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