processes

Review

Mapping the Knowledge Domain of Pressure Vessels and Piping Fields for Safety Research in Industrial Processes: A Bibliometric Analysis

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Abstract: With the rapid advancement of modern industries, pressure vessels and piping have become increasingly integral to sectors such as energy, petrochemicals, and process industries. To grasp the research and application status in the field of pressure vessel and piping safety, 670 publications in the Web of Science core database from 2008 to 2024 were taken as data samples in this paper. The knowledge mapping tools were used to carry out co-occurrence analysis, keyword burst detection, and co-citation analysis. The results show that the research in this field presents a multidisciplinary and cross-disciplinary state, involving multiple disciplines such as Nuclear Science and Technology, Engineering Mechanics, and Energy and Fuels. The "*International Journal of Hydrogen Energy*", "*International Journal of Pressure Vessels and Piping*", and "*Nuclear Engineering and Design*" are the primary publication outlets in this domain. The study identifies three major research hotspots: (1) the safety performance of pressure vessels and piping, (2) structural integrity, failure mechanisms, and stress analysis, and (3) numerical simulation and thermal–hydraulic analysis under various operating conditions. The current challenges can be summarized into three aspects: (1) addressing the safety risks brought by new technologies and materials, (2) promoting innovation and the application of detection and monitoring technologies, and (3) strengthening the building capacity for accident prevention and emergency management. Specific to China, the current challenges include the safety and management of aging equipment, the effective detection of circumferential weld cracks, the refinement of risk assessment models, and the advancement of smart technology applications. These findings offer valuable insights for advancing safety practices and guiding future research in this multidisciplinary field.

Keywords: pressure vessels; pressure piping; safety; industrial processes; research progress; bibliometric analysis

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1. Introduction

Pressure vessels are sealed containers built to endure internal and external pressures from gases or liquids, requiring strict safety standards. They are widely used in industrial processes like reactions, heat exchange, separation, and storage. Similarly, pressure piping is designed to transport fluids in various environments, both onshore and offshore, with safety being equally important [1,2]. The safety of pressure vessels and piping fundamentally depends on principles such as material strength, design stress limits, and strict inspection protocols, aimed at preventing failures caused by corrosion, fatigue, or overpressure. As core equipment in industries such as petrochemicals, energy, and metallurgy, they operate under high-temperature, high-pressure, and complex conditions over prolonged periods [3], with safety concerns remaining paramount in industrial production, environmental protection, and accident prevention. As industrialization advances, operational conditions become increasingly demanding, heightening the risk of equipment failure. In recent years, major accidents have occurred at an alarming frequency, such as the 2013 Qingdao oil pipeline explosion in China, the 2018 explosion in Guizhou caused by the rupture of a natural gas pipeline weld, and the 2022 Nord Stream pipeline explosion [4]. These incidents not only hinder industrial progress but also result in significant economic losses for nations. Therefore, the safe and efficient maintenance of pressure vessels and piping, regarded as the "lifeline" of the industry, is not only vital to advancing peaceful development strategies but also serves as a key pillar in ensuring the long-term stability of the nation's socio-economic fabric.

In response to the increasing frequency of pressure vessel and piping accidents during the 1960s and 1970s, the United Kingdom's Atomic Energy Authority and the Health and Safety Executive introduced the concept of risk assessments, emphasizing the necessity for managers to establish equipment inspection and management strategies [5]. In the 1980s, Norwegian authorities further revised risk management assessment standards for pressure vessels, piping, and other pressure-bearing equipment used on offshore platforms [6,7]. Additionally, scholars developed methodologies such as fracture mechanics and structural integrity assessments [8] to enhance the safety and reliability of pressure equipment. He and Isozaki [9] investigated the fracture behaviors of various defect types and stainless-steel cladding under transient pressure and temperature conditions, analyzing the impact of these factors on fracture assessments. Chen et al. [10] simulated crack initiation in the beltline region of reactor pressure vessels under transient pressure and temperature conditions to evaluate their structural integrity. Simultaneously, significant progress has been made in the application of novel materials, advanced manufacturing processes, and intelligent detection technologies. For instance, Lei et al. [11] proposed a method based on the equivalent stress–strain relationship, improving the accuracy of crack assessments in circumferential welds. Suzuki [12] examined the application of new high-strength materials in pressure vessels, demonstrating their superior performance in enhancing structural compressive capacity. Giglio [13] conducted low-cycle fatigue analysis on various types of pressure vessel nozzles, elucidating failure mechanisms under complex operational conditions. Kabir [14] utilized a fuzzy Bayesian belief network to construct a safety assessment model for oil and gas piping, significantly improving risk prediction accuracy and decision-support capabilities. With the development of smart manufacturing and big data technologies, scholars have begun applying emerging technologies such as digital twins and machine learning to the safety research of pressure vessels and piping, aiming to achieve full lifecycle safety management and intelligent maintenance. Bhowmik et al. [15] proposed an automated framework for subsea pipeline design using the cloud-based digital twin platform Subsea-XD, enabling the rapid design and optimization of complex subsea pipeline systems. El-Abbasy et al. [16] developed five condition prediction models using artificial neural network technology to effectively predict changes in the operating conditions of pressure vessels and piping. Similarly, Shaik et al. [17] introduced a pipeline condition prediction model based on the artificial neural network method, which integrates key parameters such as pressure flow, metal loss, weld seam anomalies, and wall thickness to accurately predict the operational state of crude oil piping.

These findings highlight significant advancements in pressure vessel and piping safety research. However, as this domain encompasses multiple disciplinary branches and interdisciplinary research activities continue to become increasingly prevalent, fully grasping the comprehensive scope of developments in this area is becoming progressively more difficult. The rapid expansion of scientific knowledge further complicates the task of gaining a deep understanding of research trends in this field. What thematic shifts have occurred in the study of pressure vessel and piping safety? What have been the focal points and emerging directions of research in recent years? These questions need to be explored further. In the early stages of research, scholars primarily relied on review articles authored by seasoned experts to keep abreast of developments in the field. However, this approach, being reliant on individual expertise, is inherently subjective and lacks quantitative analysis, making it difficult to comprehensively assess the breadth, depth, and interconnections within the research landscape. With the advent of digitalization in the scientific literature and advances in analytical techniques, bibliometrics has emerged as a crucial quantitative tool for the systematic analysis of the literature, revealing the trends and knowledge structures within a given field. In recent years, propelled by advancements in computer technology, bibliometric tools such as VOSviewer and CiteSpace have come into prominence, offering researchers more efficient methods for uncovering knowledge structures and developmental trajectories within various domains. For example, Liu et al. [18] employed bibliometric methods to conduct a visual analysis of the knowledge structure and research trends in the field of emergency evacuation. Lawal et al. [19] utilized VOSviewer software to perform a bibliometric analysis of research on ionic liquids from 1930 to 2017, exploring their potential applications in modified adsorbents and the adsorption of organic pollutants. Similarly, Lang et al. [20] systematically analyzed research papers in the field of fire safety using both VOSviewer and Citespace. Therefore, in this study, bibliometric software will be used to sort out and analyze the research in pressure vessel and piping safety comprehensively. A total of 670 publications related to pressure vessel and piping safety will be analyzed from the time distribution, country/region distribution, research institution distribution, journal distribution, research hotspots, and frontiers. The rest of the article is organized as follows: The data sources and research methods are briefly described in Section 2. The study results are described in detail in Section 3 and discussed in Section 4. Finally, Section 5 draws the relevant conclusions of the research in pressure vessel and piping safety.

2. Data and Methods

2.1. Data Collection

As one of the most authoritative academic databases globally, the Web of Science (WOS) database, encompasses literature across a wide range of disciplines, establishing itself as an essential tool for both literature retrieval and bibliometric analysis [21,22]. In this study, the literature related to pressure vessel and piping safety was gathered using the SCI-E and SSCI datasets within the WOS Core Collection. The selection of publications was based on their relevance to the research on pressure vessel and piping safety, with a focus on studies published between 2008 and 2023. Following a thorough review of the titles, abstracts, and full texts of the articles, a total of 670 publications were ultimately included in the analysis. The specific data retrieval process is detailed in Table 1.

Table 1. Dataset establishment of pressure vessel and piping safety studies.

Dataset	Retrieval Strategies	Number of Records	Period
1	TS = (“pressure piping” OR “pressure vessels”) AND TS = (“safety” OR “security”)	670	2008–2024

Note: TS means topic, which searches the title, abstract, keywords plus, and author keywords.

Table 2 presents information regarding each type of publication included in the study. As shown in the table, the documents are classified into four categories. The most prevalent type is the Article, with 585 publications, averaging 9.04 citations per paper. Following this, there are 54 Proceedings Papers. The Review category comprises 24 publications, with an average citation count of 22.20. Lastly, there are 7 Early Access publications, with an average citation count of 0.43.

Table 2. Types of publications relevant to the field of pressure vessel and piping safety.

NO.	TD	TP	SOTC	H-Index	ACI
1	Article	585	5828	33	9.04
2	Proceedings Paper	54	643	15	11.91
3	Review	24	555	12	22.20
4	Early Access	7	3	1	0.43

Note: TD means type of document, TP means total publications, SOTC means sum of times cited, and ACI means average citations per item.

2.2. Research Methods and Tools

Bibliometrics is an interdisciplinary science that employs mathematical and statistical methods to conduct quantitative analyses of various knowledge carriers [23]. It is frequently used to assess the developmental trends and dynamics within a particular field [24]. The origins of bibliometrics can be traced back to the early 20th century. In 1969, renowned British scientist Alan Pritchard was the first to coin the term "bibliometrics", replacing the previously used "statistical bibliography", which marked the formal establishment of the field. Today, bibliometrics is widely applied in various research domains, including research hotspots [25], co-authorship network analysis [26], and co-citation analysis [27], and has become an essential tool in academic research.

For this study, we retrieved publications on the safety of pressure vessels and piping from the Web of Science Core Collection database. After obtaining the dataset, we preprocessed the data using CiteSpace (6.2R6) [28] to ensure the accuracy of the analysis. This preprocessing step involved removing duplicate entries and merging identical items. We then performed the visualization analysis of the preprocessed data using VOSviewer (1.6.20.0) [29].

The analysis included several key components: co-authorship network analysis to explore collaboration patterns among scholars, institutions, and countries; co-citation network analysis to cluster documents based on content relevance and identify core research themes; and high-frequency keyword co-occurrence analysis to extract frequently occurring keywords, revealing the research hotspots and frontiers in the field.

We selected VOSviewer and CiteSpace for the bibliometric analysis because of their ability to effectively visualize and analyze large volumes of bibliographic data. VOSviewer, developed by scholars Van Eck and Waltman from Leiden University, is particularly well suited for constructing co-occurrence networks [30]. CiteSpace, developed by Professor Chaomei Chen at Drexel University, excels at identifying citation patterns and research trends over time. Together, these tools enable a comprehensive understanding of research dynamics in the field of pressure vessel and piping safety [31]. The overall analytical framework and methodology employed in this study are illustrated in Figure 1.

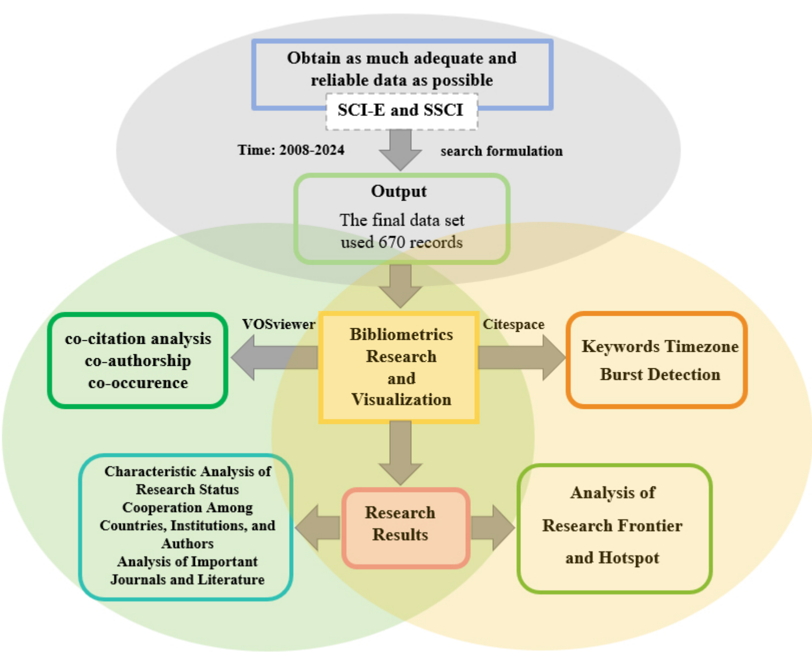


Figure 1. The main research steps and methods of this paper that are carried out.

3. Results

3.1. Subsection

The publication trends in the field of pressure vessel and piping safety offer valuable insights into the temporal and spatial distributions of research activities, reflecting the global focus on this domain and the concentration of research efforts [32]. A comprehensive analysis of publication patterns is provided in this section, encompassing the temporal distribution trends as well as the geographical distribution and international collaborations. These findings will serve as a robust foundation for further exploration of the current state of research, the construction of the knowledge base, and the identification of key research hotspots and emerging frontiers.

3.1.1. Temporal Distribution Analysis

The temporal distribution of the literature related to pressure vessel and piping safety is analyzed in this section, with the overall developmental trends in the field thereby being revealed. Figure 2 illustrates the time distribution of publications in this domain, where SOTC represents the total number of citations. As shown in Figure 2, since 2008, the volume of publications in this field has generally exhibited a growth trend. Despite fluctuations in publication output from 2008 to 2018, this period is considered a critical phase for the foundational construction and development of the field. The publication of a series of seminal studies during this time likely exerted a significant influence on subsequent research. In 2019, there was a decline in the number of publications compared to previous years, a phenomenon that may be attributed to the outbreak of the COVID-19 pandemic, which disrupted global research activities. In recent years, however, the rapid advancement of modern information technologies, such as the Internet of Things (IoT), big data, and artificial intelligence (AI), has led scholars to explore sustainable solutions in the design, manufacturing, and maintenance of pressure vessels, as well as networked remote operation and maintenance technologies based on real-time safety parameter monitoring and early warning systems. The application of these emerging technologies has driven a sustained increase in the volume of related publications.

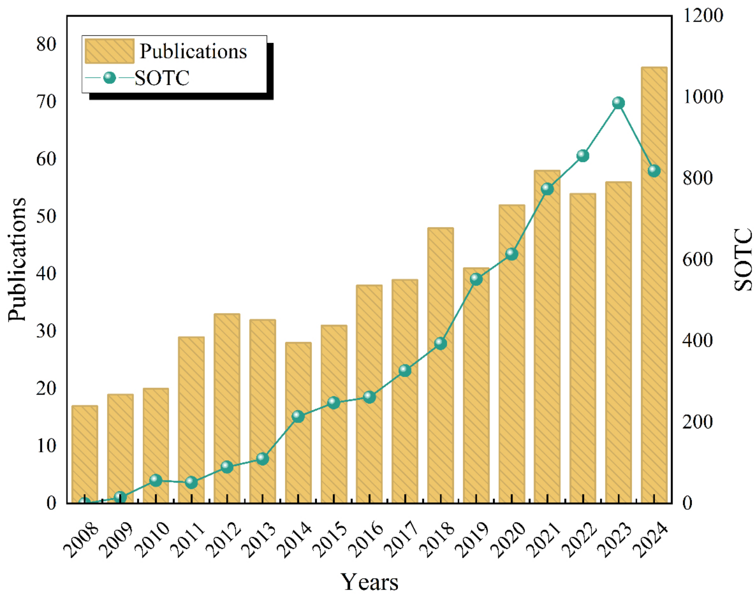
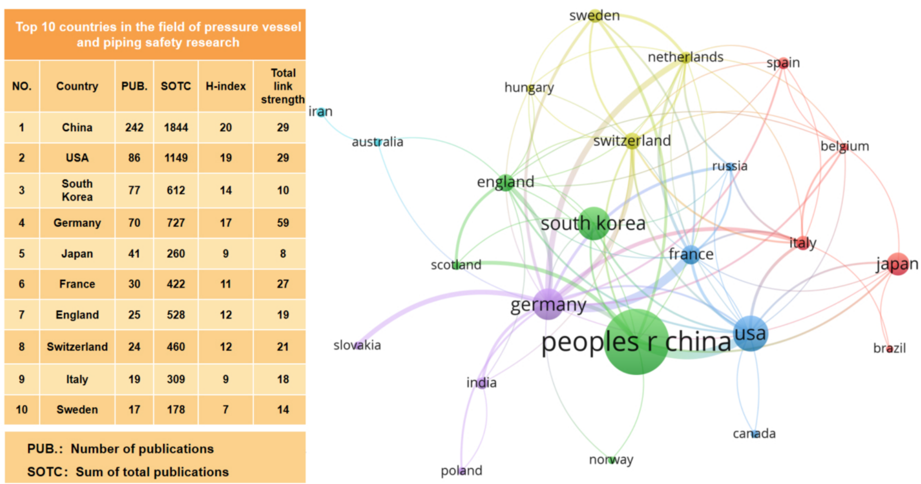


Figure 2. Temporal distribution of the relevant literature in the field of pressure vessel and piping safety.

3.1.2. Country/Region Distribution Analysis

Between 2008 and 2024, a total of 57 countries published studies related to pressure vessel and piping safety. Among these, 25 countries have contributed at least five publications, as illustrated in Figure 3. In the figure, each node represents a country, with the size of the node corresponding to the country's publication volume, while the thickness of the connecting lines indicates the strength of collaboration between countries. The H-index reflects the academic impact of each country's publications, whereas the "Total Link Strength" measures the frequency of a country's collaborations with others.



Top 10 countries in the field of pressure vessel and piping safety research

NO.	Country	PUB.	SOTC	H-index	Total link strength
1	China	242	1844	20	29
2	USA	86	1149	19	29
3	South Korea	77	612	14	10
4	Germany	70	727	17	59
5	Japan	41	260	9	8
6	France	30	422	11	27
7	England	25	528	12	19
8	Switzerland	24	460	12	21
9	Italy	19	309	9	18
10	Sweden	17	178	7	14

PUB.: Number of publications
SOTC: Sum of total publications

Figure 3. Inter-country/inter-regional academic cooperation in the field of pressure vessel and piping safety.

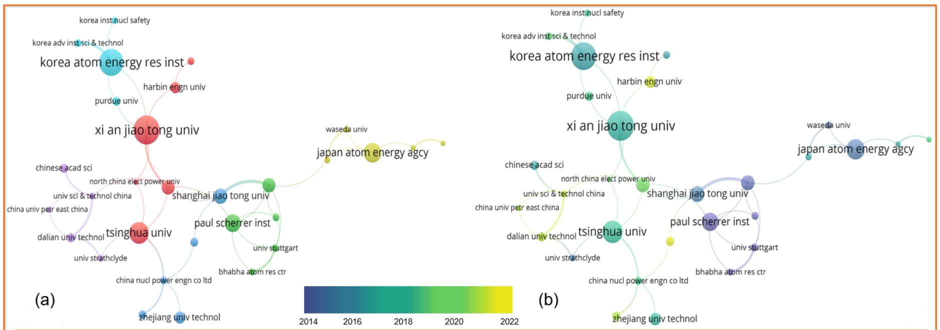
The statistical results indicate that international collaboration is prevalent to varying degrees among countries in the field of pressure vessel and piping safety. Germany exhibits the most extensive collaboration with other nations, followed by China (29 connections), the United States (29 connections), and France (27 connections). In terms of the publication volume, China ranks first with 242 publications, while the United States (86 publications) and South Korea (77 publications) occupy the second and third places, respectively. Notably, academic collaboration between China and the United States, as well as between Germany and France, is particularly strong, likely reflecting the substantial research funding allocated by these nations. China's H-index of 20 surpasses that of the United States (H-index of 19) and Germany (H-index of 16), suggesting that China has been highly active in pressure vessel and piping safety research, with its research output standing among the global leaders in this domain.

3.2. Academic Cooperations and Major Research Positions for Pressure Vessel and Piping Safety Studies

A thorough analysis of author collaborations and institutional partnerships in the collected literature was conducted to gain a deeper understanding of the key research institutions and groups, knowledge dissemination pathways, and the overall academic collaboration network within the field of pressure vessel and piping safety [33]. In addition, the disciplinary and journal distributions of relevant publications will be explored in this section, providing a preliminary identification of the significant research themes that may be implicated in this domain. Crucial support for the subsequent evaluation of the field's current state and the construction of foundational theoretical frameworks will be offered by this analysis.

3.2.1. Key Institutions and Cooperation Analysis

According to data from the WOS Core Collection, a total of 699 institutions have published literature related to pressure vessel and piping safety. We extracted institutions with at least five publications and constructed a collaboration network map, resulting in 40 nodes, of which only 30 formed cluster relationships, as shown in Figure 4. The size of the nodes in the figure is proportional to the number of publications by each institution, while the lines connecting the nodes represent collaborative relationships between institutions. The thickness and number of these lines indicate the closeness and extent of collaboration among different institutions. The table in Figure 4 lists the top 10 institutions in terms of the publication volume in this field, along with related parameters such as the total publications, collaboration strength between institutions, H-index, and ACI. The Links index is used to measure the collaboration intensity of an institution in the field, while the ACI and H-index reflect the influence and academic standing of the institution's research output.



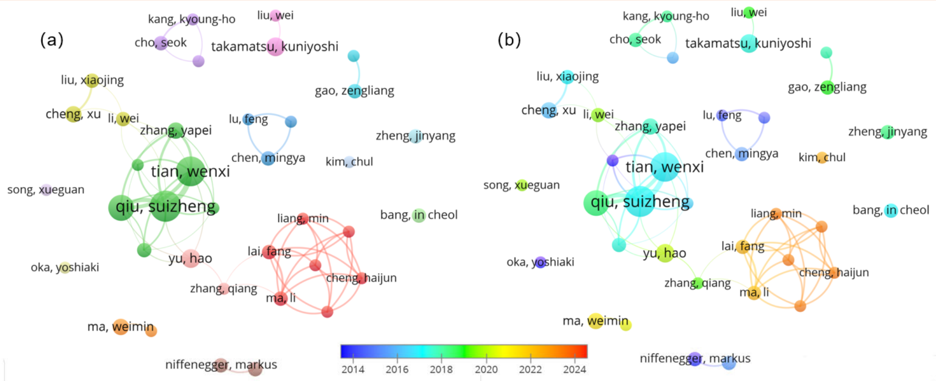
Top 10 institutions in the field of pressure vessel and piping safety							
NO.	Institution	Country	Quantity	Citations	Links	ACI	H-index
1	Xi'an Jiaotong University	China	27	279	7	10.33	10
2	Korea Atomic Energy Research Institute	Korea	25	151	7	7.59	8
3	Tsinghua University	China	20	147	5	7.35	6
4	Japan Atomic Energy Agency	Japan	18	129	3	7.16	6
5	Paul Scherrer Institute	Switzerland	16	350	5	20.94	11
6	Shanghai Jiao Tong University	China	14	157	6	10.67	7
7	Karlsruhe Institute of Technology	Germany	13	169	8	14.28	8
8	Nuclear Power Institute of China	China	13	82	7	6.31	6
9	Zhejiang University of Technology	China	11	89	1	8.09	5
10	Harbin Engineering University	China	10	23	2	2.30	4

Figure 4. Inter-agency cooperation in pressure vessel and piping safety research. (**a**) Collaborative network diagram; (**b**) Time superposition diagram.

Figure 4a reveals that the collaboration network among institutions in this field is relatively sparse, with fewer clusters and inter-node connections, indicating that the intensity of cooperation between institutions is comparatively low. Upon analyzing the tabulated data in Figure 4, we observe that the top three institutions in terms of publication output are Xi'an Jiaotong University (27 papers), Korea Atomic Energy Research Institute (25 papers), and Tsinghua University (20 papers). The Paul Scherrer Institute stands out with both a high ACI (20.94) and H-index (11), signifying the significant academic impact of its research contributions in the field of pressure vessel and piping safety. However, its Links value ranks at a mid-level among all institutions, suggesting that there is room for improvement in terms of external collaboration. The time overlay map in Figure 4b further shows that this institution began its research on pressure vessel and piping safety relatively early. It is also noteworthy that six of the top ten institutions by publication output are based in China, highlighting the country's highly active role in this field on a global scale.

3.2.2. Major Authors and Cooperation Analysis

The research domain of pressure vessel and piping safety is extensive, attracting numerous scholars. According to data from the WOS Core Collection, a total of 2421 researchers have contributed to this field. Using the VOSviewer software, we selected authors with more than four publications for analysis, resulting in 38 nodes and 15 clusters, as depicted in Figure 5.



Top 10 authors by the number of articles published on pressure vessel and piping safety							
NO.	Author	Quantitly	Institution	Country	Links	ACI	Citations
1	Qiu,Suizheng	14	Xi'an Jiaotong University	China	36	15.33	221
2	Tian,Wenxi	13	Xi'an Jiaotong University	China	35	15.86	213
3	Su,Guanghui	11	Xi'an Jiaotong University	China	29	17.38	164
4	Yu,Hao	7	Harbin Engineering University	China	8	2.67	42
5	Takamatsu, Kuniyoshi	7	Japan Atomic Energy Agency	Japan	0	5.86	41
6	Zhang, Yapei	6	Michigan State University	America	18	12.50	75
7	Cheng, Xu	6	Shenyang Agricultural University	China	6	12.50	75
8	Ma, Weimin	6	Royal Institute of Technology	Sweden	0	8.60	46
9	Wang, Mingjun	5	Xi'an Jiaotong University	China	13	19.40	97
10	Liu, Xiaojing	5	Shanghai Jiao Tong University	China	6	6.33	60

Figure 5. Main researchers and cooperation in the field of pressure vessel and piping safety. (**a**) Collaborative network diagram; (**b**) Time superposition diagram.

The top three clusters by the number of publications are the red cluster (7 authors), the green cluster (4 authors), and the blue cluster (4 authors). As shown in Figure 5, the red cluster is not only the largest but also comprises nodes that are relatively larger compared to other clusters. Furthermore, the temporal overlay in Figure 5b reveals that the red cluster initiated research activities earlier, suggesting that the collaborative group it represents has maintained a leading position both in terms of collaboration scale and publication output, potentially playing a pioneering role in the field. Based on the table of the top ten authors by publication output in Figure 5, we observe that the top three authors are from Xi'an

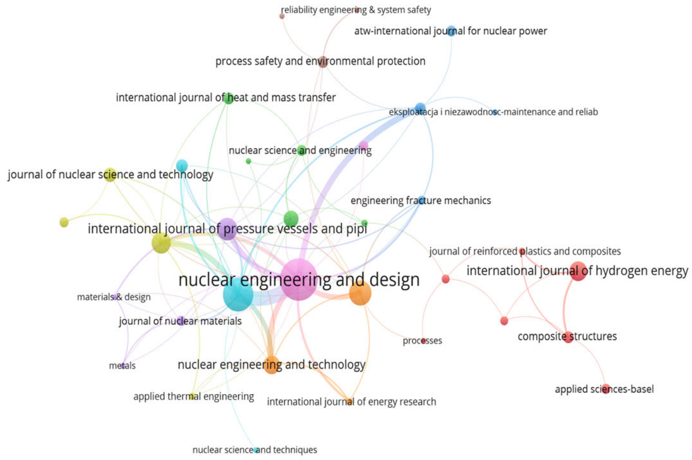
Jiaotong University, namely Qu Suizheng (14 publications), Tian Wenxi (13 publications), and Su Guanghui (11 publications). These three scholars also rank among the highest in terms of ACI (15.33, 15.86, and 17.38, respectively) within the top ten authors. Their publications suggest that these authors likely belong to the same research team, primarily focused on thermal-hydraulics and safety analysis in reactors. However, as shown in Figure 5, a significant collaborative network has yet to form among the core author teams, possibly due to the lack of close cooperation between these research groups. In the future, fostering collaboration and communication among key authors will be of great importance for advancing the field.

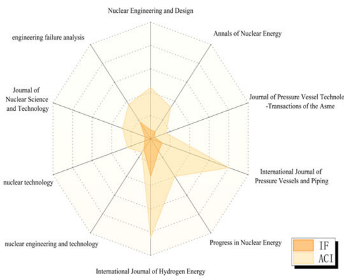
3.2.3. Subject Areas and Journal Distribution Analysis

Analyzing the disciplinary distribution of the literature helps to elucidate the primary research directions within the field. In the domain of pressure vessel and piping safety, the disciplinary scope is relatively broad. The top 15 disciplines by publication volume, as depicted in Figure 6, are the focus of this study. The data indicate that the top three disciplines, ranked by publication volume, are Nuclear Science Technology, Engineering Mechanics, and Energy Fuels. Among these, "Engineering, Mechanical" plays a crucial role in the design, analysis, assessment, and maintenance of pressure vessels and piping. This discipline encompasses various subfields, including the mechanics of materials, structural mechanics, and elasticity, which form the theoretical foundation essential for ensuring the safety of pressure equipment. Research in the field of "Energy Fuels" is closely tied to the practical applications of pressure vessels and piping, particularly in the processes of energy production and transportation. Many pressure vessels and piping are employed for the storage, transmission, and conversion of fuels, as well as in related safety technologies. Simultaneously, "Nuclear Science Technology" emerges as a significant research direction, covering topics such as nuclear reactors, nuclear energy utilization, and radiation protection, all of which are closely associated with the safety of pressure vessels and piping. The combined analysis of these disciplines reveals that pressure vessel and piping safety is a highly interdisciplinary research field, involving multiple key technological directions.

After the disciplinary distribution patterns in the field of pressure vessel and piping safety have been analyzed, the distribution of research across academic journals is further examined in this paper. By conducting a cluster analysis on journals with more than three publications, 35 nodes were identified, resulting in nine distinct clusters. The detailed information for each cluster, as well as the top 10 journals by publication volume, are presented in Figure 6. The figure reveals that the three largest clusters are represented by the colors red, green, and blue. Journals in the red and blue clusters are primarily related to materials, engineering, and mechanical sciences, while those in the green cluster predominantly focus on energy and thermodynamics. An analysis of the key parameters for the top ten journals by publication volume (shown in Figure 6) reveals that the three journals with the highest publication counts are "*Nuclear Engineering and Design*", "*Annals of Nuclear Energy*", and the "*Journal of Pressure Vessel Technology-Transactions of the ASME*". However, aside from "*Nuclear Engineering and Design*", the remaining two journals exhibit relatively low ACI and impact factors, indicating their limited influence within the field of pressure vessel and piping safety research. In terms of ACI, the top three journals are the "*International Journal of Hydrogen Energy*", "*International Journal of Pressure Vessels and Piping*", and "*Nuclear Engineering and Design*", with impact factors of 8.1, 3.0, and 1.9, respectively. The radar chart in Figure 6 shows a positive correlation between the ACI and impact factor for most journals, with the exception of "*Nuclear Engineering and Design*". This suggests that in the field of pressure vessel and piping safety, there is a certain correlation between a journal's impact factor and its average citations per article but no significant relationship with the publication volume. Considering the combination of the publication volume, ACI, and impact factor, this paper concludes that articles published in the "*International Journal of Hydrogen Energy*", "*International Journal of Pressure Vessels and Piping*", and "*Progress in Nuclear Energy*" hold high academic value.

Top 10 Subjects in the field of pressure vessel and piping safety research	
Web of Science Category	**QTY**
Nuclear Science Technology	301
Engineering Mechanics	129
Energy Fuels	63
Materials Science Multidisciplinary	54
Engineering Multidisciplinary	52
Mechanics	43
Engineering Chemical	39
Chemistry Physical	27
Metallurgy Metallurgical Engineering	27
Electrochemistry	26
Thermodynamics	24
Materials Science Composites	21
Materials Science Characterization Testing	19
Physics Applied	15
Chemistry Multidisciplinary	14





Top 10 journals in the field of pressure vessel and piping safety research			
Literature Resources	**QTY**	**ACI**	**Impact Factor**
Nuclear Engineering and Design	97	11.04	1.9
Annals of Nuclear Energy	66	8.33	1.9
Journal of Pressure Vessel Technology-Transactions of the Asme	37	3.95	1.0
International Journal of Pressure Vessels and Piping	31	20.06	3.0
Progress in Nuclear Energy	28	10.00	3.3
International Journal of Hydrogen Energy	24	21.25	8.1
Nuclear Engineering and Technology	21	3.67	2.8
Nuclear Technology	18	6.00	1.5
Journal of Nuclear Science and Technology	13	7.23	1.5
Engineering Failure Analysis	11	9.09	4.4

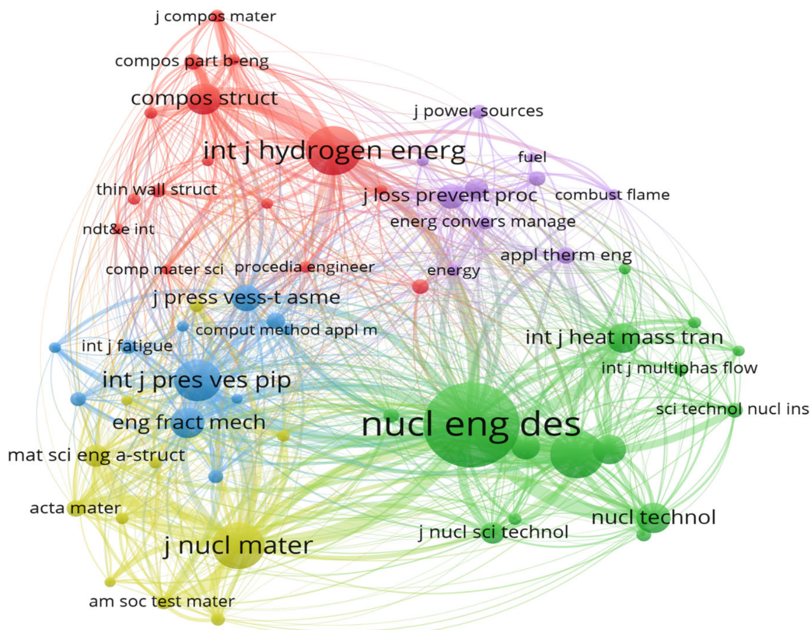
Figure 6. Analysis of the distribution of disciplines and journals of the related research literature in the field.

3.3. *The Research Current Status and Basic Knowledge Analysis for Pressure Vessel and Piping Safety Studies*

The concept of co-citation analysis was first introduced by American information scientist H. Small in 1973 [34]. Its fundamental principle is that when two documents are cited simultaneously by a third document, a co-citation relationship is established between them [35]. As research has progressed, the scope of co-citation analysis has expanded from individual documents to encompass broader domains such as authors and journals. Through co-citation analysis, researchers are able to systematically grasp the evolving knowledge structure of a particular field, identify key journals and seminal works, and uncover trending research topics [36]. This method provides an effective tool for academic inquiry, facilitating the revelation of the underlying patterns and trends in knowledge development.

3.3.1. Highly Co-Cited Journals Analysis

Journal co-citation analysis is a method that reveals relationships between journals through their external citation patterns. This analytical approach enables the identification of connections between journals and helps to discern core journals within a field [37]. In this study, VOSviewer was employed to analyze journals with co-citation frequencies exceeding 30, resulting in 62 nodes divided into five clusters (as shown in Figure 7). The size of each node represents the total co-citation frequency of the journal, with larger nodes indicating higher co-citation counts. The thickness and length of the lines connecting nodes reflect the strength of co-citation relationships between journals: the shorter and thicker the line, the higher the frequency with which the journals are cited together, indicating a closer relationship between them.



Top 10 journals with high citations for pressure vessel and piping safety research				
NO.	**Highly Co-cited journals**	**Citation**	**Links**	**Cluster**
1	***Nuclear Engineering and Design***	1500	18,963	🟢
2	***International Journal of Hydrogen Energy***	547	8938	🔴
3	***Annals of Nuclear Energy***	504	7885	🟢
4	***Journal of Nuclear Materials***	489	11,029	🟡
5	***International Journal of Pressure Vessels and Piping***	401	7511	🔵

Top 10 journals with high citations for pressure vessel and piping safety research				
NO.	**Highly Co-cited journals**	**Citation**	**Links**	**Cluster**
6	***Composite Structures***	233	5330	🔴
7	***Nuclear Technology***	226	3160	🟢
8	***Engineering Fracture Mechanics***	221	3473	🔵
9	***Progress In Nuclear Energy***	217	3919	🟢
10	***International Journal of Heat and Mass Transfer***	217	3375	🟢

Figure 7. Distribution analysis of highly co-cited journals in the field of pressure vessel and piping safety.

Figure 7 reveals that the clusters of substantial size are represented by the red, green, and blue clusters. A comprehensive analysis of the journals within these clusters indicates that the green cluster primarily encompasses research related to technology, design, and safety within the nuclear energy sector, with prominent journals including "*Nuclear Engineering and Design*", "*Annals of Nuclear Energy*", and "*Nuclear Technology*". The purple cluster pertains to studies on nuclear materials, as exemplified by the "*Journal of Nuclear Materials*". The majority of journals within the red cluster focus on composite structures and composite materials, such as "*Composite Structures*". In contrast, the blue cluster primarily addresses the assessment of engineering structural integrity and the fracture behavior of engineering materials, featuring journals like "*International Journal of Pressure Vessels and Piping*" and "*Engineering Fracture Mechanics*". The yellow cluster is associated with process safety, represented by the "*Journal of Loss Prevention in the Process Industries*". The table in Figure 7 lists the top ten journals ranked by their co-citation frequency along with their associated parameters. Among these, "*Nuclear Engineering and Design*", "*International Journal of Hydrogen Energy*", and "*Annals of Nuclear Energy*" occupy the top three positions in co-citation frequency, with 1500, 547, and 504 citations, respectively. Based on the integrated analysis of clustering and highly co-cited journals, we identify "*Nuclear*

Engineering and Design", "*International Journal of Hydrogen Energy*", and "*International Journal of Pressure Vessels and Piping*" as the primary source journals for research in pressure vessel and piping safety.

3.3.2. High-Cited Literature Analysis

The co-citation relationships among publications reflect the interconnections between them. A higher frequency of co-citation between two articles typically indicates a stronger relevance in their academic research directions [38]. Table 3 presents the top ten publications ranked by citation frequency within this research domain. The table includes pertinent information regarding these works, such as the publication details, authors, year of publication, as well as the number of co-authored institutions and countries.

Table 3. The top 10 most cited core publications.

NO.	Title	Journal	Author	Year	IN	CN	Cations	ACY
1	A review on different pipeline fault detection methods	*Journal of Loss Prevention in the Process Industries*	Datta et al. [39]	2016	1	1	255	31.56
2	Developing structural, high-heat flux and plasma facing materials for a near-term DEMO fusion power plant: The EU assessment	*Journal of Nuclear Materials*	Stork et al. [40]	2014	5	4	211	20.18
3	Pipeline corrosion and leakage monitoring based on the distributed optical fiber sensing technology	*Measurement*	Ren et al. [41]	2018	3	1	195	31.00
4	Experimental and numerical studies on the explosion severities of coal dust/air mixtures in a 20-L spherical vessel	*Powder Technology*	Cao et al. [42]	2017	3	1	193	25.75
5	Effects of hydrogen and initial pressure on flame characteristics and explosion pressure of methane/hydrogen fuels	*Fuel*	Li et al. [43]	2018	1	1	135	20.29
6	Integrated leakage detection and localization model for gas pipelines based on the acoustic wave method	*Journal of Loss Prevention in the Process Industries*	Jin et al. [44]	2018	1	1	133	12.27
7	Small and Medium sized Reactors (SMR): A review of technology	*Renewable and Sustainable Energy Reviews*	Rowinski et al. [45]	2015	2	2	131	14.3
8	Explosion characteristics of argon/nitrogen diluted natural gas–air mixtures	*Fuel*	Zhang et al. [46]	2014	2	1	130	11.91
9	Effects of hydrogen on combustion characteristics of methane in air	*International Journal of Hydrogen Energy*	Ma et al. [47]	2014	1	1	119	10.82
10	Influence of inert gas addition on propagation indices of methane–air deflagrations	*Process Safety and Environmental Protection*	Mitu et al. [48]	2016	3	1	115	12.89

Note: IN: number of institutions; CN: number of countries; ACY: average citations per year.

Table 3 reveals that among the top ten most cited publications, six exhibit inter-institutional collaboration, while only two involve multinational cooperation. This indicates that, although a significant collaborative framework has emerged within research on pressure vessel and piping safety, such collaborations are primarily confined to institutions within the same country, lacking the establishment of a comprehensive international academic cooperation network. The most frequently cited publication is an article by Datta et al. [39], titled "A Review on Different Pipeline Fault Detection Methods", published in 2016 in the "*Journal of Loss Prevention in the Process Industries*". This article has garnered 255 citations, with an average annual citation frequency of 31.56, significantly surpassing that of other publications listed in Table 2. The paper systematically evaluates the advantages and disadvantages of various pipeline fault detection methods. The second most cited work is a study by Stork et al. [40], which discusses the findings of the European Union's Materials Assessment Group in the context of implementing the EU Fusion Roadmap. The third publication ranking highly in citations is authored by Ren et al. [41], who proposed a novel method for effectively monitoring pipeline corrosion and leakage based on circumferential strain theory and distributed fiber sensor technology.

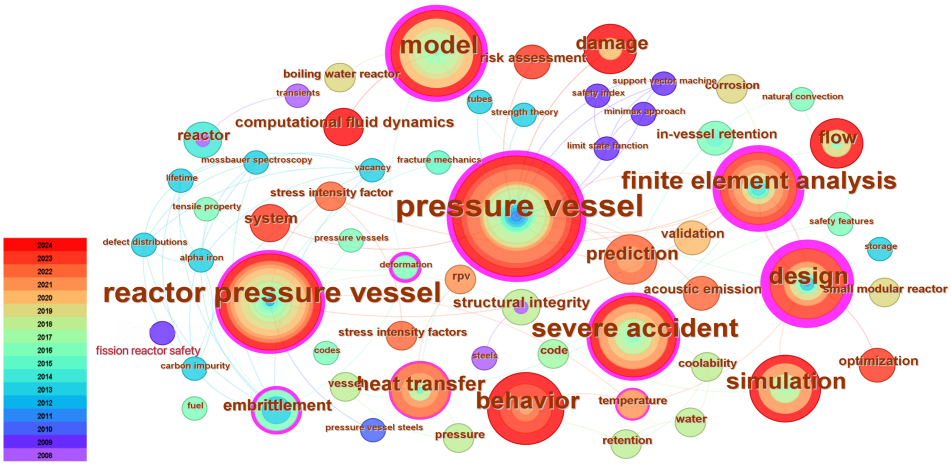
Among the remaining seven publications, five are focused on the study of fuel combustion and explosion characteristics. For instance, Cao et al. [42] conducted experiments using a 20 L spherical vessel and numerical simulations to assess parameters indicative of explosion severity, revealing the underlying mechanisms of coal dust explosions. Li et al. [43] systematically investigated the flame characteristics and explosion pressures in lean, stoichiometric, and enriched mixtures by adjusting the blending ratios of hydrogen and the initial pressure. The research by Ma et al. [47] concentrated on the influence of hydrogen on the combustion characteristics of methane in air, employing both experimental and numerical simulation approaches to explore methane combustion under varying hydrogen blending ratios. Zhang et al. [46] conducted an in-depth analysis of explosion characteristics through measurements of pressure variations within the vessel, concluding that a reduction in initial pressure narrows the range of flammability limits. This phenomenon arises because an increase in the initial pressure decreases the intermolecular spacing of gas molecules, thereby enhancing the likelihood of effective collisions and facilitating the progression of chemical reactions. Mitu [48] focused on observing the propagation characteristics of laminar deflagration in methane–air mixtures under dilution with several inert gases. Meanwhile, Jin et al. [44] developed a simulation platform for leakage in high-pressure, long-distance circular piping and proposed an integrated model for detecting and locating gas pipeline leaks. Rowinski et al. [45] provided a review of the designs of 25 small- and medium-sized reactors that are currently under development, seeking licensure, or have already been commissioned.

3.4. Research Hotspots and Frontier Analysis for Pressure Vessel and Piping Safety Studies

3.4.1. Research Hotspot Analysis

In order to analyze the research hotspots in the field of pressure vessels and piping safety in recent years, a keyword co-occurrence analysis was conducted using CiteSpace software in this study [49]. Prior to visualization, the software was configured to use a one-year time slicing approach and employed the Minimum Spanning Tree method for network pruning. By selecting keywords that ranked within the top 2% in terms of co-occurrence frequency, we ultimately generated a co-occurrence network diagram consisting of 64 nodes and 127 edges, with a network density of 0.0451, as illustrated in Figure 8. In this diagram, the size of each node reflects the frequency of keyword occurrences, with larger nodes indicating a higher frequency. The color of the nodes represents the timing of co-occurrences, with darker colors signifying more recent co-occurrence events. Furthermore, centrality is employed to assess whether a node serves a pivotal role within the research domain (a centrality value greater than 0.1 indicates strong centrality), which aids in inferring the research hotspots within the field [50,51]. By examining the accompanying table in Figure 8, we observe that keywords such as "pressure vessel", "model", "reactor pressure vessel", and "finite element analysis" exhibit both a high frequency of occurrence and centrality.

Figure 9 illustrates a clustering structure composed of 64 nodes, with a Q value of 0.7304 and an S value of 0.9026. Based on these metrics, it can be concluded that this clustering structure is significant and that the clustering information is valid [52]. The six identified clusters are as follows: Cluster #0 (pressure vessel), Cluster #1 (severe accident), Cluster #2 (risk assessment), Cluster #3 (numerical simulation), Cluster #4 (finite element analysis), and Cluster #5 (boiling water reactor). Drawing upon hierarchical clustering, the frequency of keyword occurrences, and centrality analysis, we categorize the recent research hotspots in the field of pressure vessels and pipeline safety into three principal categories: studies on the safety of pressure vessels and piping; investigations into the structural integrity, failure mechanisms, and stress analysis of pressure vessels and piping; and numerical simulation studies and thermohydraulic analyses of pressure vessels and piping under varying operational conditions.



Top10 keywords with the highest frequency in the field of pressure vessel and piping safety research				
NO.	Keyword	Count	Centrality	Year
1	pressure vessel	56	0.53	2009
2	reactor pressure vessel	38	0.28	2010
3	severe accident	27	0.27	2015
4	model	25	0.50	2016
5	finite element analysis	21	0.73	2013
6	design	20	0.88	2011
7	behavior	20	0.04	2021
8	simulation	16	0.05	2017
9	heat transfer	13	0.19	2015
10	flow	9	0.02	2016

Network : N = 64,E = 127

(Density = 0.0451)

Modularity Q = 0.7304

Weighted Mean

Silhouette S = 0.9026

Harmonic Mean

(Q,S) = 0.8075

Figure 8. High-frequency keywords in the field of pressure vessel and piping safety.

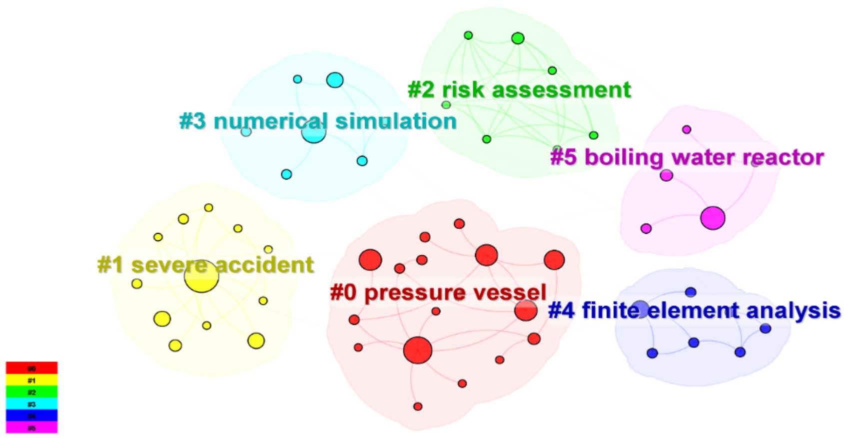


Figure 9. Clustering of keywords for pressure vessel and piping safety research.

(1) Research on the safety of pressure vessels and piping: This specifically entails a discussion of the behavior and consequence analysis of pressure vessels and piping under varying operational conditions, particularly in accident scenarios or extreme conditions. The research focuses on several critical aspects, including the evolution of accidents, mechanisms of failure, predictions and control measures for accident consequences, and emergency response strategies.

Salehi et al. [53] investigated the impact of accumulator coolant injection into the Westinghouse reactor pressure vessel during a small-scale loss-of-coolant accident under severe accident conditions. Their findings indicated that the injection operation effectively delayed the failure of the reactor vessel. Bianchini [54], through an analysis of accident data, explored the frequency and characteristics of incidents within natural gas distribution systems, emphasizing the safety of fluid transport pipeline systems and accident prevention strategies. Liu et al. [55] conducted a study on check valve design based on a random forest model, aiming to enhance the safe application of pipeline systems, particularly under specific soil conditions such as soft ground. Wang [56] focused on ensuring the safety of pipeline systems in adverse geological conditions through design and operational controls. Patnaik [57] analyzed the effectiveness of carbon fiber-reinforced polymer protection for underground steel piping subjected to explosive loads. Fernandez-Cosials [58] explored emergency response strategies in the context of large-break loss-of-coolant accidents and assessed how to manage incidents when the safety systems of nuclear power plants fail through the flex emergency response strategy. Such studies concentrate on the performance and response measures of pressure vessels and piping in accident scenarios. Shirazi [59] elaborated on the influence of various stress factors and their combinations on different stages of pipeline crack mechanisms, including surface corrosion, initial crack growth, the reactivation of dormant cracks, and their propagation. Reyes [60] reviewed the existing safety assessment outcomes and compared them with the fusion safety standards guidelines of the U.S. Department of Energy, as well as insights drawn from the safety and licensing activities of the International Thermonuclear Experimental Reactor (ITER) project, thereby summarizing the latest perspectives on the safety of future nuclear fusion facilities.

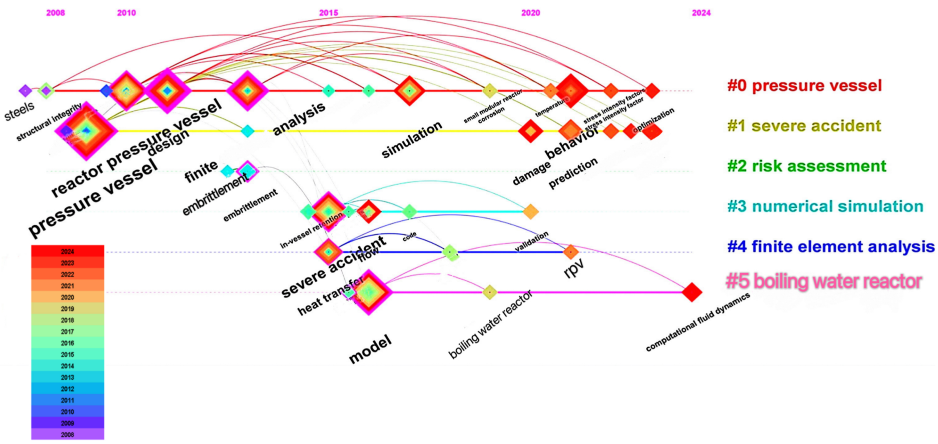
(2) Structural integrity, failure mechanisms, and stress analysis of pressure vessels and piping: This category of research primarily addresses the mechanical properties of materials used in pressure vessels and piping, along with their failure mechanisms, as well as the relationship between structural design parameters and the burst pressure. Huang et al. [61] investigated the stress and deformation characteristics of large heat exchangers (a specific type of pressure pipeline equipment) under high-temperature conditions, examining the effects of corrosion, elevated temperatures, and fluid loads on structural integrity. Lopes [62] focused on the plastic yielding behavior of thin-walled elastic–plastic pipes subjected to internal pressure and axial loads, revealing the deformation patterns and failure mechanisms under combined loading conditions. Xie et al. [63] studied the creep behavior of reactor pressure vessels at elevated temperatures, analyzing the interrelationships among various parameters in the creep constitutive equations, which is crucial for predicting the mechanical performance of materials under prolonged high-temperature exposure. Chen [64] introduced a "Failure Window Method" for predicting the burst pressure in piping, demonstrating that identifying the range of internal pressure leading to burst failure through this method is feasible. Zhu [65] conducted both theoretical and empirical evaluations of burst pressure prediction accuracy across different pipeline steel grades and sizes, utilizing a burst pressure database. Aljaroudi [66] proposed a risk-based comprehensive assessment method to predict the probability of failure in subsea oil piping and the potential consequences, with a particular focus on corrosion-related failures. This methodology integrates limit state functions with Monte Carlo simulations to calculate the probabilities of various failure mechanisms and quantifies the consequences of failures in terms of economic loss.

(3) Numerical simulation and thermohydraulic analysis of pressure vessels and piping under various operating conditions: Through numerical simulation methods, such as finite element analysis and computational fluid dynamics, researchers have investigated the stress distribution, fluid dynamics, heat transfer characteristics, and explosive impacts in pressure vessels and piping to gain a more profound understanding of their physical behavior under complex conditions, thereby enhancing the accuracy of safety assessments and design processes. Farkas [67] validated the accuracy of computational fluid dynamics models in simulating the primary coolant circuit of pressurized water reactors using experimental data from the Rossendorf Coolant Mixing Model, particularly in scenarios involving small-

scale coolant leakage events triggered by station power outages. The results indicated that the injection operation of the accumulator could effectively delay the failure of the reactor pressure vessel. Florescu [68] combined material strength theory with structural behavior analysis to compare numerical algorithms in classical problems with those based on finite element methods, estimating the critical buckling load of cylindrical components. Rahman et al. [69] explored design proposals for supercritical water-cooled reactors, analyzing the distribution of thermal flux density under high-temperature and high-pressure conditions and its implications for safety. Cao [70] focused on the accident behavior of supercritical water reactors under normal and abnormal conditions, discussing the principles of heat transfer within the melt pool and the two-dimensional thermal effects on the lower head wall, with findings indicating that the design possesses a significant critical heat flux density and safety margin. Fogaca [71] concentrated on the impact of honeycomb porous plate structures on thermal flux density, revealing that such configurations substantially increase the heat transfer area of the fluid, thereby enhancing cooling efficiency and elevating critical heat flux density levels. Kawsar [72] developed a probabilistic and numerical model to assess the risk posed by impact objects to subsea piping. This model employs scenario sampling methods to estimate the collision probability of impact objects and utilizes finite element analysis techniques to simulate and evaluate the potential consequences of such incidents.

3.4.2. Combing Evolution Path

The temporal visualization feature in CiteSpace software reveals the developmental trends of prominent keywords within a research domain over time, thereby providing a foundation for exploring research frontiers. Keyword emergence analysis can be employed to identify highly active research themes within a field and to illustrate emerging research trends. We conducted temporal visualizations and keyword emergence analyses on the collected literature, with the results presented in Figure 10.



Top 10 keywords related to burst intensity in pressure vessel and piping safety research					
NO.	Keyword	Year	Strength	Begin	End
1	behavior	2021	6.39	2021	2024
2	model	2016	5.81	2017	2020
3	pressure vessel	2009	5.01	2011	2012
4	prediction	2021	4.63	2021	2022
5	embrittlement	2013	2.90	2013	2016
6	reactor	2008	2.57	2008	2014
7	simulation	2017	2.42	2017	2018
8	severe accident	2015	2.31	2020	2021
9	in-vessel retention	2015	2.28	2015	2016
10	finite element analysis	2013	1.83	2021	2024

Figure 10. Map of keyword time zones in the field of pressure vessel and piping safety.

The frequency of keyword occurrences is represented by the size of the nodes, while the color of the inner circles indicates the different time periods in which the keywords appeared. The connecting lines between nodes denote co-occurrence relationships among the keywords; thicker lines signify stronger co-occurrence, and the color of the lines indicates the years in which the keywords co-occurred. From Figure 10, it is evident that by 2008, several keywords were already prominent, such as “structural integrity” and “steel”. In the realm of bibliometric research, frontier analysis relies on the fluctuations in the frequency of vocabulary or phrases, facilitating a precise understanding of research dynamics and highlighting how keywords can reveal emerging trends and shifts in research focus. The ranking of emergent keywords indicates that the top three are “behavior” (6.39), “model” (5.81), and “pressure vessel” (5.01). The frontier terminologies in the study of pressure vessel and pipeline safety predominantly include pressure vessel, non-destructive testing technology, optimization design, pressure vessel manufacturing, reactor-type pressure vessels, finite element analysis, non-destructive testing, austenitic stainless steel, and stress analysis. Consequently, research on pressure vessels and piping safety is primarily divided into two segments: studies addressing conventional design issues and those focused on novel composite materials, fatigue life, and failure prediction. The transition from conventional design to analytical design represents a particularly popular area of investigation.

4. Discussion

4.1. Challenges for Future Research

In the field of pressure vessels and piping safety, the primary challenges currently faced internationally include the following aspects:

(1) Addressing the safety risks associated with new technologies and materials: The development of new materials and the application of innovative technologies offer enhanced possibilities for the design and manufacturing of pressure vessels and piping. While these advancements offer opportunities, their associated safety risks remain underexplored. Ensuring the safety and reliability of these technologies necessitates further research and testing.

(2) Innovation and application of detection and monitoring technologies: Although traditional non-destructive testing techniques, such as ultrasound, radiography, and magnetic particle testing, continue to be widely employed, there remains a pressing need to enhance the precision and reliability of these methods in complex environments. Currently, novel sensor technologies, smart monitoring systems based on the IoT, and the application of AI algorithms in defect identification and predictive maintenance are garnering significant attention. However, the effective and large-scale integration of these technologies into existing systems presents both technical and economic challenges that must be addressed.

(3) Accident prevention and emergency management: Despite the existence of stringent design standards and detection technologies, incidents involving pressure vessels and piping continue to occur with notable frequency. A critical challenge faced by the international community remains how to effectively reduce the likelihood of accidents through comprehensive risk assessment and preventive measures prior to their occurrence, as well as ensuring timely and effective responses during such incidents. This challenge is particularly pronounced in high-density industrial areas or densely populated regions, where the consequences of accidents can be profoundly severe.

In the realm of pressure vessel and piping safety, China confronts challenges that encompass both shared global issues and distinct domestic factors. The following text outlines the principal challenges faced by China in this field:

(1) Aging equipment safety and innovation in detection technologies: The rapid industrialization in China has led to the prolonged use of numerous pressure vessels and piping systems, many of which were constructed during the 1980s and 1990s. As a result,

aging and corrosion issues have become increasingly prominent, making the effective management and safety assessment of these aging assets a critical challenge. While China has made significant progress in defect detection technologies—particularly in deformation monitoring and magnetic flux leakage detection—there remain technological bottlenecks, such as the detection of circumferential cracks, which has yet to reach internationally advanced levels. Furthermore, while existing leak detection technologies can address certain demands, they often fall short in the precise localization of minor leaks, particularly micro-leaks less than 1% in scale, which traditional methods struggle to detect. Overcoming these limitations may require the integration of big data technologies to enable more accurate detection and risk assessment.

(2) Enhancement of risk assessment models: In China, a framework has been established for quantifying risks and formulating mitigation measures. However, this system exhibits limitations in estimating failure probabilities, as it primarily relies on historical failure data. The lack of a dedicated failure database for pressure piping in China, along with the absence of relevant two-dimensional modeling simulation tools, hampers the ability of these historical data to accurately reflect the complex operating conditions and environmental factors present in actual field scenarios. Consequently, the current risk assessment outcomes may exhibit certain deviations in both precision and applicability. It is imperative to further refine data collection and model construction in the future to enhance the accuracy and scientific rigor of risk assessments.

(3) Application of intelligent and digital technologies: Currently, China remains in the nascent stages of smart piping development [73], particularly in the context of comprehensive lifecycle management, which encompasses planning and design, construction, project acceptance, operational monitoring, maintenance, and decommissioning. A systematic and holistic intelligent management framework has yet to be established for these processes. The absence of intelligent systems in this field hampers timely and accurate monitoring and prediction of equipment operational conditions, thereby adversely affecting the efficacy of risk assessment and fault warning mechanisms.

4.2. Future Trends

In the face of potential deep-seated hazards, complex physical information systems, and the diverse risks encountered during the transition to digitalization, intelligence, and green low-carbon technologies, the safety landscape for pressure vessels and piping has become increasingly severe. With the evolving social environment and technological advancements, the safety of pressure vessels and pipelines is progressing toward comprehensive enhancement.

(1) Intelligent transformation:

With the continuous development of the IoT, big data, and cloud computing technologies, the future of safety operations and maintenance is expected to gradually transition toward intelligent systems. Specifically, greater emphasis should be placed on the development of intelligent sensors to monitor the operational status of equipment in real time while collecting and transmitting critical health data via IoT technologies. Additionally, through big data analysis and the integration of machine learning algorithms, the operational trends of equipment can be predicted, enabling early fault detection and optimized maintenance decision support. Future research should focus on improving the accuracy and timeliness of data analysis algorithms, thereby facilitating the widespread application of intelligent monitoring systems in industrial settings.

(2) Emergency management and accident prevention technologies:

With the maturation of real-time data collection and analysis technologies, the establishment of more efficient accident prevention and emergency management systems has become possible. In the future, focus should be placed on developing accident prediction models based on real-time monitoring data integrated with AI technologies to enable intelligent identification and early warning of potential risks. With these early warning systems, more precise emergency plans can be formulated by the relevant departments, and rapid responses can be made through data-driven decision-making systems in the event of a sudden accident. Furthermore, research should focus on the collaborative mechanisms of emergency response to enhance the efficiency and coordination of all involved parties.

(3) Innovation in green development and environmental protection technologies:

With the growing global emphasis on environmental protection and sustainable development, the innovative application of green technologies and environmental measures will play a crucial role in future safety management systems. Future research should focus on the development of materials and technologies with low environmental impact, particularly green protective materials that reduce corrosion and aging, as well as technological innovations aimed at reducing energy consumption and emissions through optimized production processes. Furthermore, the lifecycle management of pressure vessels and piping will become a key component of future green development. The widespread application of environmentally friendly technologies is expected to not only enhance industrial safety but also reduce the negative environmental impacts of industrial activities, thereby driving the industry toward sustainable development.

The future trends outlined in this section—such as the smart transformation of maintenance practices, emergency management innovations, and green technology advancements—will inevitably have profound implications for both policy development and industrial practices. Governments and industry regulators must adapt their policies to facilitate the integration of these cutting-edge technologies. For instance, the implementation of real-time data-driven safety systems will require comprehensive updates to regulatory frameworks to ensure their effective integration into existing infrastructure. Moreover, the emphasis on green technologies will likely prompt the development of new environmental standards, promoting sustainability and minimizing the environmental impact of industrial operations. As these trends evolve, industry practices will shift towards a more data-centric and environmentally conscious approach. The integration of smart technologies will not only enhance the safety of pressure vessels and piping but will also improve operational efficiency, further pushing the industry towards safer, smarter, and more sustainable practices.

5. Conclusions

Bibliometric methods are employed in this paper to conduct a systematic analysis of the research literature in the field of pressure vessel and piping safety. The key findings of this study are presented as follows:

5.1. Theoretical Contributions

This is a literature review that conducts a quantitative analysis in the field of pressure vessel and piping safety, offering an objective knowledge structure and highlighting significant research themes. Despite the substantial volume of publications on pressure vessels and piping as critical research topics, there has been a dearth of quantitative analyses encompassing the entire field. This gap is aimed to be filled by collecting and analyzing bibliometric data from 2008 to 2024 within this research domain in this paper. Unlike traditional literature review methodologies, bibliometric analysis allows for the evaluation of a vast number of papers—ranging from hundreds to thousands—in a quantitative and statistical manner. The findings of this study reveal the objective knowledge structure pertaining to research on the safety of pressure vessels and piping.

The disciplines and primary source journals involved in the field of pressure vessel and piping safety are revealed by the results of this study. Research in this domain exhibits characteristics of multidisciplinary integration, primarily focusing on the disciplines of Mechanical Engineering, Energy Fuels, and Nuclear Science and Technology. The journals with the highest citation counts include the "*International Journal of Hydrogen Energy*", the "*International Journal of Pressure Vessels and Piping*", and "*Nuclear Engineering and Design*". Considering the publication volume, average citation rates, and impact factors, it is posited in this paper that "*Nuclear Engineering and Design*", "*International Journal of Hydrogen Energy*", and "*International Journal of Pressure Vessels and Piping*" are authoritative sources of publications within this field.

Keyword analysis has revealed the primary research directions within the field of pressure vessel and piping safety, which can be broadly categorized into three core areas. First, the focus is on the safety of pressure vessels and piping under various operational conditions, accident causation, and protective technologies. This line of inquiry primarily explores the occurrence and evolution of accidents, destruction mechanisms, consequence prediction, and corresponding control and emergency response measures. The second area of research centers on explosive behavior, failure mechanisms, and stress analysis, delving into the mechanical properties of materials used in pressure vessels and piping, as well as their failure modes, particularly the relationship between structural design parameters and the burst pressure. Finally, research is conducted on the physical behaviors of pressure vessels and piping under different operational conditions through numerical simulations and thermohydraulic analyses. Such studies leverage numerical simulation tools to examine stress distribution, fluid dynamics, heat transfer characteristics, and explosive shock effects, with the aim of enhancing safety assessments and design accuracy under complex operational scenarios.

5.2. Practical Contributions

This study reveals the key challenges and technological bottlenecks currently faced by the industry while also reviewing the latest research advancements and development directions. These findings provide theoretical support for further exploration of future industry trends and contribute to advancing in-depth research and practical applications in intelligent management, new material utilization, and green development within both academia and industry.

In the field of pressure vessel and piping safety, the main challenges currently faced internationally can be summarized into three areas: first, addressing the safety risks brought about by new technologies and materials; second, promoting the innovation and application of inspection and monitoring technologies; and third, strengthening the capacity for accident prevention and emergency management. In the context of China, the main challenges in pressure vessel and piping safety management include aging equipment and the detection of circumferential cracks. As equipment ages, material degradation accelerates the propagation of cracks, with circumferential cracks posing a particularly serious threat to structural integrity. Therefore, effective aging management and crack monitoring are critical to ensuring long-term safe operation. The industrial sector should actively adopt new technologies, such as big data-based safety management systems, to enable more efficient equipment maintenance and more accurate risk early warning. These trends will not only enhance safety but also drive the further improvement of industry standards and policies.

Looking ahead, the development trends in this field are primarily focused on the following areas:

(1) The intelligent transformation of safety operation and maintenance through IoT, big data, and cloud computing technologies: This involves the development of equipment fault prediction systems with autonomous learning capabilities, the collection of real-time data using IoT technology, and the enhancement of fault diagnosis accuracy through deep learning models. In terms of pipeline monitoring, embedded sensors are used to monitor the corrosion levels of pipelines, which are then connected to cloud platforms for data sharing and remote management.

(2) The establishment of an advanced accident prevention and emergency management system based on real-time data analysis: By integrating big data and AI technologies, multi-level risk prediction models are developed, and personalized emergency response plans are formulated for different types of faults. Specifically, an intelligent early warning system is developed to monitor the safety status of pressure vessels in real time. When abnormal data are detected, the system automatically triggers the emergency response mechanism and activates the backup system in advance.

(3) The innovative application of green development and environmental protection technologies: This includes the exploration of green anti-corrosion coatings based on nanotechnology and low-energy manufacturing processes that reduce carbon emissions. Advanced green materials, such as eco-friendly coatings, are employed to protect pressure vessels from corrosion while minimizing the environmental impact of the materials.

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Abbreviations

WoS	Web of Science
SCI-E	Science Citation Index Expanded
SSCI	Social Sciences Citation Index
TS	Topic
TD	Type of document
TP	Total publications
SOTC	Sum of times cited
ACI	Average citations per item
IoT	Internet of Things
IN	Number of institutions
CN	Number of countries
ACY	Average citations per year
AI	Artificial intelligence
ITER	International Thermonuclear Experimental Reactor

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