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A bibliometric review of hydrogen storage and transportation safety research

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ABSTRACT

Rising concerns over carbon emissions from fossil fuels have fueled interest in renewable energies. Hydrogen, as a clean energy source, stands out for its free of pollution and high calorific value. However, challenges in safely storing and transporting hydrogen, such as embrittlement, fire and explosion risks, are critical. This study reviews hydrogen storage and transportation safety research through a bibliometric approach, analyzing 948 relevant publications obtained from the Web of Science Core Collection, SCOPUS, and Science Direct literature databases since 2007. Then, a bibliometric analysis is conducted to obtain the publication's distribution, organization, source, and cooperation networks. Besides, the research hotspots in different periods are identified, and the evolution trend of hot topics is analyzed. Moreover, this paper proposes the possible future research needs in this field. The main hot topics in the field of hydrogen storage and transportation safety research include microstructure, crack, susceptibility, and hydrogen embrittlement and they change over time. In the future, research topics such as hydrogen damage in materials, compatibility of hydrogen in natural gas pipelines, and risk assessment should obtain more attention.

1. Introduction

With the continuous growth in energy demand, the world increasingly focuses on the development and utilization of new energy. The non-renewable nature of fossil fuels such as oil and gas, as well as the environmental pollution caused by the massive use of these fuels, makes the development and utilization of cleaner energy the top priority at present (Midilli and Dincer, 2008; Peng et al., 2023). As a result, hydrogen becomes one of the outstanding green energy alternatives to fossil fuels since it has many advantages, such as energy saving, clean, and renewable, becoming one of the outstanding green energy alternatives to fossil fuels. Emissions Gap Report shows that countries reported new and updated climate pledges that cut their annual greenhouse gas emissions by only 7.5% from the original projections for 2030. The development of the hydrogen industry is a significant way to achieve The Paris Agreement's temperature control targets.

Although hydrogen has many advantages, its ability to embrittle metals and its inflammable and explosive characteristics lead to potential risks for hydrogen storage and transportation such as hydrogen leaks, fire, and explosion (Najjar, 2013; Basco et al., 2013; Carboni et al., 2022; Mo et al., 2024). For example, the hydrogen explosion accident in the Fukushima nuclear power plant (Song and Kim, 2014) and the "Hindenburg" air crash in Germany caused serious casualties, property losses, and environmental damage. These large accidents have aroused wide public concern around the world. Hydrogen safety is a significant prerequisite for the large-scale application and commercialization of hydrogen energy. Since the 21st century, various countries have been scrambling to introduce plans and policies for developing hydrogen technology, and governments have been increasing their support for hydrogen safety-related research. As a result, many research attempts on hydrogen storage and transportation safety are conducted and published in international journals.

Bibliometric analysis (Donthu et al., 2021) and visualization technology are effective means to explore the structure and evolution of a certain field. This method is widely used in various research fields, such as management (Fahimnia et al., 2015), medicine (Liao et al., 2018),

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tourism (Jiang et al., 2019), international entrepreneurship (Baier-Fuentes et al., 2018), to understand the general situation of hydrogen safety research around the world as soon as possible. And it intuitively and clearly shows the hot topics, development history and frontier trends of this research field. At present, no academics have applied this method in the research field of hydrogen safety.Moradi and Groth (2019) described hydrogen storage and transportation technologies, conducted reliability assessments and identified the needs and gaps in reliability efforts during hydrogen storage and transportation. Abohamzeh et al. (2021) summarized the application of hydrogen and its safety at all stages, focusing on a variety of previous computational fluid dynamics models that can predict hydrogen accidents in the system. Li et al. (2022) further studied the mechanism and model of hydrogen leakage, reviewing the safety problems of hydrogen from the perspective of hydrogen leakage and diffusion. Najjar (Najjar, 2013) reviewed the safety of hydrogen in the production, transportation, and use process, taking into account the inherent characteristics of hydrogen. Aziz (2021) analyzed the characteristics of liquid hydrogen and hydrogen liquefaction technology, reviewing the current situation and safety of the storage and transportation technology of hydrogen in liquid hydrogen form. Yang et al. (2021) calculated the data on hydrogen safety accidents from 1999 to 2019 and analyzed the key safety issues of hydrogen leakage, diffusion, ignition, and explosion in combination with the actual situation.

The current study reveals a dearth of literature utilizing bibliometric visualization methods in the investigation of hydrogen safety. Literature analysis provides an objective and comprehensive understanding of the development trends in hydrogen storage and transportation safety. To address this research gap, our study employs VOSviewer software to create visual maps illustrating keyword co-occurrence, author and institution collaboration, and the evolving trends in research topics within the Web of Science core database. This approach facilitates a quick and efficient grasp of the breakthroughs in the current hydrogen energy industry and economy, promoting advancements in hydrogen energy storage and transportation safety technology. Through visual analysis, our study aims to present an overview of research on the safety of hydrogen during storage and transportation. The research questions guiding this study are as follows: (i) What characterizes the distribution of publications, journal and country origins, and collaborative networks among institutions and authors? (ii) What are the evolving trends in research hotspots? (iii) What are the potential future development needs in hydrogen storage and transportation safety? Subsequent sections address these questions. Section 2 outlines the research methodology and database literature screening. Section 3 analyzes the bibliometric results, while Section 4 delves into the trends and evolution of research hotspots. Section 5 discusses potential future development needs, and Section 6 draws conclusions.

2. Methodology

This paper reviews the research on hydrogen safety based on the bibliometric analysis method, as shown in Fig. 1. The first step is to collect the bibliometric data from the Web of Science Core Collection, SCOPUS, and Science Direct literature databases on January 1, 2025. The retrieved pieces of literature span from 2007 to 2024, and the search results are 1227 bibliographic records. The search terms are as follows:

- Title: hydrogen;
- And title: safety OR risk OR failure OR explosion OR leak OR spill OR fire OR permeation OR crack* OR fatigue OR embrittlement;
- And Topic: storage OR transportation OR pipeline OR delivery.

The combination of search terms is defined to generate sufficient search results to ensure that the data sources of the bibliometric analysis are comprehensive and remain within the research scope specified in this paper. In the second step, data cleaning is performed. From all the

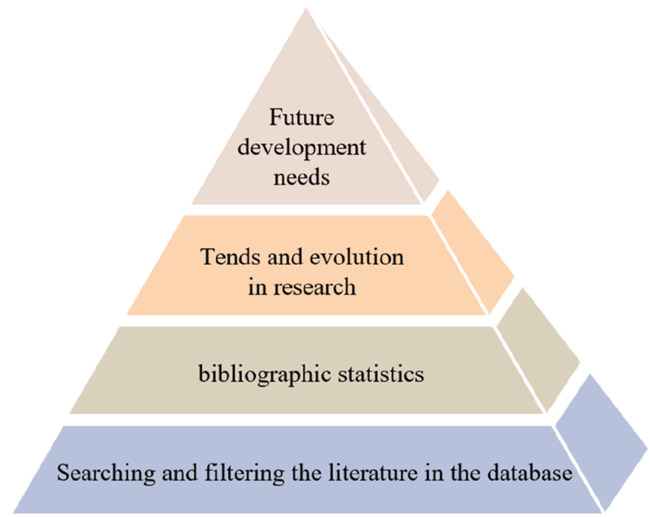

Fig. 1. Literature review methodology on the research related to hydrogen storage and transportation safety in Web of Science.

bibliographic records searched above, the title, abstract, and text of each document are checked to eliminate duplicate and incorrect entries, especially those that are not highly relevant to the field of hydrogen storage and transportation safety, such as research literature on hydrogen fuel cells and hydrogen production technology, to improve the usability of the search results. 948 publications are obtained as the research content of bibliometric analysis eventually. The third step is to use VOSviewer to carry out bibliometric analysis on the selected final database. Finally, according to the results of bibliometric analysis, the research trend and development of this field are explored, and the possible research needs in the future are discussed.

3. Bibliometric analysis

This section analyzes the publication production time, regional distribution, journal source distribution, and the distribution of the cooperation network with the support of VOSviewer software. This can be articulated through the following four aspects.

3.1. Annual publication distribution

According to the results of the literature database, the earliest literature closely related to the field of hydrogen storage and transportation safety was published in 2007 (Capelle et al., 2007), which is the reason that the start of the literature search period for this paper is set in 2007. There is a fluctuating upward trend in the number of related literature published from 2007 to 2024. The overall trend is shown in Fig. 2. The research on hydrogen storage and transportation safety has phases. Based on the number of published literature, it is possible to divide the history of hydrogen storage and transportation safety research into three main phases:

(i) Slow growth phase: The period before 2013 is classified as the first phase. In this phase, the literature on hydrogen storage and transportation safety shows a slow growth trend, with an annual number of publications of <30 and a total number of publications of <200. (ii) Stable growth phase: Classify 2013–2017 as the second phase. In this phase, the annual number of publications issued is around 40, showing a fluctuating slow upward trend. In addition, the research in the field of hydrogen storage and transportation safety is in a state of stable growth. (iii) Rapid development phase: it enters the rapid development stage after 2018. The annual number of publications on hydrogen storage and transportation safety exceeded 60, and the total number of publications exceeded 500, indicating that global attention to the research field of

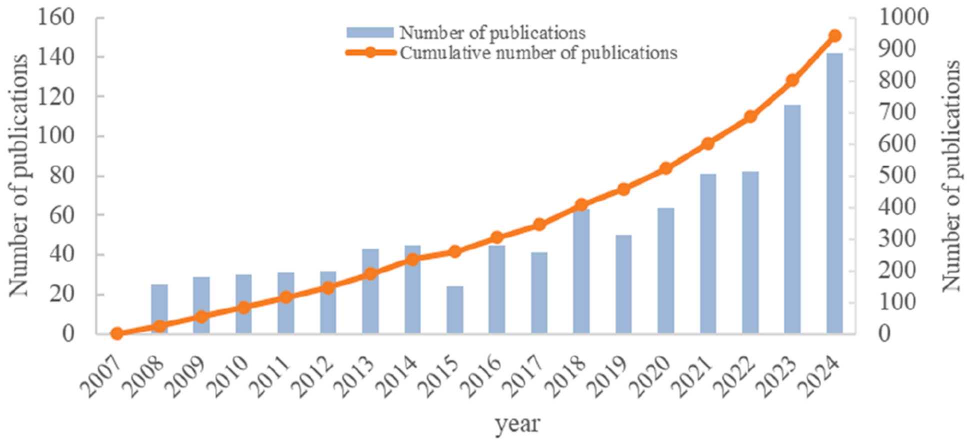

Fig. 2. Distribution of the annual on hydrogen storage and transportation safety in Web of Science.

hydrogen storage and transportation safety has been increasing.

The tri-phase evolution of publication volume is not arbitrary but mirrors the global trajectory of hydrogen energy development. The slow growth phase (pre-2013) coincides with the early, cautious exploration of hydrogen as an energy carrier, where safety research was nascent and often tied to specific, limited-scale demonstration projects. The stable growth phase (2013–2017) likely reflects the cumulative effect of sustained investment in renewable energy and early national hydrogen strategies, which gradually elevated the importance of supporting infrastructure safety. The rapid development phase (post-2018) exhibits a strong correlation with the global acceleration towards net-zero commitments. As hydrogen transitioned from a niche prospect to a cornerstone of many national decarbonization blueprints, the imperative to address the safety challenges of large-scale storage and transportation at scale became urgent, driving a surge in research output. This trend suggests that research activity in this field is highly responsive to policy and market drivers.

3.2. Regional distribution of publications

Analyzing the countries where the authors in the field of hydrogen storage and transportation safety are located can reflect the distribution of research power in this field to a certain extent. According to the database statistics, 66 countries or regions published relevant literature in the field of hydrogen storage and transportation safety. Among them, 34 countries publish >5 articles. China ranks first in this field with 292 publications. It is followed by the United States (105 articles), Canada (66 articles), South Korea, Italy, Japan, and France. In addition, the number of citations in different countries can indicate the quality of publications in each country to a certain extent. The results show that the five most cited countries are China (4298), Canada (2387), the United States (1825), France (994), and South Korea (892). Table 1 shows the specific number of publications and citations for the seven most productive countries in the relevant field, reflecting that the field of hydrogen storage and transportation safety is received extensive attention and research all over the world.

Table 1
Top-7 countries producing scientific research (number of publications and citations) in the field of hydrogen storage and transportation safety.

Country	Scientific papers	Citations
China	292	4298
USA	105	1825
Canada	66	2387
South Korea	60	892
Italy	50	589
Japan	49	858
France	46	994

3.3. Source distribution of publications

According to the database statistics, relevant papers in the field of hydrogen storage and transportation safety are published in 250 academic journals, of which 21 academic journals publish >5 papers. International Journal of Hydrogen Energy (IF5=7.7) with 247 publications and 5887 citations occupies a dominant position, followed by Corrosion Science (IF5=8.8), Materials Science and Engineering A-Structural Materials Properties Microstructure and Processing (IF5=7.0), and Engineering Failure Analysis (IF5=4.9). The three academic journals mentioned here all have over 30 publications related to hydrogen storage and transportation safety. It is worth mentioning that the total number of citations for articles in Corrosion Science (1373) and Materials Science and Engineering A-Structural Materials Properties Microstructure and Processing (1055) are much higher than the number of citations in Engineering Failure Analysis (491). This situation indicates that these two journals provide more valuable cutting-edge information for scholars studying the field of hydrogen storage and transportation safety. Table 2 shows the specific number of publications and citations for the top ten most active journals in the field of hydrogen storage and transportation safety.

The dominance of the International Journal of Hydrogen Energy reaffirms its status as the central interdisciplinary forum for hydrogen energy research, naturally capturing a significant share of safety-related work. The high ranking of Corrosion Science and Materials Science and Engineering A in terms of citations per publication highlights a critical insight: the core scientific challenge in hydrogen safety for storage and transportation is profoundly materials-centric. Hydrogen embrittlement, fatigue crack growth, and permeation are fundamentally materials degradation phenomena. The high citation impact of papers in

Table 2
Top-10 most active journals on hydrogen storage and transportation safety.

Journal	Scientific papers	Citations
International Journal of Hydrogen Energy	247	5887
Corrosion Science	35	1373
Materials Science and Engineering A-Structural Materials Properties -Microstructure and Processing	32	1055
Engineering Failure Analysis	32	491
Journal of Loss Prevention in the Process Industries	17	307
Engineering Fracture Mechanics	15	496
Energies	11	130
International journal of fatigue	10	275
Corrosion	9	66
Materials	9	64

these journals indicates that breakthroughs in understanding the micromechanisms of hydrogen-material interactions are highly valued and form the foundational knowledge driving the field. Engineering Failure Analysis and Journal of Loss Prevention represent the applied, systems-engineering side of safety research. This journal distribution reveals the field's dual pillars: advanced materials science and practical engineering integrity assessment, with the former currently generating higher citation-based influence.

3.4. Analysis of cooperative relationship network

To analyze the collaboration between different institutions and authors, we construct a visual collaboration network using VOSviewers software in this section, which can visually identify the influence of institutions and authors in the field of hydrogen storage and transportation safety. Different colors in the collaboration network represent different collaboration clusters. The nodes in the network represent research subjects, i.e., institutions or authors. The number of publications directly reflects the size of the nodes. The curves between the nodes represent the cooperation between the objects represented by the nodes, and the width of the curves depends on the frequency and closeness of the cooperation (Li et al., 2020).

3.4.1. Analysis of institution cooperation

Based on the statistical analysis of the number of institutions that have publications on hydrogen storage and transportation safety, a total of 883 institutions are identified. Among them, there are 15 institutions with >10 publications. Fig. 3 shows the network of cooperation relationships between different organizations. The number of publications and total citations for these 15 organizations are shown in Fig. 4. University of Saskatchewan and University of Calgary, the Canadian institutions, have exceptionally high citation counts compared to other institutions with similar publication counts, reflecting some extent the tendency of the institution to produce high-quality papers. These institutions are divided into 13 clusters with 300 links present and the total link strength of 427. The number of links reflects the number of partner institutions. There are five institutions with >20 total links, namely Chinese Academy of Sciences (31), Kyushu University (24), Zhejiang University (23), Zhejiang University of Science and Technology (21), and Sandia National Laboratories (20). As we can see, the Chinese Academy of Sciences (in yellow) is the institution with the most collaborators, which collaborated with 21 institutions. Kyushu University (in blue) acts as a bridge in the field of hydrogen storage and transportation safety, linking Norwegian and American institutions, which facilitates international cooperation and exchanges between different institutions.

The network comprising 883 publishing institutions exhibits a distinct core-periphery structure, indicative of the field's heterogeneous knowledge production landscape. The centrality of the Chinese Academy of Sciences, with the highest number of links (31), is a direct manifestation of a large-scale, nationally-coordinated research agenda. Its dense, predominantly intra-cluster collaboration pattern suggests a mission-oriented research paradigm, focused on addressing systemic safety challenges associated with scaling up infrastructure, likely driven by national strategic projects and rapid deployment goals. This paradigm contrasts sharply with the role of Canadian institutions, notably the University of Saskatchewan and the University of Calgary. Their exceptionally high citation counts relative to publication volume identify them as foundational knowledge anchors. Their impact stems from pioneering fundamental research, likely in areas such as the atomistic mechanisms of hydrogen embrittlement, advanced characterization of hydrogen-material interactions, and the development of predictive degradation models. Their work provides the mechanistic understanding and methodological tools that underpin applied studies globally, earning cross-cluster citation dominance.

The bridging function of Kyushu University (Japan) is structurally and strategically significant. Its connections between North American (e.g., Sandia National Laboratories) and European clusters facilitate transnational knowledge integration. This role is likely rooted in Japan's longstanding focus on materials compatibility for storage, composite tank integrity, and pre-normative research informing international standards (e.g., ISO/TC 197). This node mediates between different technological approaches and safety philosophies. Sandia National Laboratories represents another critical node type: the translational research and certification hub. Its collaborations span fundamental science and applied engineering, positioning it as a key agent in converting scientific findings into engineering practices, test protocols, and regulatory guidance.

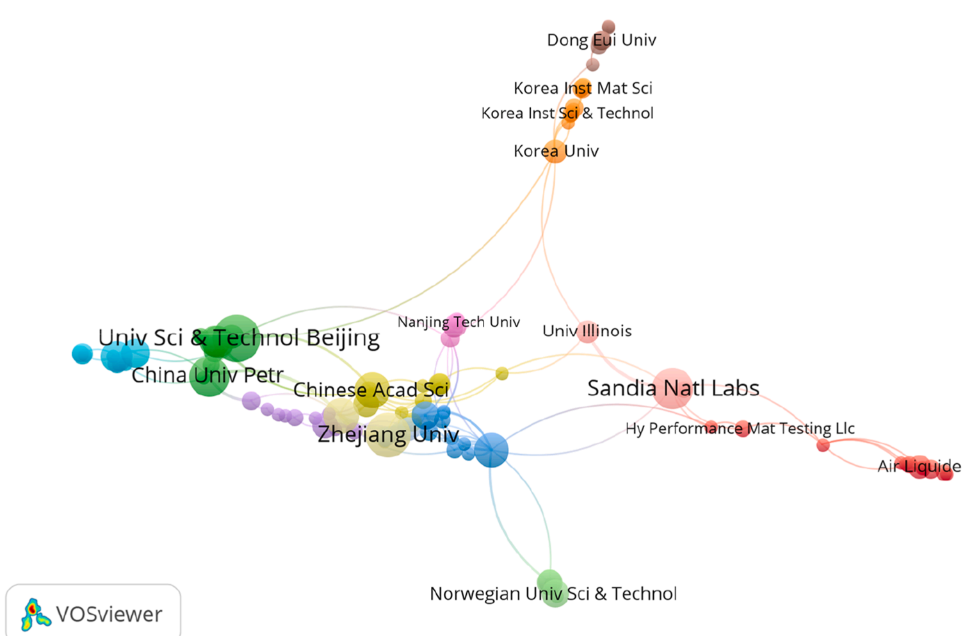

Fig. 3. Collaboration network between different institutions on hydrogen storage and transportation safety.

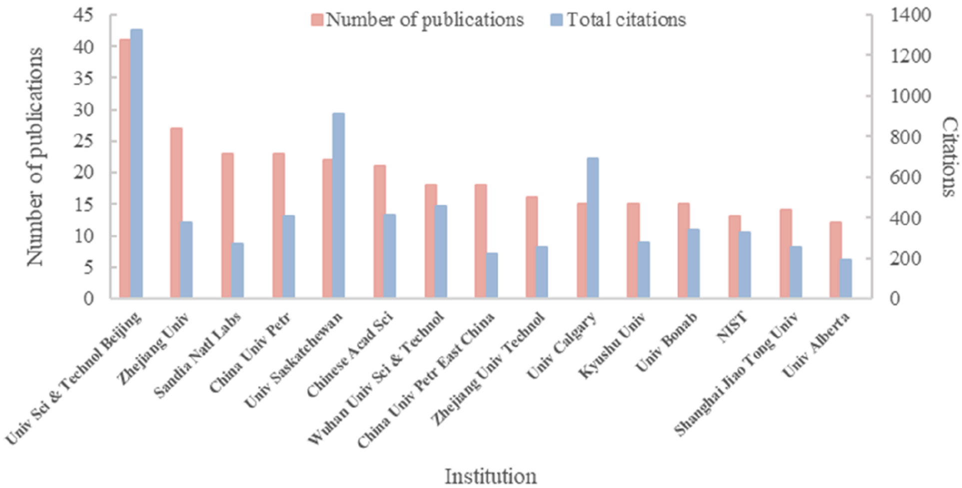

Fig. 4. Top-15 institutions on hydrogen storage and transportation safety.

3.4.2. *Analysis of author cooperation*

According to the statistics, 2945 authors published literature on hydrogen storage and transportation safety. Among them, 51 authors published at least 5 papers closely related to hydrogen storage and transportation safety research. Based on the co-authorship feature of the VOSviewer software, this section exports the collaborative network of these authors, as shown in Fig. 5. The most productive author is Jerzy A. Szpunar with 21 publications and the total link strength is 26. Followed by Mohammad Ali Mohtadi-Bonab, Lin Zhang, Jinyang Zheng, Xiaogang Li, Laifei Cheng, Brian P. Somerday, and Chengshuang Zhou, all of whom have >10 publications. Among these 51 authors, Jerzy A. Szpunar, Mohammad Ali Mohtadi-Bonab, Xiaogang Li, Laifei Cheng, and Eskandari Mostafa are cited >400 times in their articles, illustrating their outstanding contributions to the safety of hydrogen storage and transportation.

Analysis at the author level refines the understanding of collaboration into distinct "invisible clusters". The configuration of high-output author clusters essentially constitutes a visual mapping of the primary academic communities or potential schools of thought within a field. The largest and most cohesive cluster, centered on Jerzy A. Szpunar, is characterised by high internal link strength, suggesting a tightly integrated research program. Its high output and citation influence likely originate from systematic investigations into microstructure-governed hydrogen diffusion, the role of grain boundaries, and texture evolution under hydrogen exposure. This cluster represents a paradigm focused on enhancing intrinsic safety through microstructural design. The high-impact profile of authors like Mohammad Ali Mohtadi-Bonab, with high citation counts per publication, typically indicates seminal contributions to experimental methodology or mechanistic explanation.

Authors such as Brian P. Somerday (Sandia National Laboratories) occupy crucial nexus points, connecting academic research with national laboratory mandates. The cluster around him likely focuses on

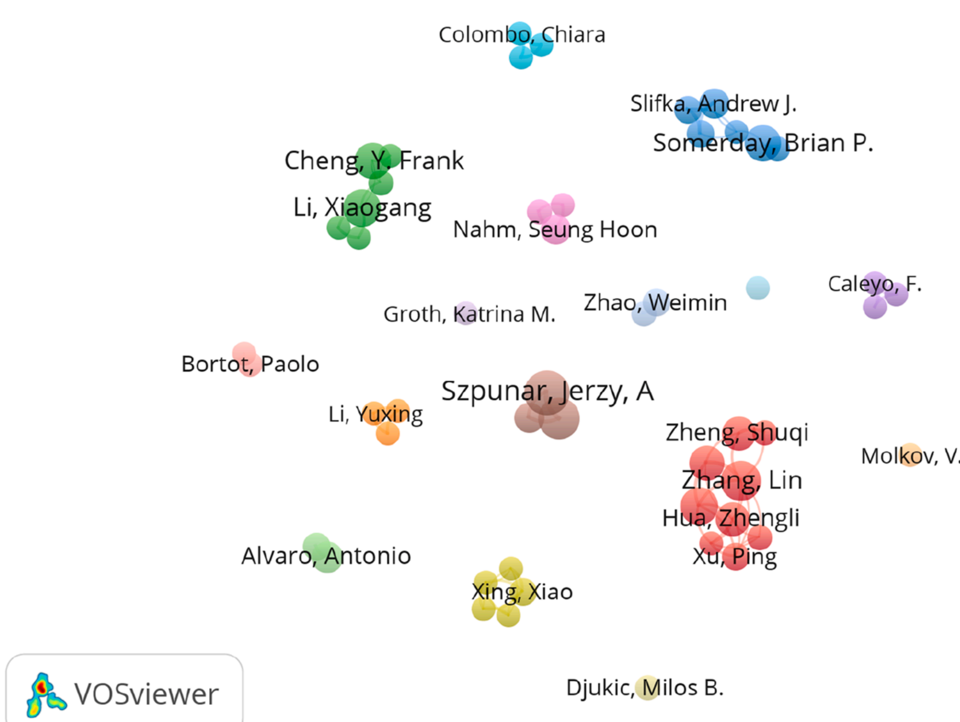

Fig. 5. Cooperation network between different authors on hydrogen storage and transportation safety.

quantitative integrity assessment, including fatigue crack growth rate measurements for engineering alloys under service-relevant conditions and the development of probabilistic fracture mechanics models, directly feeding into code and standard development. The presence of smaller, less-connected clusters or isolated nodes is analytically significant. These often represent specialized, emerging, or niche research fronts that are not yet fully integrated into the mainstream discourse. Potential foci of these clusters may include the safety of liquid organic hydrogen carriers, failure modes of cryogenic liquid hydrogen systems, or AI-driven real-time risk monitoring. Their current peripheral status highlights potential growth areas and opportunities for future interdisciplinary convergence.

4. Evolution and trends in research

In the keyword co-occurrence analysis, this paper considers that the number of occurrences of keywords determines the selection of hot topics (Chen et al., 2021), and the top five topics with the most frequency of occurrences are considered to be the hot topics in each period, which can reflect the international research hotspots in the field of hydrogen storage and transportation safety in the corresponding period. This paper screens out general descriptive words such as "steel", "paper", "pipeline", and "hydrogen". The results of keyword co-occurrence (Fig. 6) show that scholars in the field of hydrogen storage and transportation safety always focus on “microstructure”, “crack”, “susceptibility”, and “hydrogen embrittlement”, and deeply cultivate different research directions around these keywords, to achieve the purpose of in-depth research and study. (Notes: SCC- stress corrosion cracking, HIC- hydrogen-induced cracking, SSRT- slow strain rate test).

Microstructure: Microstructure is the fundamental determinant of material performance in hydrogen environments. It governs hydrogen diffusion pathways and trapping efficiency at defects, including dislocations, grain boundaries, and phase interfaces. This trapping significantly influences the local hydrogen concentration and distribution under stress. High-angle grain boundaries often provide preferential paths for crack propagation, a behavior explained by the hydrogen-enhanced decohesion mechanism (HEDE), which posits a reduction in atomic cohesive strength. Conversely, a high density of fine, reversible traps can delay failure by homogenizing hydrogen distribution, a principle explored in the Hydrogen-Enhanced Localized Plasticity (HELP) model. HELP posits that hydrogen facilitates dislocation mobility, leading to localized plastic deformation and micro-void coalescence. Consequently, the intensive research on bainitic, martensitic, and advanced high-strength steels focuses on tailoring microstructures to maximize beneficial trap sites and minimize susceptibility, directly supporting the development of safer pipelines and high-pressure storage vessels. The vigorous research on microstructure promotes the solid-state hydrogen storage technology (Kumar et al., 2022; Zacharia and Rather, 2015; Muduli and Kale, 2023; Lee et al., 2010) and hydrogen compression technology (Tarasov et al., 2021), realizing the landing of high-efficiency hydrogen storage materials and safe hydrogen storage containers (Lee et al., 2010; Zhang et al., 2017; Salehabadi et al., 2020).

Crack: The initiation and propagation of cracks under hydrogen influence are the ultimate failure events. Research transcends mere observation, focusing on the interplay between hydrogen and local stress fields at crack tips. The dominant mechanistic models provide different lenses: HEDE explains cleavage-like fracture by postulating that hydrogen reduces the atomic bonding strength at critical sites ahead of a crack. HELP accounts for the enhanced dislocation activity and strain localization in the plastic zone, promoting ductile fracture mechanisms even in otherwise brittle materials. Adsorption-Induced Dislocation Emission (AIDE) bridges surface and bulk effects, suggesting hydrogen adsorption at the crack surface lowers the stress required to emit dislocations. In practical terms, for hydrogen storage and hydrogen transport materials, the transition from internal pitting corrosion to stress-oriented hydrogen-induced cracking (SOHIC) or blistering is a major concern (Elboujdaini and Revie, 2009). This drives the development of advanced inspection technologies (like nonlinear ultrasonics for early micro-crack detection (Zhou et al., 2022)) and predictive models that integrate fracture mechanics with hydrogen diffusion and trapping kinetics to forecast remaining service life (Okoroafor et al., 2023; Shamsuddin et al., 2023).

Susceptibility: Quantifying a material's susceptibility to hydrogen damage is fundamental for material selection and design. Susceptibility is not an intrinsic property but a system response dependent on microstructure, mechanical loading conditions, and environmental hydrogen activity. Standardized testing methods, including slow strain rate tests and fracture mechanics-based approaches measuring threshold stress intensity or fatigue crack growth rates (Messaoudani et al., 2016), provide essential comparative metrics. It should be noted that quantitative metrics such as hydrogen diffusivity, threshold stress intensity factor, density of hydrogen traps, and fatigue crack growth rate serve as critical bases for quantifying susceptibility. However, a critical research frontier is developing predictive frameworks that move beyond empirical rankings. This may involve quantifying "hydrogen trap states" through thermal desorption spectroscopy (TDS) and linking them to

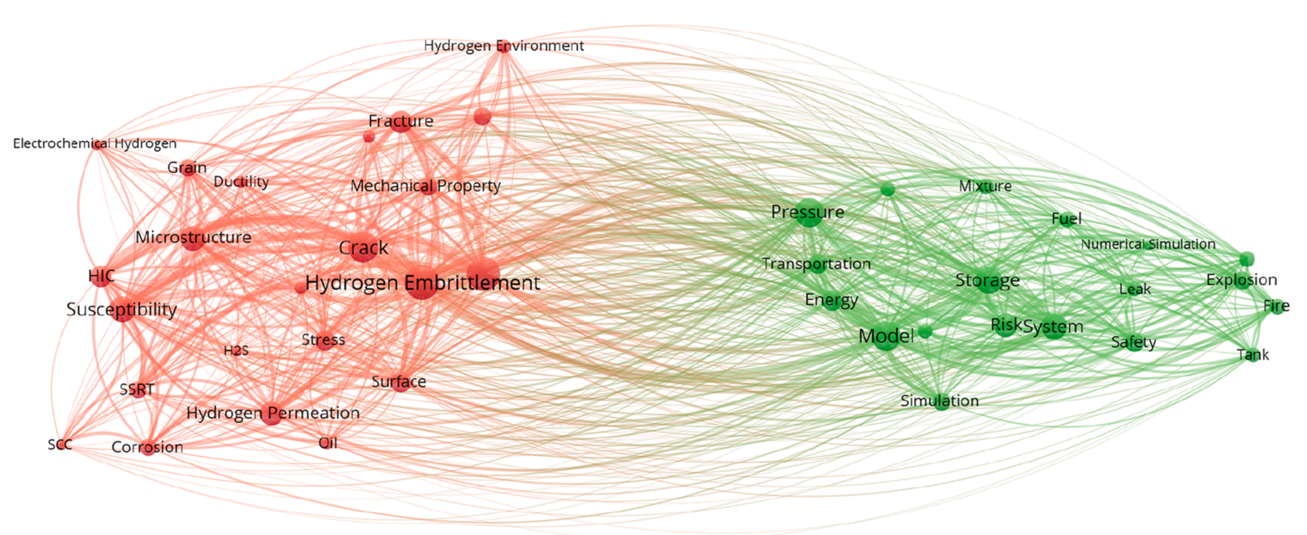

Fig. 6. Research hotspots on safety of hydrogen storage and transportation in Web of Science. (Notes: SCC- stress corrosion cracking, HIC- hydrogen-induced cracking).

mechanical performance. Furthermore, susceptibility under realistic, transient service conditions (e.g., pressure cycles in hydrogen refuelling stations, dynamic pressures in pipelines) is an area of intense investigation, as laboratory constant-load data may be non-conservative.

Hydrogen embrittlement: Hydrogen Embrittlement is the overarching phenomenon integrating these elements. Hydrogen is dissociated into H atoms under certain conditions and adsorbed on the metal surface, leading to the hydrogen damage phenomenon of hydrogen embrittlement, hydrogen blistering, and hydrogen corrosion after a series of reactions (Fig. 7). Contemporary research acknowledges that multiple mechanisms, including HEDE, HELP, and AIDE, can operate synergistically or sequentially depending on the specific material-loading-environment combination. Therefore, hydrogen embrittlement usually occurs in high-strength materials, such as high-strength steels (Martin et al., 2020) or alloys (Cabrini et al., 2019), especially in the presence of stress. With the rapid development of industrialization, equipment in many fields needs to work in harsh environments such as high temperature, high pressure, and strong corrosion, thus requiring materials with higher hydrogen embrittlement resistance. In-depth study of materials with high threshold stress intensity factor, low diffusion coefficient, and high dislocation density to meet the current market demand for the development of more hydrogen embrittlement-resistant equipment.

From the previous section, this study categorizes the research in the field of hydrogen storage and transportation safety into three phases based on the number of publications: (i) Slow growth phase: before 2013; (ii) Stable growth phase: 2013–2017; (iii) Rapid development phase: 2018–2024. The keywords of the literature in these three phases are visualized and analyzed using the co-occurrence function of the VOSviewer software. This method can identify the research hotspots and evolutionary trends in the field during the development process, which is beneficial for the advancement of research work in future generations.

4.1. Research hotspots before 2013

During this phase, 148 documents exist in the database, and 32 of the 3556 keywords appear >10 times. According to the density viewable graph exported from the VOSviewer in this phase, the hot topics related to safety research in hydrogen storage and transportation are "crack", "microstructure", "hydrogen-induced cracking (HIC)", "susceptibility", and "failure" (Fig. 8). The hot topics during this period have an obvious feature: "microstructure", "susceptibility", "hydrogen-induced cracking", and "failure" are all coupled and derived around the "crack". Failure research as one of the hotspots during this period mainly focuses on two aspects. On the one hand, failure conditions in the process of hydrogen storage and transportation. Hu et al. (2009) utilized thermos-mechanical analysis and neural network to predict the failure pressure of hydrogen storage materials. On the other hand, material failure in hydrogen environment. For material failure, crack research in this period is a key issue in the damage caused by hydrogen to materials. Cracking studies include the following three categories of cracking. (i) In terms of hydrogen-induced cracking, Jin et al. (2010) established a correlation between hydrogen-induced cracking and inclusions in API5L X100 steel to explore the influence of non-metallic materials on hydrogen-induced cracking; Dong et al. (2010) showed that charging time, charging current density and solution pH play a key role in the occurrence and propagation of hydrogen-induced cracking in X80 steel by means of electrochemical charging and tensile tests. (ii) In terms of stress corrosion cracking (SCC), Pan et al. (2012) investigated that hydrogen content and anodic dissolution have an almost equally important role in stress corrosion cracking for API X-60 pipeline steel in aqueous soils. Cheng et al. (2008) found that the occurrence of stress corrosion cracking in pipelines at near-neutral pH depends on the synergistic effects of stress at the crack tip of the steel, hydrogen and anodic dissolution (iii) In terms of load cracking, load cracking is investigated the sustained load cracking test (Nibur et al., 2008) and the threshold test for sustained load cracking (Nibur et al., 2008) of steel in storage and transportation of hydrogen environment. Alongside the clear focus on pipeline steel integrity, initial research into storage safety began to emerge, primarily concerning high-pressure gaseous storage vessels. Studies investigated the basic mechanical response and hydrogen compatibility of materials used for Type I steel cylinders. The

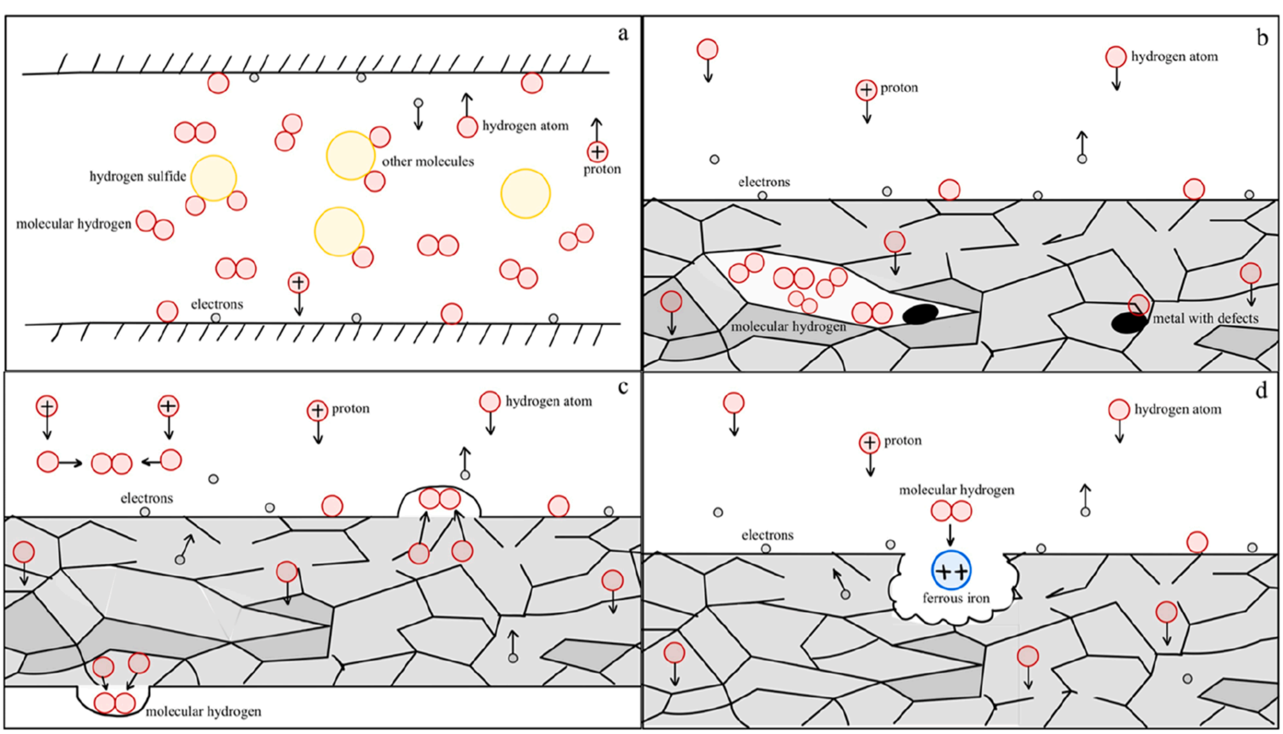

Fig. 7. Mechanisms of hydrogen damage (Lynch, 2012): (a) Hydrogen dissociation and H atom adsorption, (b) hydrogen embrittlement, (c) hydrogen blistering, (d) hydrogen corrosion.

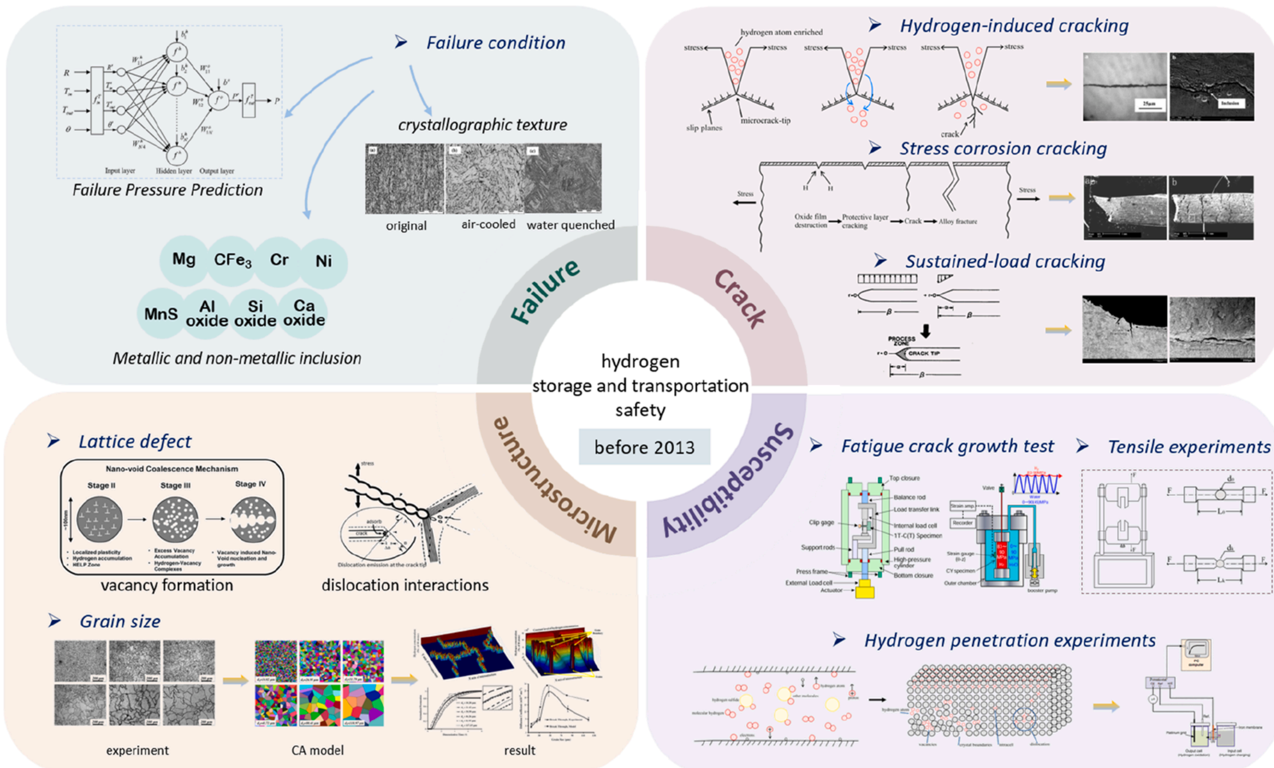

Fig. 8. Research topic evolution on safety research on hydrogen storage and transportation before 2013 (Hu et al., 2009; Jin et al., 2010; Nibur et al., 2008; Wada et al., 2009; Shirband et al., 2012; Zheng et al., 2013; Yazdipour et al., 2012; Li et al., 2020).

susceptibility of these materials to hydrogen-assisted fracture under static loading was a key concern, linking directly to the broader themes of crack initiation and microstructure. Research on composite materials for storage, which would later become prominent, was still nascent at this stage. In addition, the coupling of microstructure and susceptibility to cracking is one of the mainstream research directions in the field of hydrogen storage and transportation safety at this phase. For the study of the influencing factors of cracking, the main focus in this period is on the microstructure (Cipera et al., 2010), including crystalline texture (Venegas et al., 2009, 2010), crystal structure (Takasawa et al., 2012), etc. Susceptibility research likewise focuses on hydrogen-induced cracking susceptibility which is typically studied by tensile experiments (Ballesteros et al., 2010), hydrogen penetration experiments, and fatigue crack growth (Wada et al., 2009) to quantitatively analyze and provide data support for improved material design. The period's legacy is the establishment of a fundamental materials science foundation relevant to both transport pipelines and early storage vessel designs.

This period was characterized by foundational research, driven primarily by the need to understand the Damage mechanism of basic materials under hydrogen exposure, especially hydrogen embrittlement, which manifests as various cracking modes. Countries such as China still classify hydrogen as a hazardous chemical. The U.S. Department of Energy initiated a series of hydrogen energy research projects and introduced Basic research needs for the hydrogen economy, as well as the Hydrogen Posture Plan, to start developing the hydrogen economy. The European Union approved 30 research projects on hydrogen energy. The hydrogen economy was still largely in conceptual or early demonstration phases globally, with limited large-scale infrastructure deployment. Consequently, research concentrated on controlled laboratory experiments (electrochemical charging, tensile tests) to unravel the complex interactions between hydrogen, material microstructure, and mechanical stress, providing the essential scientific basis for future safe design. The predominance of "crack", "microstructure", and "susceptibility" reflects this in-depth exploration of the fundamental science of hydrogen-material compatibility.

4.2. Research hotspots between 2013 and 2017

From 2013 to 2017, the database in the field of hydrogen storage and transportation safety screens 206 literatures. VOS software selects the keywords that appear >10 times from the 4492 keywords to analyze research hotspots in the stable growth phase. The research focuses on “test”, “pressure”, “hydrogen embrittlement”, “temperature” and “microstructure” (Fig. 9). Test becomes a research hotspot in this phase, which shows that test is an important research method in the field of hydrogen storage and transportation safety. Compared with the test in the field of hydrogen safety before 2013, the test research in this phase highlighted the explosion experiment (Basco et al., 2015; Emami et al., 2013), fire experiment (Lowesmith and Hankinson, 2013; Zheng et al., 2013), not only hydrogen penetration test (Svoboda et al., 2014), fatigue test (Zheng et al., 2013), tensile test and other low-risk experiments. This phenomenon shows that the equipment, technology and safety measures of scientific experiments are constantly improving, and the research on hydrogen storage and transportation safety continues to expand to a deeper level. Pressure, temperature and microstructure are the key problems in hydrogen embrittlement that receive extensive attention during this period. With the prominence of climate change and sustainable energy issues, hydrogen energy becomes the focus of research and development around the world. As hydrogen becomes a huge global market, the requirements for storage and transportation of hydrogen shift to high pressure or low temperature conditions. Under the premise of improving the efficiency of hydrogen storage and transportation and reducing the cost of storage and transportation, the market demand can be met. Therefore, the safety of hydrogen storage and transportation under high or low temperature conditions become a hot topic. Fassina et al. (2013) found that the effect of low temperature on fatigue crack growth of pipeline steel is related to the hydrogen diffusion rate by using electrochemical charging method. Zheng et al.

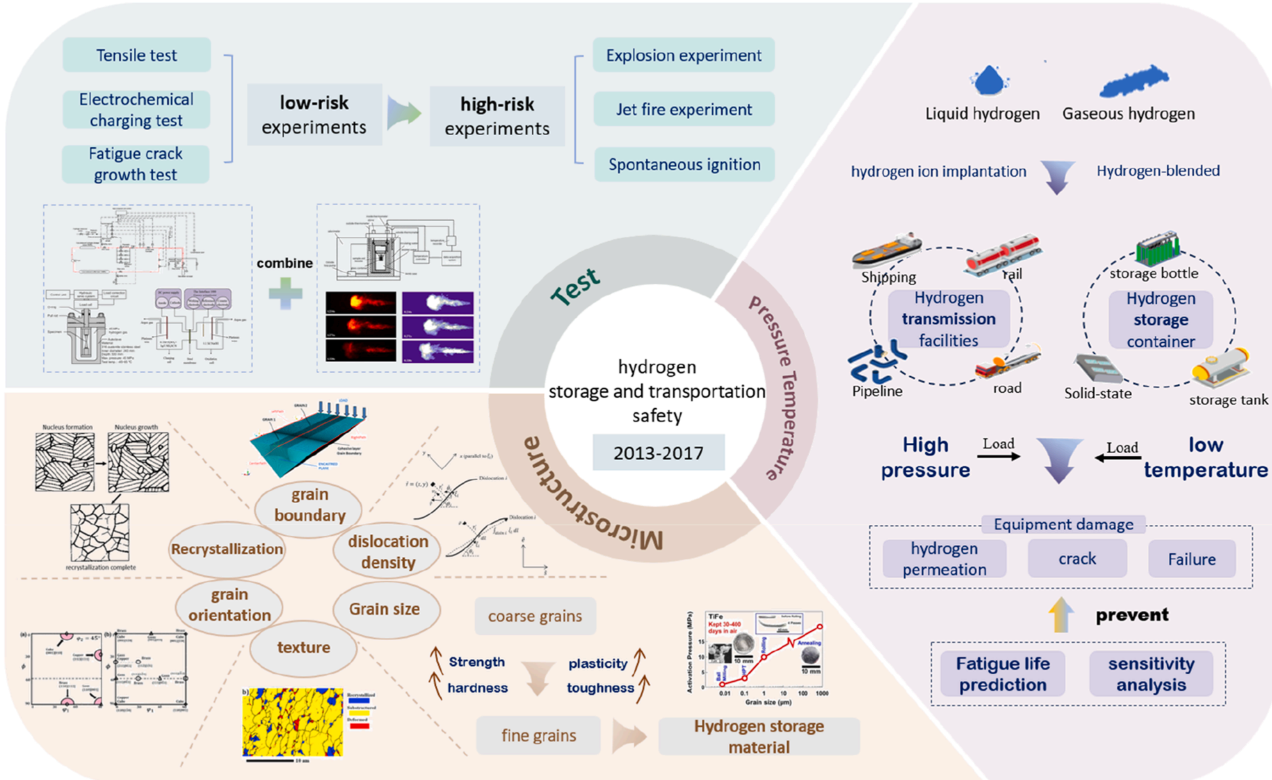

Fig. 9. Research topic evolution on safety research on hydrogen storage and transportation, 2013–2017 (Takasawa et al., 2012; Kessler et al., 2014; Mohtadi-Bonab et al., 2015; Chen et al., 2016; Huang et al., 2011; Mohtadi-Bonab et al., 2014; Alvaro et al., 2015; Masoumi et al., 2017a, 2017b; Leung and Ngan, 2016).

(2013) conducted fire test of high-pressure gas storage tanks to verify the safety performance of such tanks under localized fire exposure. Kessler et al. (2014) built an experimental platform to study the spontaneous combustion behavior of hydrogen jet in a high-pressure storage tank, and explored the changes of various data during the experiment. In addition, using natural gas pipelines to transport hydrogen enters the field of vision of research teams in various countries, and the compatibility of high-pressure hydrogen transportation in natural gas long-distance pipelines becomes a research hotspot at this phase. Amaro et al. (2014) built a model for pipeline steel in high-pressure gaseous hydrogen to reflect the fatigue crack propagation of pipeline steel in a similar in-service environment due to deformation mechanism. Bae et al. (2014) studied the effect of hydrogen content on the hydrogen embrittlement of API X70 steel under high pressure hydrogen by tensile experiments. Balueva (2014) solved the coupling problem between the elastic theory of crack opening under high gas pressure and the diffusion theory of gas diffusion into the crack cavity by establishing a model. For storage safety, these keywords signified critical advancements in two areas. First, the safety of Type III and Type IV composite overwrapped pressure vessels for vehicular and stationary storage became a major research thrust. Studies focused on liner compatibility, composite fiber degradation in hydrogen, and the cyclic fatigue performance of these vessels under high-pressure fuelling cycles. Second, the challenges of liquid hydrogen storage gained attention, spurring research into boil-off gas management, the thermal stress and contraction of materials at cryogenic temperatures, and the integrity of insulation systems. Compared with the slow growth phase, the microstructure of the research focus extends in multiple dimensions. The microstructure of this period adds to the research content, including the role of grain boundaries (Rajagopalan et al., 2017), recrystallization fraction (Mohtadi-Bonab et al., 2015), and lattice strain (Beres et al., 2017) on hydrogen damage in pipeline materials.

This phase witnessed a significant shift driven by escalating global climate commitments, notably the landmark Paris Agreement (2015). The U.S. and Europe enter the mid-stage transition to a hydrogen economy, presenting plans for hydrogen infrastructure development and investment. China specified the liquid hydrogen storage and transportation technology attack in the Energy Technology Revolution Innovation Action Plan in 2016. This catalyzed stronger national strategies promoting hydrogen as a clean energy vector. Consequently, research pivoted towards enabling practical hydrogen infrastructure. The surge in "pressure" and "temperature" reflects the focus on high-pressure storage and cryogenic liquid hydrogen technologies. And the focus on hydrogen-blended natural gas equipment compatibility was driven by the attractive prospect of repurposing existing infrastructure for hydrogen transport and storage, essential for meeting energy density and efficiency targets for transportation and storage applications. The emergence of higher-risk "Test" methods (explosion, fire, jet flame) directly stems from advances in experimental safety protocols and facilities, allowing researchers to address the real-world hazards associated with these higher-energy-density storage modes and larger-scale demonstrations.

4.3. Research hotspots between 2018 and 2024

Among 594 literatures analyzed between 2018 and 2024, we screen 226 keywords with >10 occurrences using VOSviewer software. For each of the 226 terms, the keyword co-occurrence analysis in the VOSviewer software calculates a relevance score. According to this score, the 60% of words with the highest relevance are selected to derive the density of research hotspots in the rapid growth phase (Fig. 10). The five most common hotspots during this period are “crack”, “pressure”, “susceptibility”, “microstructure” and “risk”. As for the hotspot of crack in this period, in addition to the well-known hydrogen induced crack, a large number of scholars pay attention to the research of fatigue crack growth., including the influence of stress (Tehinse et al., 2021; Ronevich

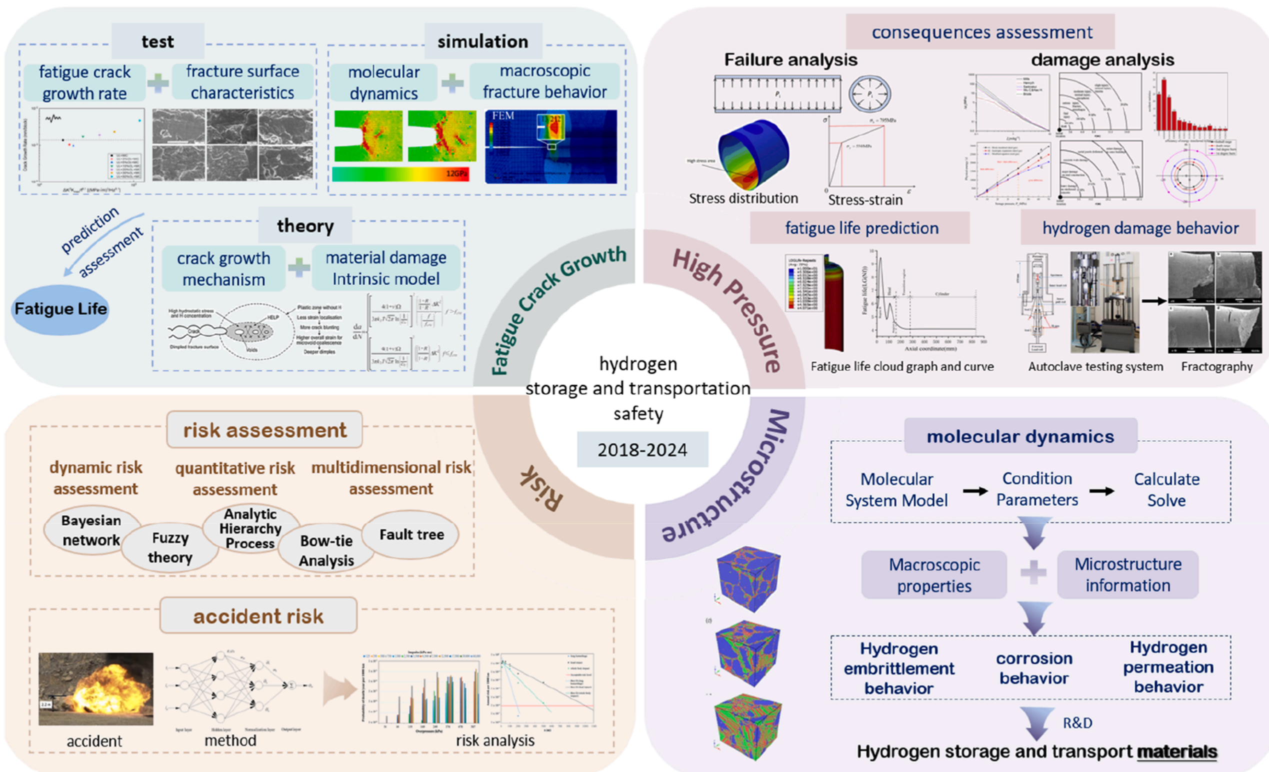

Fig. 10. Research topic evolution on safety research on hydrogen storage and transportation, 2017–2024 (Tehinse et al., 2021; Chen et al., 2020; Shen et al., 2018; Wu et al., 2021; Russo et al., 2020; Xing et al., 2019; Dogan et al., 2021).

et al., 2020; Peng et al., 2023), the influence of strain rate (Wang et al., 2023), the influence of metal elements (Ronevich et al., 2020), the impact of carbon monoxide and other gases (Komoda et al., 2019; Chandra et al., 2021), and the influence of hydrogen isotopes (Connolly et al., 2019). Obviously, we can easily understand that fatigue crack growth is the main way to quantify hydrogen embrittlement at this stage. Similar to the stable growth phase, the pressure conditions in the phase growth stage are still the research focus in the field of safety. Studies related to high pressure conditions include failure analysis (Chen et al., 2020), consequences assessment (Shen et al., 2018), fatigue life prediction (Wu et al., 2021), and hydrogen damage behavior (Bae et al., 2014; Nguyen et al., 2020). The persistent focus on "crack" and "pressure" now encompasses a dual emphasis: ensuring long-term pipeline integrity and validating the durability of high-pressure storage vessels over thousands of operational cycles. In this period, microstructure related research focuses on molecular simulation (Xu et al., 2024; Fang and Ji, 2023) and corrosion research (Chen et al., 2022a, 2022b), coating development, etc. Xing, Gou (Xing et al., 2021) used molecular dynamics simulations to study the fracture strain of polycrystalline α-iron at three different hydrogen concentrations and three crystal sizes to reveal the microscopic mechanisms of hydrogen embrittlement. Hwang et al. (2020) gained insight into the ways in which microstructures interact with hydrogen and develop new protective coatings and materials to reduce hydrogen penetration and accumulation, thereby mitigating the effects of hydrogen embrittlement. The application of molecular simulation to microstructure studies extendes to the investigation of hydrogen permeation and trapping in polymer liners of composite tanks and in solid-state storage materials. The risk research in this period is carried out from two aspects: risk assessment and accident risk. (i) In terms of risk assessment, including dynamic risk assessment (Borgheipour et al., 2021), quantitative risk assessment (Correa-Jullian and Groth, 2022; Lee et al., 2021), multidimensional risk assessment (Viana et al., 2022), etc. Bow-tie Analysis and Bayesian networks are effective means to assist in the research of risk assessment in the field of hydrogen storage and transportation safety (Borgheipour et al., 2021). (ii) In terms of accident risk, including leakage (Stalker et al., 2022), fire (Zhao et al., 2022; He et al., 2023), explosion (Russo et al., 2020; Malik et al., 2023), etc. Research addressed complex accident scenarios like high-pressure jet fires from tanks or pipeline leaks, explosions of the hydrogen refuelling station, and the dispersion of cold clouds from liquid hydrogen spills. Furthermore, safety considerations for emerging solid-state hydrogen storage technologies entered the literature, focusing on system thermal management during absorption/desorption and the mechanical stability of hydride beds. It is worth mentioning that these are the terms with the highest relevance scores in the bibliometric analysis, which reflects the future research direction of hydrogen storage and transportation safety to a certain extent. Compared with the period from 2013 to 2017, the research methods in this period focus on numerical simulation (Yang et al., 2021) or a combination of experiment and simulation (Carboni et al., 2022).

This most recent phase is dominated by the global push towards "Net Zero" emissions targets announced by numerous countries around 2020. For instance, the European Union issued A hydrogen strategy for a climate-neutral Europe, Germany formulated the National Hydrogen Energy Strategy, the U.S. Department of Energy released the Hydrogen Program Plan 2020, and South Korea passed the Promoting Hydrogen Economy and Hydrogen Safety Management Act. This has accelerated plans for large-scale hydrogen production, storage, transport, and utilization. The persistent focus on "crack" and "pressure" underscores ongoing efforts to ensure the long-term integrity and durability of high-pressure infrastructure (e.g., tanks, pipelines) under cyclic loading conditions expected in real-world applications. The rise of "microstructure" studies employing molecular simulation reflects the maturation and increased accessibility of advanced computational materials science tools, enabling deeper, atomistic-level insights into hydrogen embrittlement mechanisms and guiding the design of resistant materials and coatings. Crucially, the emergence of "risk" as a top-tier keyword is a direct consequence of the impending large-scale deployment and associated societal safety concerns. Research on quantitative risk assessment, dynamic risk assessment, and specific accident scenarios (leakage, fire, explosion) is essential for informing robust safety standards, regulations (e.g., updates to ISO 19880, Compressed Gas Association standards), site planning, and public acceptance as hydrogen infrastructure moves from demonstration to commercial scale. The increased reliance on "numerical simulation" is driven by the need to model complex, large-scale scenarios that are prohibitively expensive or risky to test experimentally, leveraging advances in computational power and multi-physics modeling software.

In summary, research hotspots at different phases in the field of hydrogen storage and transportation safety are interrelated and extended with each other, mainly characterized by the following evolution. The research methods gradually shift from experimental studies with low risk to large-scale experimental studies with high risk factors, while numerical simulation becomes one of the mainstream research tools in recent years. The research of microstructure is no longer limited to the crystal structure itself, but is broadened to new fields such as molecular simulation. Hydrogen-induced cracking research is transformed from qualitative to quantitative research, and fatigue crack growth is the main research direction to quantify hydrogen-induced cracking in recent years. The research direction of hydrogen storage and transportation conditions evolve towards low temperature and high pressure, due to the changing market demand for hydrogen storage and transportation. The topic of risk is focused on research by international research teams over the past five years. Risk analysis in hydrogen environments involving leakage, diffusion, explosion, jet fire and other accidents may become a future research trend.

5. Future development needs for hydrogen storage and transportation safety

This paper analyzes the literature metrology database of hydrogen storage and transportation safety formed by screening. The previous sections explore the country distribution, source distribution and cooperative relationship network in institutions and authors, and obtain the changing trends of research hotspots in different periods. On this basis, this section aims to discuss possible future development needs for hydrogen storage and transportation safety.

5.1. International communication and cooperation

In the realm of hydrogen storage and transportation safety research, distinct countries and institutions exhibit varying research priorities. Fostering harmonious international exchanges is crucial for the advancement of this field. Section 4, which delves into institutional cooperation networks and the distribution of publications by country, reveals the closeness of academic exchange and collaboration in the domain of hydrogen storage and transportation safety. Notably, Norway and South Korea, both high-output countries in terms of publications, exhibit zero links between their research institutions, indicating limited collaboration to some extent. In contrast, research institutions in the United States, China, France, and Italy demonstrate relatively close collaboration, with a Total Link Strength greater than 30. Measures such as Joint research projects, shared facilities, and international conferences effectively promote cooperation between different countries and research institutions. Governments or research institutions can co-finance research funds, establish transnational research teams, and invest in transnational laboratories to support challenging scientific research projects across national borders, to promote the output of innovative results. In addition, countries are encouraged to regularly set up international cooperation forums and organize international academic conferences which provide a platform for exchange and cooperation among governments, research institutions, and enterprises, promoting academic exchanges and cooperation on global issues, and obtaining innovations in scientific research and the in-depth development of international cooperation. At present, many countries and institutions implement hydrogen energy multinational collaborative activities. For example, the International Energy Agency (IEA) implements the Hydrogen Technology Collaboration Program (Khalil, 2017, 2018; Kodoth et al., 2019). The participants of the program cover researchers from European, American, Japanese, Chinese institutions, and other countries, which is a demonstration and guidance of the results of multinational cooperation on hydrogen energy safety. To a certain extent, it means that international communication and collaboration on hydrogen energy security will be promoted in a more profound and broad direction.

5.2. Hydrogen damage in materials

Examining the evolution of research hotspots in hydrogen storage and transportation safety across various stages reveals a consistent interest among international scholars in the topic of cracks. "Crack" emerges as a hotspot in 473 publications within the established literature database, accounting for one-third of the total publications. This topic remains highly prevalent during the rapid development phase, being addressed in 254 publications. The interaction between hydrogen atoms and specific components in metals leads to alterations in the mechanical properties of metal materials. Consequently, containers and equipment at every stage of the hydrogen storage and transportation process are often susceptible to the risk of hydrogen damage. Existing literature highlights the concentration of international scholarly attention on the behavioral transformations of metal materials following hydrogen damage in the storage and transportation process. Notably, there is a noticeable gap in research focused on preventing hydrogen damage in metallic materials. This kind of research mainly focuses on specific types of equipment, such as hydrogen refueling units, transmission pipelines, and storage tanks. Future research on the prevention of hydrogen damage to materials will cover a wider range of equipment types and sizes to facilitate the implementation of safe hydrogen delivery and storage materials.

5.3. Compatibility of hydrogen in natural gas storage and transportation equipment

Many countries develop hydrogen policies and strategies, investing in research, development and deployment of hydrogen technologies to drive the clean energy transition (Wu et al., 2021). Hydrogen-blended natural gas pipeline transportation is regarded as one of the efficient ways to realize long-distance and low-cost hydrogen transportation, which is an inevitable trend of future research. Therefore, this issue will inevitably face the compatibility of hydrogen in natural gas storage and transportation equipment. According to the bibliometric analysis, the current relevant research mainly focuses on the adaptability of general factors such as pressure, hydrogen content and temperature to Hydrogen-blended natural gas equipment. However, the storage and transportation environment in actual engineering is relatively complex. The presence of hydrogen itself must be the fundamental driver of hydrogen embrittlement in materials. Under this premise, environmental factors and impurities may significantly influence the susceptibility and severity of HE. For hydrogen-blended natural gas pipelines and storage tanks, sulfide species, which can be residual impurities in natural gas streams or introduced during purification, are known to potentially exacerbate HE through mechanisms like promoting hydrogen entry or inhibiting recombination. The role of carbon dioxide impurities in HE is less clear-cut and remains an area of active research and debate. Consequently, understanding the potential synergistic effects between hydrogen and various impurities or environmental constituents within the blended gas stream is essential for assessing long-term pipeline integrity. However, research comprehensively addressing the influence of such complex impurity profiles on HE susceptibility in hydrogen-blended natural gas equipment is still developing. In addition, with the application of advanced detection technology, the research on the microscopic mechanism of hydrogen damage based on molecular simulation becomes a hotspot (Moradi and Groth, 2019), which provides data verification for experimental research. The gradual clarification of the microscopic mechanism of hydrogen damage is conducive to the development of the adaptability of hydrogen-blended natural gas storage and transportation equipment from the microscopic perspective.

5.4. Establishment of experimental database

The establishment of a shared and comprehensive database of hydrogen experiments contributes to researchers and industry reference, which advances the field of hydrogen safety. Based on the bibliometric analysis, the research on hydrogen overpressure, leakage, explosion, fire and other accidents is mainly carried out from two aspects: numerical simulation and experiment. Considering the safety and cost control, it is difficult to build a large-scale accident experiment platform at present. Therefore, the research teams mainly improve the precision and accuracy of numerical simulation from the aspects of mesh density, model optimization, and condition setting. The establishment of databases enables to disseminate knowledge and information in the field. Teams capable of conducting experimental research upload experimental data to the database, and the other academic researchers are able to easier access to information, which facilitates collaboration and communication between different research teams or institutions. Sharing resources not only reduces duplication of investment and effort, but also encourages academic innovation through access to existing data and results. For example, the Hydrogen Incident and Accidents Database (HIAD) (Cristina Galassi et al., 2012) is a database that records and analyzes hydrogen-related events and accidents. This database is designed to provide scientists, engineers, government agencies and researchers with information on hydrogen-related events to promote the safe and sustainable development of hydrogen energy. The establishment and maintenance of a shared database of hydrogen experiments face challenges such as difficulties in sharing data, data quality, and technological updates. Therefore, technical and logistical factors need to be considered to ensure data quality and accessibility. In terms of technical aspects, a reasonable database architecture should be designed based on hydrogen safety experiments, and a data validation mechanism should be set up to carry out data preprocessing operations to improve data quality. In addition, data encryption and access control can be used to ensure data security and user privacy. In terms of logistics, a professional database management team and a clear workflow and division of responsibilities can provide users with database technical support and consulting services. In addition, ensuring continuous updating and regular checking of the hydrogen experimental database is an important guarantee for maintaining the stable operation of the database.

5.5. Developments in risk assessment

The research trends of different periods in Section 4 show that risk assessment is one of the current research hotspots. During the Rapid Development Phase, publications related to "risk" doubled, accounting for 141 publications focused on risk research within the hydrogen storage and transportation safety domain. The flammability of hydrogen is determined by its high ignition point range, high heat transfer rate and low ignition energy. Therefore, the risk of fire, explosion and other accidents is permanent, which partly reflects that risk assessment will remain a hot topic for some time to come. Risk assessment is a systematic process used to identify, assess and understand potential risks and hazards to make informed decisions and take appropriate actions to mitigate or manage those risks. Due to the lack of experimental data leading to the difficulty of experiments, risk assessment in the field of hydrogen safety is still in its infancy. Risk modeling is an important part of risk assessment. In the process of risk assessment, risk modeling generates quantitative data, which helps to determine the probability and characteristics of potential risks (Messaoudani et al., 2016). Currently, the accuracy and completeness of data, inconsistencies in model assumptions, simplification of complex risk situations, errors in risk modeling software, and other factors contribute to the inaccuracy of risk modeling in the hydrogen domain. Addressing the limitations of risk assessment methods in the field of hydrogen safety requires multifaceted exploration. Strengthening basic research on the physical and chemical properties of hydrogen, expanding data collection to improve existing models, and developing new risk assessment methods based on big data and machine learning can provide research directions for the development of risk assessment in the field of hydrogen storage and transportation safety, promoting the development of risk assessment methods in the direction of greater accuracy and reliability. Risk assessment is an evolving process that demands continual monitoring and enhancement to maximize the precision of assessment outcomes. There is a pressing need to formulate widely applicable quantitative risk models and optimize assessment methods, aligning with the evolving requirements of hydrogen risk assessment trends.

6. Conclusions

This paper conducts a thorough literature review of hydrogen storage and transportation safety, offering insights into distribution, sources, cooperation networks, and evolving research hotspots. Addressing the introduced questions, the findings are summarized as follows:

(1) The field's development exhibits a three-phase evolutionary pattern driven by global energy transition policies. The publication counts from 2007 to 2024 exhibit a generally upward trend, with China leading in productivity, and the United States, Canada, France, and South Korea also prominent in articles and citations. While intra-country collaboration is robust, inter-regional cooperation remains limited—particularly between high-output nations such as Norway and South Korea. The International Journal of Hydrogen Energy serves as the primary academic platform, accounting for nearly 26% of relevant publications, reflecting its central role in disseminating cutting-edge research.

(2) Enduring research focus on "microstructure," "crack," "susceptibility," and "hydrogen embrittlement" is a testament to the unresolved complexity of hydrogen-material interactions. This is the field's foundational scientific frontier. The hotspots' evolution signals an ongoing and necessary expansion beyond this core. In material behavior, research has advanced from macro-scale observations to atomistic-level investigations of microstructure-hydrogen interactions using molecular dynamics simulations. In operating conditions, the focus has shifted from ambient parameters to extreme environments and complex scenarios, driven by the need to optimize storage/transport efficiency while ensuring safety. In research methods, the paradigm has transitioned from low-risk experimental studies to a hybrid approach combining high-risk experiments, numerical simulation, and data-driven modeling. In risk assessment, the focus has moved from qualitative analysis to quantitative risk assessment and accident scenario modeling, reflecting the growing emphasis on industrial applicability and public safety.

(3) Future research requires support for the expansion of hydrogen storage and transportation safety. Literature metrology analysis identifies future development needs in "International Communication and Cooperation," "Hydrogen damage in materials," "Compatibility," "Establishment of the experimental database," and "Risk Assessment." In essence, this study employs bibliometric methods to objectively portray the current state and evolving trends in hydrogen storage and transportation safety research. The insights provided serve as a valuable reference for

researchers, technicians, and the energy industry, contributing to the sustainable development and safe application of hydrogen energy.

CRediT authorship contribution statement

Jiali Tang: Writing – original draft, Methodology, Data curation. **Chao Chen:** Writing – review & editing, Supervision, Conceptualization. **Bo Wang:** Resources. **Changjun Li:** Writing – review & editing, Resources. **Jie Li:** Writing – review & editing, Visualization. **Ming Yang:** Investigation. **Ernesto Salzano:** Validation.

Declaration of competing interest

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

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