A bibliometric analysis of process safety research in China

Understanding safety research progress as a basis for making China's chemical industry more sustainable

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DOI
10.1016/j.jclepro.2020.121433

Publication date
2020

Document Version
Final published version

Published in
Journal of Cleaner Production

Citation (APA)
Yang, Y., Chen, G., Reniers, G., & Goerlandt, F. (2020). A bibliometric analysis of process safety research in China: Understanding safety research progress as a basis for making China's chemical industry more sustainable. *Journal of Cleaner Production*, *263*, Article 121433. https://doi.org/10.1016/j.jclepro.2020.121433

Journal of Cleaner Production 263 (2020) 121433

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

A bibliometric analysis of process safety research in China: Understanding safety research progress as a basis for making China's chemical industry more sustainable

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ARTICLE INFO

Article history:
Received 7 November 2019
Received in revised form
11 March 2020
Accepted 29 March 2020
Available online 4 April 2020

Handling Editor: Dr. Govindan Kannan

Keywords:
Process safety
Bibliometric analysis
China
International cooperation
Research trend
Sustainability

ABSTRACT

Along with the expansion of China's chemical industry, a series of catastrophic chemical accidents have occurred, often with severe human casualties, resulting in adverse effects on the sustainable development. In line with these developments, process safety research is also developing rapidly in China. This paper aims to present insights in the progress of process safety research in China using bibliometric analysis. The results indicate that in China the most productive authors, institutions, and provinces are located in economically developed coastal areas and in areas with more universities specializing in safety science and engineering. As for the international cooperation, the most significant collaborating countries are economically developed countries or China's neighbors, and these countries have published a large number of papers important in this field. The citation analysis shows that Chinese process safety research currently still has a relatively limited international impact. The analysis of hot topics shows that there currently are very few new methods or research topics introduced in recent years, and there is still significant room for the Chinese research community to improve in some subdomains of the research field. Based on these trends and apparent shortcomings in the literature, future research directions are proposed. The results contribute to understanding the overall situation of process safety research in China, and can serve as a high-level synthesis of the research field. This information is useful for developing research and development policies and industrial strategies, and benefits the safety and sustainability of China's chemical industries.

Contents

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https://doi.org/10.1016/j.jclepro.2020.121433
0959-6526/

1. Introduction

In line with its rapid economic development, China has become the second largest petrochemical country in the world. In 2018, the overall business income of the petroleum and chemical industries of China was 12.4 trillion CNY, with a 13.6% annual growth rate (Zeng and Hu, 2019). However, while the petrochemical industry brings significant economic and social benefits, it has also brought new safety and sustainable problems to Chinese communities, due to the complex and hazardous processes involved (Chen et al., 2019b; Wang et al., 2018b). Although the Chinese government has made safety a top priority, and while great efforts have been and are dedicated to chemical industrial safety (Wang et al., 2018b; Chen and Reniers, 2020; Wang et al., 2020), catastrophic accidents have occurred relatively frequently in the recent past, which have enormously adverse effects on the sustainable development and the cleaner production in China's chemical industry. For example, major explosions happened in the Henan Yima gasification plant in July 2019, resulting in 15 deaths and 16 serious injuries (Wang and Zhu, 2019). A fire and explosion accident occurred in Jiangsu Tianjiayi Chemical plant on March 21, 2019, killing 78 people and seriously injuring more than 600 people (Zhang et al., 2019). This is the deadliest industrial accident since the Tianjin Port fire and explosion in China on August 12, 2015 which left 173 people dead (Zhou and Fan, 2017). A major fire and poisonous accident in Shandong pharmaceutical company caused 10 deaths and 12 injuries on April 15, 2019 (Xinhua Net, 2019). This series of catastrophic accidents suggests that China's safety and sustainable development in the chemical industries remains grim. Therefore, it is of high socio-economic importance to further develop accident prevention and implement safety control measures in China's chemical industries, and to strengthen the scientific community concerned with this domain, such that a safe, sustainable and cleaner chemical process can be ensured.

Sustainability is widely recognized as one of the most important challenges facing the world today, and numerous studies confirm that safety and sustainability are closely linked (Wang and Wu, 2020). Through a systematic literature review and various practical examples, Nawaz et al. (2019) argue that focusing on safety initiatives can contribute towards sustainability because both disciplines share the same pillars: environment, society, and economy. Therefore, the advancements in the field of safety may be extended further to overcome the operational shortcomings of sustainable development. Historical events suggest that disregarding the safety-sustainability nexus may lead to more dangerous consequences than ever before, due to the growing human interest to adopt new technologies and products (Nawaz et al. (2019)). Aberdeen Group conducted a survey, at the organizational level, showing that 71% of the respondents ($n = 110$) believe that the health, safety, and environment (HSE) department in organizations should be responsible for the organizations' sustainability. This indicates that HSE professionals can play an important role in achieving the sustainable aspirations of their organizations. Based on a semi-structured interview questionnaire on how industrial occupational safety and health innovation affects sustainable development of socio-economical aspects, Jilcha and Kitaw (2017) argue that the innovation of workplace safety and health lead to sustainable development through healthy people, safer workplace, reduced cost of accidents, controlled environment, managed workplace accidents and improved workplace safety knowledge. Liew et al. (2014) used text mining techniques to analyze 112 sustainability reports of major companies in the chemical process industry, revealing that safety is one of the top sustainability focus topics of the chemical process industry. Therefore, safety is a key element for sustainable development of chemical industries.

Process safety is a relatively young and evolving field, which aims at preventing and mitigating major process accidents such as fires, explosions, and toxic releases. Thus, process safety is a core aspect of safe, effective and sustainable production in the chemical industries. While it links to various aspects of the safety sciences, it traditionally focuses mostly on hazard identification, risk assessment and management (Khan et al., 2015; Kletz, 2012). The term "process safety" originates from the 1960s, whereas several process safety efforts have been successfully applied to process industries even before that period (Khan et al., 2015). The scientific study of process safety began around the same time, with the 1970s widely being considered as the golden decade of research in this field (Khan et al., 2015; Kletz, 2012; Planas et al., 2014). Several research institutions dedicated to process safety have been set up worldwide, with Khan et al. (2015) and Amin et al. (2019) pointing to and discussing some influential institutions. Amin et al. (2019) show in a statistical analysis that as of August 2018, at least 7000

publications related to process safety were included in the three widely used academic databases: Scopus, Web of Science Core Collection (WoS), and Compendex. China, as an emerging region of academic activity, ranked as the third most productive country on process safety in the world, with 590 publications. Significantly, 575 of these publications (97.5%) were published since 2000 (Amin et al. (2019)). This shows that Chinese Scholars started relatively late in process safety research, but that the Chinese scientific community working in this area has developed rapidly in recent years.

Literature reviews are an effective way to systemize knowledge in a research domain. A number of articles have presented extensive reviews of various topics within process safety research. The review by Qi et al. (2012) focused on the critical challenges and needs of process safety in the new millennium. Khan et al. (2015) reviewed the methods and models for process safety focusing on three aspects: hazard identification and analysis, risk assessment, and safety management; furthermore proposing future research directions. Khan et al. (2016) proposed a framework for dynamic risk management based on a review of the main publications on dynamic risk assessment. Swuste et al. (2016) reviewed the process safety indicators from the scientific and professional literature in light of the following three themes: safety metaphors, models and theories; leading and lagging indicators; indicators of management and organization. Besserman and Mentzer (2017) summarized global process safety regulations and made comparisons between the United States, the European Union, the United Kingdom, China, and India. Jafari et al. (2018) identified 35 process safety indicators by reviewing 63 papers from 1990 to 2017. Mkpat et al. (2018) conducted an exhaustive literature survey on process safety education through a proposed process safety model. Specifically focusing on process safety in China, Zhao et al. (2013) identified process safety challenges for small and medium sized enterprises in China. A summary of lessons learned from chemical accidents in China was made by Zhao et al. (2014), who also proposed several recommendations for process safety management in China. Zhou et al. (2017) summarized 12 core elements for process safety management of China. Wang et al. (2018b) described opportunities, problems, challenges, and tasks based on hazardous chemical accidents and governmental regulations in China.

Although the above review articles provide valuable insights and research directions on process safety in general and with a focus on China, the analyses and syntheses do not provide a complete picture of process safety research in China. For example, useful knowledge about the development of the field, such as who are the most productive and influential authors; which are the most active countries, institutions, journals and conferences; what author collaboration networks exist in the field; what are narrative clusters in the research domain; and what are topical research trends in the field of process safety, are questions which difficult to answer using traditional review methodologies (Grant and Booth, 2009). Such information however is very useful for researchers on process safety, to understand the structure of their research field, its narrative clusters and trends. As outlined above, such knowledge on process safety research can contribute to achieve more sustainable industrial practices.

Bibliometric analysis is an effective way to address the above questions by giving high-level insights in characteristics of a large number of publications within a given research domain. By quantitatively analyzing citation-related information of authors, institutions or journals using statistical methods, networks and clusters can be identified within the research domain (Daim and Pilkington, 2018). Through visualization of such citation-related structural clusters and mined textual data, insights in the research domain can be obtained (Li et al., 2020).

Bibliometric analysis has been applied to provide insights in several sub-domains of safety science, such as university laboratory safety (Yang et al., 2019), safety culture (van Nunen et al., 2018), construction safety (Jin et al., 2019), and road safety (Zou et al., 2018); see Li et al. (2020) for a recent overview. Amin et al. (2019) also applied the bibliometric analysis method to the field of process safety, to quantitative investigate the overall situation of process safety research. However, this bibliometric analysis only provides selected insights at the global level, without much detailed information about China. Given the fast development of the process safety research domain in China as indicated above, this article aims to specifically focus on this research domain using bibliometric methods, providing insights in its structure and development, to help scholars have a clear understanding of the overall research situation and shortcoming of China's process safety research. This can be beneficial to the safety and sustainable development of China's and even the world's chemical industry.

The analyses presented in the remainder of this article are structured around the following questions: (i) What are the trends in terms of the number of publications on process safety in China; (ii) Who are the most productive and influential scholars, institutions, provinces and conferences in China; (iii) What international cooperation relationships exist based on the countries, institutions, and authors; (iv) What are the most impactful articles and journals in terms of their citations and co-citation among Chinse scholars; (v) What are the main topics and what are their trends; (vi) What funding agencies and grants are the most important to support the sustainable development of the field?

The remainder of this article is organized as follows. Section 2 introduces the data sources used, and outlines the bibliometric method used in the analyses. Section 3 presents the results of the analysis, providing answers to the above listed research questions. Several significant findings and future directions of process safety research in China are discussed in Section 4, further contributing to the advancement of this research field and the sustainable chemical industries in China. Section 5 concludes.

2. Methodology

2.1. Search and exclusion criteria

The scientific publications used in this study were retrieved on September 5, 2019 from SCI-EXPANDED, SSCI, A&HCI, CPCI—S, CPCI-SSH and ESCI citation index databases in the Web of Science Core Collection, which are the most authoritative and widely used databases in bibliometric analysis, with highest data quality (Li et al., 2020). The search process and the steps to obtain the final dataset for analysis this study is shown in Fig. 1. The topic of analysis "process safety" consists of two key elements (i.e., "process" and "safety"), thus the search topics included two strings: a process-related string and a safety-related string (see Appendix A).

These strings were combined in the Web of Science search using "AND". The use of quotation marks in the strings indicates that only the exact phrases in the quotes can be retrieved. Moreover, both singular and plural versions of relevant terms are applied to avoid relevant missing publications. Corresponding to the longest available period in the WoS database as accessible at the KU Leuven, the time span was selected from 1955 to 2019. The latest update date of WoS for the current analysis was September 4, 2019. An initial search yielded 25,419 results, whereas 2996 publications remained when further limiting the country of origin to People's Republic of China. Hong Kong, Macao and Taiwan, as three special administrative regions of China, are divided into three separate regions in the Web of Science database. Therefore, the present work only collected the publications in collaborations with the mainland of

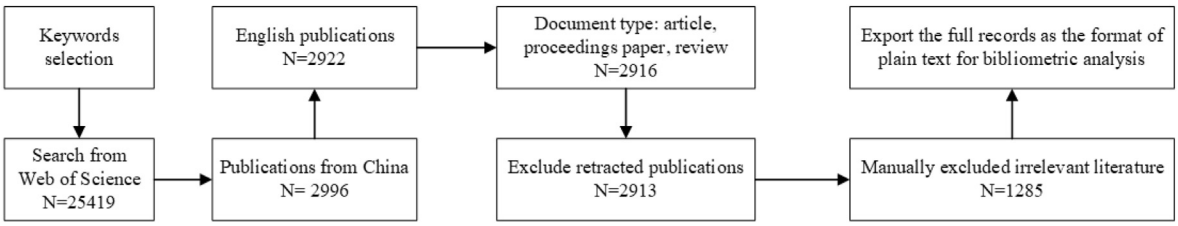

Fig. 1. Flowchart illustrating the search and database construction process of academic publications addressing process safety in China.

China, excluding Hong Kong, Macao and Taiwan. The language of publication was limited to English, the currently most widely used academic language. As document types, articles, proceedings papers, and review articles were included. Due to the limitations of the search of WoS, it is necessary to further manually exclude documents in this dataset which do not address process safety, such as environmental and ecological risk emerging from the chemical industries, food safety, nuclear safety, etc. The manual filtering was performed by the first author based on the titles and abstracts of the papers. Finally, a total of 1285 publications were considered within scope and retained for further analysis in the present work. A full list of publications included in the final dataset can be obtained from the supplementary document in this paper (available online). The full records and cited references of these publications were exported as plain text for further bibliometric analysis. It should be noted that the reason why the number of publications is quite different from Amin et al. (2019) is that these authors only searched for keywords in the titles, while the present work searched for keywords in the titles, keywords and abstracts.

2.2. Bibliometric analysis tool

In order to realize the quantitative analysis and visualization of the retrieved publications of process safety research in China, VOSviewer, a software tool for analyzing and visualizing scientific literature developed by van Eck and Waltman (2010), was utilized in the present work. VOSviewer can be used to visualize co-authorship networks of authors, institutions and countries/regions, co-citation networks of articles and journals, and co-occurrence networks of keywords. Clustering techniques allow the visual identification of structural patterns in the research domain, and text mining functionalities allow for identifying patterns and trends in topics addressed in the field (Van Eck and Waltman, 2007). Li et al. (2020) present an overview of the meaning, interpretation, and construction of bibliometric mapping techniques included in the VOSviewer software. VOSviewer has been widely used in the field of bibliometric analysis of safety science (Li et al., 2017; Jin et al., 2019; Merigó et al., 2019; Amin et al., 2019; van Nunen et al., 2018; Yang et al., 2019; Zou et al., 2018; Yang and Qiu, 2019; Huang et al., 2020; Tao et al., 2020), see Li et al. (2020) for an overview. In addition, the data analysis function of Web of Science was also used in the present study, in combination with VOSviewer for citation analyses and counts of publications per year.

3. Results

3.1. Publication trends

Fig. 2 illustrates the annual number of journal papers (including articles and review articles) and conference papers on process safety research in China, and the cumulative number of papers. It is evident that the number of annually published journal papers has overall steadily increased since about 2004. The annual total number of publications and the annual number of conference papers show a fluctuating growth trend. The number of journal papers each year was less than that of conference papers before 2015, but it exceeded the number of conference papers since 2015.

According to the dataset retrieved from Web of Science, the earliest paper on process safety written by Chinese scholars in English, was published in January, 1996 (Tan and Reynolds, 1996). The number of articles in English was relatively low before 2008, i.e. this period can be regarded as the initial stage of internationalization of the process safety research in China. Considering that the publications retrieval was performed in September, 2019, the number of publications in 2019 is not complete. Disregarding this year, Fig. 2 shows that the total number of articles published in English has seen an approximately linear growth since 2008. Therefore, 2008 can be considered a pivotal year in the internationalization of China's process safety research. This result is consistent with the growth in the number of colleges and universities with safety related majors in China, which indicates that the fastest growth year was 2008 (Jiang et al., 2019).

3.2. Cooperation network analysis

3.2.1. Influential authors and their research interests

Scholars with a large number of highly-cited publications often dominate the conceptual and methodological trends of research domains, and have an important role in the development of the field. Hence, identifying those influential scholars allows obtaining insights in who leads the academic discourse. Due to the characteristics of Chinese names, their abbreviations and even full names can easily lead to duplicate entries in the Web of Science database, resulting in different authors being identified as the same author.

Therefore, the present work identified the top 10 most productive Chinese authors (together having published 216 articles, accounting for 16.8%) by comparing their institutions and ORCID ID, and their information and research interests which were obtained from their university website profiles, see Table 1. The most productive and most cited author is Laibin Zhang from China University of Petroleum (Campus Beijing) with 48 publications and 364 citations, followed by Juncheng Jiang from Nanjing Tech University with 47 publications, and Guohua Chen from South China University of Technology with 30 publications. Wei Liang from China University of Petroleum (Campus Beijing) is the second most cited author with 253 citations. With 13.32 citations per paper, he is the author with the highest average number of citations, indicating that his research received relatively high attention from other scholars. Zongzhi Wu is a scholar who works in the government (State Administration of Work Safety and China Academy of Safety Science and Technology), and who also carried out research related to process safety in several universities, including China University of Mining & Technology (Campus Beijing) and Nankai University. Therefore his 18 publications are distributed among these four institutions. Focusing on the research topics addressed, the authors

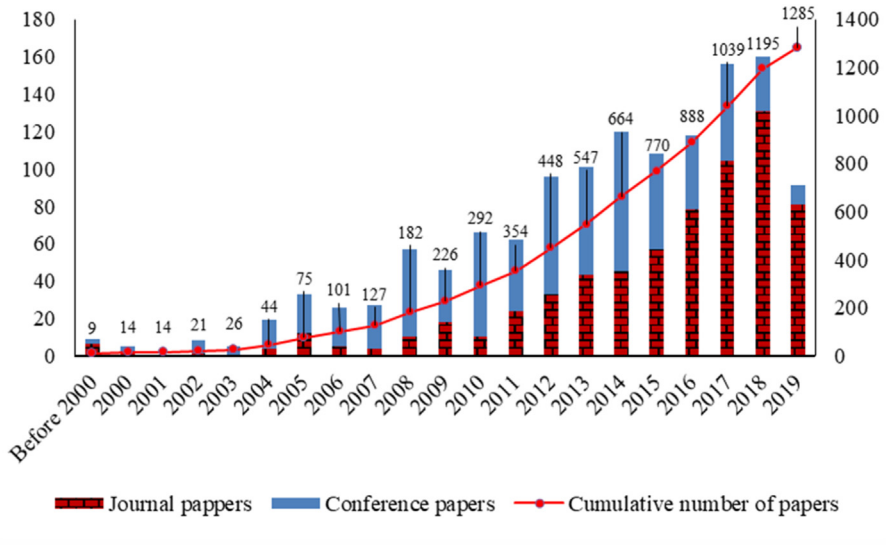

Fig. 2. Annual and cumulative distribution of the number of research publications on process safety in China.

Table 1
Top 10 most productive Chinese authors on process safety research.

Rank	Author	Institution	TP	TC	AC	Main research interests
1	Laibin Zhang	China University of Petroleum (Campus Beijing)	48	364	7.58	Safety Detection, Diagnosis and Dynamic Assessment of Oil and Gas Production Process; Early Warning of Large Power Units for Oil Well Pipe and Oil and Gas Production
2	Juncheng Jiang	Nanjing Tech University	47	217	4.62	Hazardous Chemicals and Chemical Process Safety; Urban Public Safety and Emergency Response
3	Guohua Chen	South China University of Technology	30	160	5.33	Industrial Safety and Risk Assessment; Reliability, Integrity and Safety of Process Equipment and Pipeline
4	Zhirong Wang	Nanjing Tech University	29	91	3.14	Fires and Explosions Prevention; Hazardous Chemicals and Chemical Process Safety; Safety Management Engineering; Urban and Industrial Safety
5	Jinsong Zhao	Tsinghua University	26	239	9.19	Chemical Safety and Risk Management Technology
6	Jinqiu Hu	China University of Petroleum (Campus Beijing)	23	82	3.57	Monitoring and Early Warning Data Science of Oil and Gas Equipment
7	Wenhua Song	Tianjin Polytechnic University	22	19	0.86	Fires and Explosions Prevention Engineering; Safety System Engineering; Industrial Safety Technology and Engineering; Safety Evaluation; Safety Monitoring and Management Engineering
8	Wei Liang	China University of Petroleum (Campus Beijing)	19	253	13.32	Monitoring and Diagnosis of Oil and Gas Storage and Transportation Equipment; Leakage Monitoring and Safety Assessment of Oil and Gas Pipeline
9	Guoming Chen	China University of Petroleum (Campus Tsingtao)	18	38	2.11	Safety Technology of Offshore Structures; Oil and Gas Safety Engineering; Information and Intelligent Technology of Safety Engineering; Equipment Technology for Offshore Oil and Gas Exploitation
10	Zongzhi Wu	China University of Mining & Technology (Campus Beijing) State Administration of Work Safety China Academy of Safety Science and Technology Nankai University	18	53	2.94	Major Hazard Monitoring; Risk Assessment; Accident Emergency Response; Safety Management

Notes: TP = Total publications; TC = Times cited; AC = Average number of citations per publication.

from China University of Petroleum (Laibin Zhang, Jinqiu Hu, Wei Liang and Guoming Chen) mainly worked on oil and gas safety, whereas other authors focused on safety and accidents in chemical industries, dealing with topics such as risk assessment, accident emergency response, monitoring, and early warning.

3.2.2. *Influential research institutions*

The analysis of the number of publications and the collaborations of Chinese research institutions on process safety allows obtaining insights in their comparative productivity and linkages to other academic, government, and industry institutions. The 1285 retrieved publications involved by 704 institutions, including the international partners with whom Chinese institutions collaborate. Table 2 shows the top 15 most productive Chinses institutions on process safety research, which together account for 622 publications, or 48.4% of the total publications. This result shows that a small number of institutions dominate the field of process safety in China. China University of Petroleum, with campuses in Beijing and Tsingtao (Shandong Province), is the most productive institution with 169 publications, followed by Nanjing Tech University (68 publications) and Tsinghua University (67 publications). Tsinghua University ranks second in total number of citations, but first in average number of citations. The big three state-owned Chinese oil companies and their branches, i.e. CNOOC, CNPC and SINOPEC, are the only industrial organizations in the top 15 of most productive institutions: the other twelve institutions are universities. Hence, universities are of key importance to drive and direct process safety research in China, with intersectoral collaborations between

Table 2
Top 15 most productive Chinses institutions on process safety research.

Rank	Institution	Province	TP	TC	AC	TL
1	China University of Petroleum	Beijing Shandong	101 68	805	4.76	39
2	Nanjing Tech University	Jiangsu	67	239	3.58	19
3	Tsinghua University	Beijing	60	394	6.57	17
4	Beijing University of Chemical Technology	Beijing	55	356	6.47	6
5	South China University of Technology	Guangdong	39	172	4.41	6
6	East China University of Technology	Shanghai	37	123	3.32	11
7	Dalian University of Technology	Liaoning	35	119	3.4	5
8	Zhejiang University	Zhejiang	31	158	5.1	11
9	China National Offshore Oil Corporation (CNOOC)	Beijing	31	89	2.87	25
10	Xi'an Jiaotong University	Shaanxi	29	147	5.07	4
11	China National Petroleum Corporation (CNPC)	Beijing	28	73	2.61	20
12	China Petroleum and Chemical Corporation (SINOPEC)	Beijing	28	46	1.64	13
13	Beijing Institute of Technology	Beijing	28	130	4.64	14
14	Tianjin University	Tianjin	26	75	2.88	6
15	Shanghai Jiaotong University	Shanghai	26	109	4.19	2

Notes: TP = Total publications; TC = Times cited; AC = Average number of citations per publication; TL = Total links in the collaboration network maps. The two campuses (Beijing and Tsingtao) of China University of Petroleum are identified as the same institution in the Web of Science database, in order to be consistent with the Section 3.2.3, the TP of two campuses were manually screened based on the addresses of the institutions mentioned in the articles.

academia and industry mainly occurring with the big three oil companies.

Fig. 3 presents the co-authorship network of institutions on process safety research in China. The threshold for the number of publications was set at 10, with a total of 43 institutions meeting the threshold. In this figure, the sizes and fonts of the spheres indicate the number of publications, and the colors of the spheres indicate the clusters to which the institutions belong. The larger the sphere, the more publications. A line between two spheres indicates that the corresponding institutions have collaborated in publishing articles in the dataset. The thicker the line, the more jointly authored articles the two connected institutions have published. Fig. 3 and the right column of Table 2 shows that China University of Petroleum is the institution which published most collaborative papers with 39 total links, mainly with oil-related companies (CNOOC, CNPC and SINOPEC). Furthermore, China University of Petroleum also cooperated with universities in other northern cities, mainly Beijing and Tianjin, due to the geographical vicinity. Consequently, China University of Petroleum is considered as the core of the red cluster for the above reason. The institutions in the blue cluster were mainly geographically located in the Yangtze River Delta Region (Jiangsu, Zhejiang, Anhui and Shanghai), with Nanjing Tech University being considered the center of this cluster. The yellow cluster can be considered as the Pearl River Delta Region centered on South China University of Technology. It is interesting to note that South China University of Technology has established links with institutions in other regions through Delft University of Technology (TU Delft, the Netherlands). The institutions in the green cluster are universities and research institutions located in or near Beijing with Beijing University of

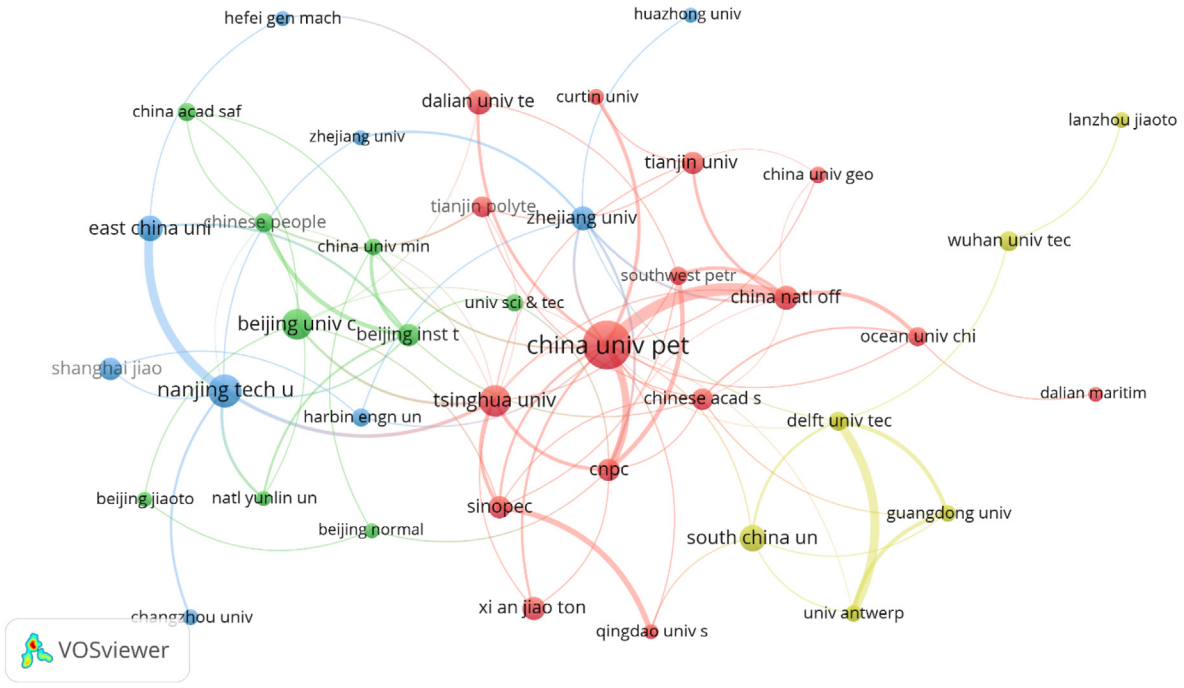

Fig. 3. Institutional collaboration network on process safety research in China. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Chemical Technology being the core of this cluster. The preceding analysis shows that cooperation between research institutions in China is clustered geographically. It is also noteworthy that by far most research of the dominant institutions occurs at a national level, with few international linkages having been established.

3.2.3. Distribution of publications in the provinces of China

Fig. 4 shows a map of China, where the number of articles published by institutions located in the different provinces is highlighted, based on the addresses of the institutions mentioned in the articles. Full counting is applied, i.e. if a paper is the result of a cross-provincial collaboration, the article is counted in full for each province. As highlighted in Section 2.1, Hong Kong, Macao, and Taiwan are not included in the dataset and hence no conclusions should be drawn for these. The figure clearly shows that there are clear geographical clusters of higher academic activity on process safety.

It is seen that Beijing is the most productive province with 405 publications, which accounts for 31.6% of the total. It is followed by Shandong province with 148 publications (11.5% of the total), Jiangsu province with 133 publications (for 10.4% of the total), and Shanghai with107 publications (8.3% of the total). The remaining provinces in the top 10 of most productive provinces are Tianjin, Guangdong, Liaoning, Zhejiang, Hebei and Hubei.

3.2.4. International cooperation

By analyzing the extent of China's international collaboration in the field of process safety research, insights are obtained in which countries, international institutions and scholars are actively cooperating with China, and which Chinese institutions and scholars are at the frontier of international collaborative research in this field. This information is useful for Chinese and foreign scholars to find potential partners to further engage in and develop academic collaboration and joint educational activities, and possibly to apply for research funding in the field of process safety.

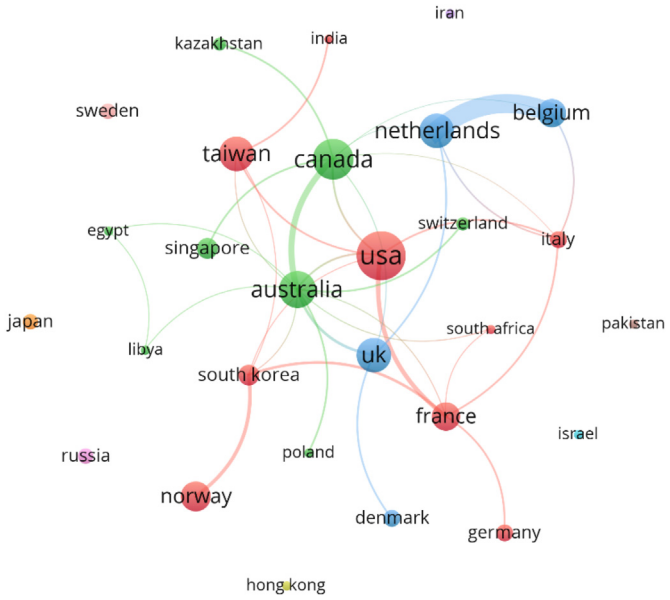

Fig. 5. Network of countries and/or regions which collaborate with China in the field of process safety research. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Internationalization of research is widely regarded as an important means of sharing know-how, exchanging ideas, and providing educational opportunities for graduate students (Aldieri et al., 2018; Yang et al., 2019).

Fig. 5 shows the network of countries and/or regions collaborating with China on process safety research. To increase the legibility of the map, China itself is not included in the figure. The size of the spheres represents the number of publications, and the width of the connecting lines denotes the number of articles

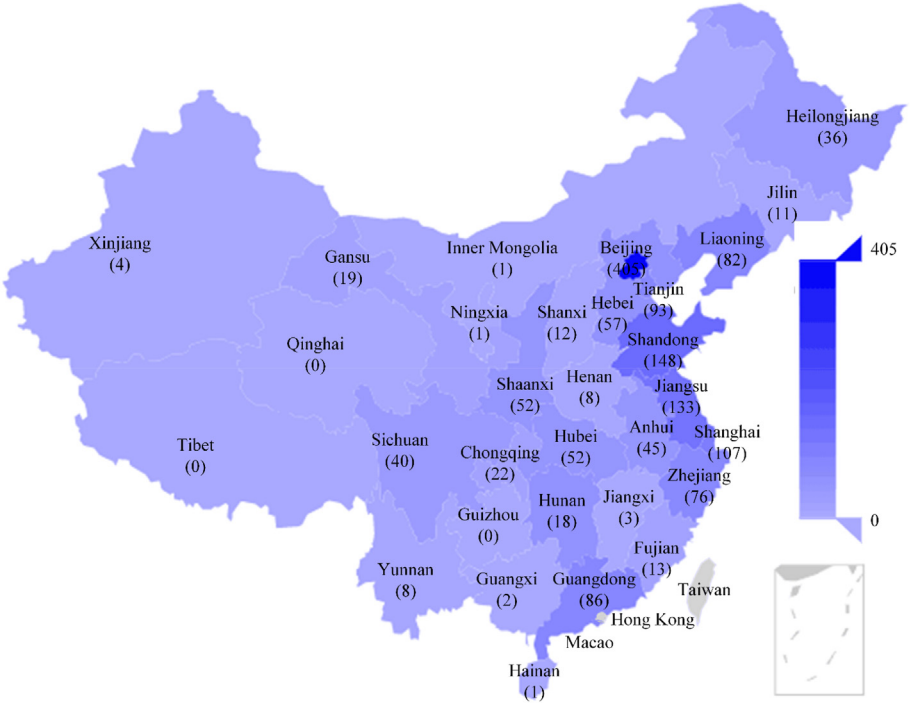

Fig. 4. Distribution of the number of publications on process safety research among the provinces in China. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

published jointly by two countries. A total of 28 countries or regions published 197 papers in collaboration with China in the discipline. The United Stated of America (USA) is the country with most collaborations with China, with 46 joint publications. Canada (30 papers) and Australia (24 papers) complete the top three. Other top 10 countries or regions are Taiwan, the United Kingdom (UK), the Netherlands, Norway, Belgium, France, and Singapore. These countries are among the most impactful in the field of process safety (Amin et al., 2019), showing that China is seeking collaboration with and learning from countries which are more advanced in this field. In addition, due to its geographical location, China also had more cooperation with neighboring countries and regions, such as Taiwan, Singapore, and South Korea.

Fig. 6 shows the network of institutions with more than three international collaboration papers on process safety in China. 47 institutions meet this threshold. The symbols and interpretations in Fig. 6 are the same as those in Fig. 3. China University of Petroleum is the Chinese organization which published most articles (28) through international cooperation. It is followed by Tsinghua University (13 publications), Nanjing Tech University (12 publications), Guangdong University of Technology (8 publications) and Zhejiang University (5 publications). TU Delft, located in the Netherlands, is the institution from other countries or regions with the highest number of publications (18 papers) on process safety in collaboration with China. It is followed by the University of Antwerp in Belgium (13 papers), Curtin University in Australia (12 papers), KU Leuven in Belgium (11 papers), and National Yunlin University of Science & Technology in Taiwan (11 papers). According to the line width between the spheres representing the two institutions in Fig. 6, TU Delft (the Netherlands), University of Antwerp (Belgium) and KU Leuven (Belgium) have the closest cooperation with Guangdong University of Technology and South China University of Technology. National Yunlin University of Science & Technology (Taiwan) cooperated most frequently with Anhui University of Science and Technology and Nanjing Tech University. Norwegian University of Science & Technology (Norway) collaborated most frequently with China University of Petroleum, whereas University of Alberta (Canada) and Tsinghua University also frequently cooperate with each other.

In order to identify the most active Chinese and foreign scholars in publishing international collaboration articles on process safety, Table 3 summarizes the Chinese and foreign scholars who have published more than four such international cooperation papers. Juncheng Jiang from Nanjing Tech University is the Chinese scholar who published the most international cooperation papers (8 publications), with 4 of these in collaboration with Ahmed Mebarki (Universite Paris-Est, France) see e.g. Mebarki (2019). Jianfeng Zhou from Guangdong University of Technology is the second most productive Chinese Scholar in terms of international cooperation publications, all of his international collaboration articles being in collaboration with Genserik Reniers who works in three universities, namely, TU Delft (the Netherlands), University of Antwerp (Belgium) and KU Leuven (Belgium). Their collaboration began in 2016, when Jianfeng Zhou was a visiting scholar at TU Delft for one year (Reniers, 2019; Zhou et al., 2016). Genserik Reniers is also the foreign scholar who published most international collaboration papers (14 publications) with Chinese scholars on process safety. This has led to a close relationship between the three universities with which he is affiliated, as seen in Figs. 3 and 6. Laibin Zhang and Guoming Chen from China University of Petroleum both published five international collaboration articles and tied for the third place among Chinese scholars. Five of their collaborators, each being affiliated with institutions in two different countries (China and other countries), were involved in seven out of their ten articles (Guo et al., 2018; Shi et al., 2018a; Shi et al., 2018b, 2019; Wu et al., 2014, 2016; Yu et al., 2018). The reason why these scholars are affiliated with two institutions is that they carried out academic exchanges and research visits outside China as visiting scholars or visiting PhD students. Most other Chinese scholars also cooperated with foreign institutions in this way, such as Jihao Shi from China

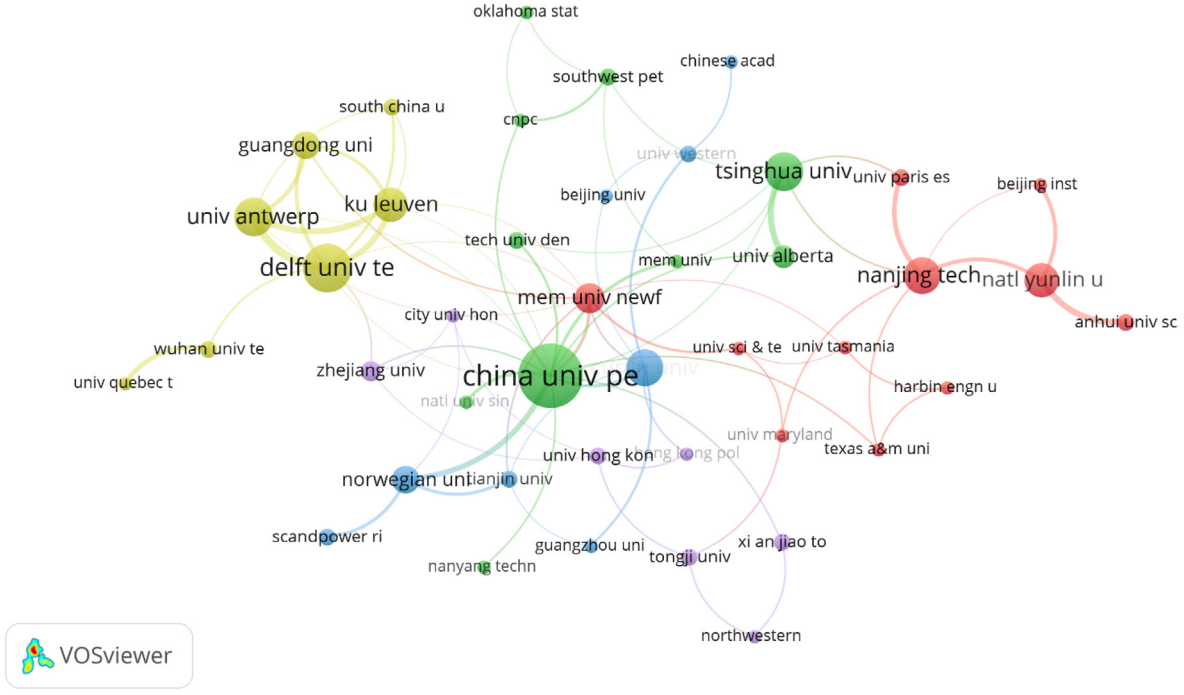

Fig. 6. Collaboration network of institutions jointly authoring articles with Chinese institutions on process safety. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Scholars who published more than four international collaboration articles on process safety in China.

Chinese Scholar	Institution	TIP	International Scholar	Institution	Country/region	TIP
Juncheng Jiang	Nanjing Tech University	8	Genserik Reniers	Delft University of Technology University of Antwerp KU Leuven	The Netherlands Belgium Belgium	14
Jianfeng Zhou	Guangdong University of Technology	7	Chi-Min Shu	National Yunlin University of Science & Technology	Taiwan	12
Laibin Zhang	China University of Petroleum (Campus Beijing)	5	Faisal Khan	Memorial University of Newfoundland	Canada	9
Guoming Chen	China University of Petroleum (Campus Tsingtao)	5	Jingde Li	Curtin University	Australia	7
Guohua Chen	South China University of Technology	4	Torgeir Moan	Norwegian University of Science & Technology	Norway	6
Yuan Zhu	China University of Petroleum (Campus Tsingtao)	4	Laobing Zhang	Delft University of Technology	The Netherlands	5
Shanghao Liu	Anhui University of Science & Technology	4	Ahmed Mebarki	Universite Paris-Est	France	4
Zhan Dou	Nanjing Tech University Tsinghua University	4	Xiangyu Wang	Curtin University	Australia	4
Jihao Shi	China University of Petroleum (Campus Tsingtao)	4				
Zhirong Wang	Nanjing Tech University	4				
Fan Yang	Tsinghua University	4				

Note: TIP = Total international collaboration publications.

University of Petroleum (Campus Tsingtao) who studied at Curtin University (Australia); Shanghao Liu from Anhui University of Science & Technology who studied at National Yunlin University of Science & Technology (Taiwan); Zhan Dou from Nanjing Tech University who studied at Universite Paris-Est (France), and Fan Yang from Tsinghua University who studied at the University of Alberta (Canada). Most foreign scholars cooperated with Chinese scholars as supervisors of these visiting scholars or PhD students.

3.3. Citation and co-citation network analysis

3.3.1. Publications citation and co-citation analysis

Citation analysis is a way of measuring the influence and quality of a publication by counting the number of times that the publication has been cited by other publications (Li et al., 2020). The retrieved 1285 papers were cited 4712 times by 3791 publications from 1426 publication sources. 2203 out of the 3791 citing publications were published by Chinese scholars, which accounted for 58.1% of all the citing publications. This indicates that articles written by Chinese authors are more frequently used within the Chinese research community compared to the international research community. Out of the 1285 retrieved papers, 633 papers have been never cited by other publications as of September 5, 2019, i.e. nearly half of the papers have not attracted any attention from other scholars.

Table 4 presents the top 10 most highly cited publications on process safety published by Chinese authors. The paper *"Recent advances in vibration control of offshore platforms"* by Zhang et al. (2017) is the most cited article, which also has the highest average citation. In order to keep offshore platforms in a reliable and safe state, this paper reviewed the research progress on offshore platform safety from the perspective of vibration control, proposing future research directions in this field. Table 5 also lists the top 10 papers that were cited by Chinese authors in the field of process safety. The article *"The assessment of risk caused by domino effect in quantitative area risk analysis"* by Cozzani et al. (2005) was the most impactful article among Chinese scholars within the process safety research community.

Co-citation is defined as the frequency with which two documents are cited together by other documents (Small, 1973), and co-citation analysis is an effective tool to measure document similarity and to identify narrative patterns in the research domain, by grouping publications into different clusters (Li et al., 2020). A total of 21,827 references were cited by 1285 retrieved publications, of which only 2611 references were cited more than twice.

Fig. 7 shows the co-citation network of references which are cited more than 10 times by Chinese scholars working on process safety research. VOSviewer is applied for this analysis, and a total of 58 references which meet this threshold are shown in the network. The sizes of the spheres are associated with the number times a publication was cited, whereas the colors represent different clusters, which are associated with broad narrative patterns in the research field. The total link strength signifies the total strength of the links of a unit with other units. The larger the total link

Table 4
Top 10 most highly cited publications on process safety published by Chinese authors.

Article	Title	TC	ACY
Zhang et al. (2017)	Recent advances in vibration control of offshore platforms	75	25.00
Liu et al. (2004)	Fuzzy rule-based evidential reasoning approach for safety analysis	70	4.38
Duan et al. (2011)	The situation of hazardous chemical accidents in China between 2000 and 2006	61	6.78
Guo et al. (2009)	Criticality evaluation of petrochemical equipment based on fuzzy comprehensive evaluation and a BP neural network	54	4.91
He et al. (2011)	Managing major chemical accidents in China: Towards effective risk information	51	5.67
Zhou et al. (2013)	Epsilon-Constraint and Fuzzy Logic-Based Optimization of Hazardous Material Transportation via Lane Reservation	50	7.14
Yang et al. (2010)	A survey on hazardous materials accidents during road transport in China from 2000 to 2008	48	4.80
Shi et al. (2014)	Fuzzy fault tree assessment based on improved AHP for fire and explosion accidents for steel oil storage tanks	47	7.83
Liu et al. (2006)	Optimal siting of fire stations using GIS and ANT algorithm	47	3.36
Zhao et al. (2012)	Analysis of factors that influence hazardous material transportation accidents based on Bayesian networks: A case study in China	46	5.75

Notes: TC = Times cited; ACY = Average citations per year.

Table 5
Top 10 papers that were cited by Chinese authors in the field of process safety.

Article	Title	TCP	TC	ACY
Cozzani et al. (2005)	The assessment of risk caused by domino effect in quantitative area risk analysis	31	341	15.50
Erkut and Verter (1998)	Modeling of transport risk for hazardous materials	25	162	7.36
Kara and Verter (2004)	Designing a road network for hazardous materials transportation	23	128	8.00
Khakzad et al. (2013)	Dynamic safety analysis of process systems by mapping bow-tie into Bayesian network	21	166	23.71
Cozzani et al. (2006)	Escalation thresholds in the assessment of domino accidental events	20	119	8.50
Khan and Abbasi (1998)	Models for domino effect analysis in chemical process industries	20	104	4.73
Erkut and Ingolfsson (2000)	Catastrophe avoidance models for hazardous materials route planning	19	79	3.95
Venkatasubramanian et al. (2003)	A review of process fault detection and diagnosis Part III: Process history based methods	19	890	52.35
Zografos and Androutsopoulos (2004)	A heuristic algorithm for solving hazardous materials distribution problems	18	88	5.50
Venkatasubramanian et al. (2000)	Intelligent systems for HAZOP analysis of complex process plants	18	102	5.10

Notes: TC = Times cited; ACY = Average citations per year; TCP = Total times cited by Chinese scholars on process safety research.

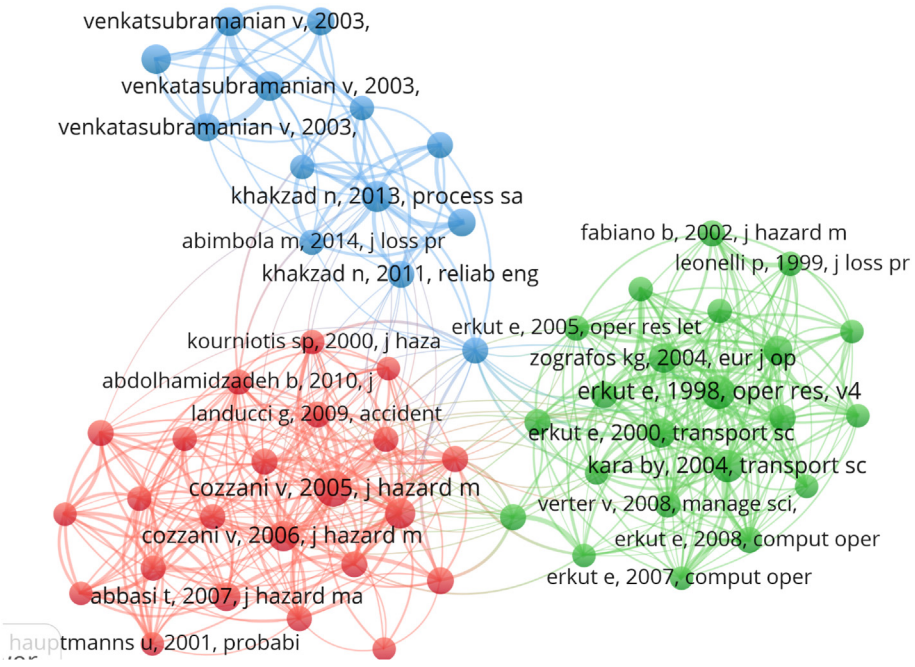

Fig. 7. Co-citation network of references cited more than 10 times by Chinese scholars on process safety. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

strength, the closer it is to other units. According to Fig. 7, the 58 references are divided into three clusters according to their co-citation relationship. The main research topics for each cluster, which are associated with major narrative patterns within the research community, were identified by analyzing the title and abstract of each reference in the three clusters.

The red cluster (on the bottom left) is the largest with 23 references. It is mainly focused on the analysis of domino effects and fire and explosion accidents. In this cluster, the article *"The assessment of risk caused by domino effect in quantitative area risk analysis"* by Cozzani et al. (2005) is the most cited paper (31 citations), also having the largest total link strength (31). Hence, it can be considered as the core paper in this cluster. The green cluster (on the bottom right) is the second largest cluster with 22 references. It is mainly focused on the transportation of hazardous chemicals. The article *"Modeling of transport risk for hazardous materials"* by Erkut and Verter (1998) has the highest number of citations (25), as well as the largest total link strength (25) in this cluster. Hence, it can be regarded as the core paper of this cluster. The smallest cluster is the blue cluster (on the top) with 13 references. Its main topics address analysis methods for process safety, including Bayesian networks, dynamic risk analysis, bow-tie, fuzzy set, and fault tree. The article *"Dynamic safety analysis of process systems by mapping bow-tie into Bayesian network"* by Khakzad et al. (2013) can be considered the core publication in this cluster with the highest number of citations (21) and the largest total link strength (19).

3.3.2. Distribution and co-citation analysis of publication sources

To identify which journals are most frequently read and influential among Chinese scholars in the field of process safety, and to help other scholars selecting suitable journals to contribute to their manuscripts, an analysis is made of the number of documents and their citations parameters, for different publication sources. The 1285 retrieved articles in the dataset are published in 661 unique publication sources. Of these, a total of 667 journal articles are derived from 255 journals.

Table 6 lists the top 10 most significant journals on process safety research to which by Chinese authors have contributed. *Journal of Loss Prevention in the Process Industries* contains most articles and is also the most citied journal in this regard. The journals *Process Safety and Environmental Protection* and *Process Safety Progress* rank second and third in terms of the number of publications. The *Journal of Hazardous Materials* ranks second with respect to the total number of citations and highest in average

Table 6
The top 10 most journals to which Chinese scholars on process safety research have contributed.

Rank	Journal	TP	TC	AC	IF
1	Journal of Loss Prevention in the Process Industries	111	898	8.09	2.069
2	Process Safety and Environmental Protection	30	128	4.27	4.384
3	Process Safety Progress	22	94	4.27	0.885
4	Chinese Journal of Chemical Engineering	21	97	4.62	1.911
5	Safety Science	20	249	12.45	3.619
6	Journal of Hazardous Materials	17	398	23.41	7.65
7	Engineering Failure Analysis	14	106	7.57	2.203
8	Ocean Engineering	13	55	4.23	2.73
9	Industrial & Engineering Chemistry Research	11	106	9.64	3.375
10	International Journal of Hydrogen Energy	10	55	5.5	4.084

Notes: TP = Total publications; TC = Times cited; AC = Average number of citations per publication; IF = Impact factor in 2018 according to Clarivate Analytics.

citations. This is also consistent with the journal's impact factor ranking, where *Journal of Hazardous Materials* has the highest impact factor among the top 10 most productive journals in the list.

The journal co-citation analysis can be used to classify journals on different topics and to identify the core journals of each category. This can be very helpful for scholars to unstand the most relevant and influential journals for a given research topic. In total, the 1285 retrieved articles cited 21,827 references from 9278 publication sources. Of these sources, 6932 publication sources (74.4%) were cited only once.

Fig. 8 shows the 50 journals which have been cited more than 50 times using VOSviewer. These journals clearly have a significant impact on Chinese scholars in the field of process safety. The colors of the spheres represent different journal topics, whereas their sizes denote the number of citations. The total link strength is associated with the closeness to other journals. As can be seen from Fig. 8, *Journal of Loss Prevention in the Process Industries* (1452 citations) is the most cited journal by Chinese scholars, followed by the *Journal of Hazardous Materials* (941 citations), *Reliability engineering and System Safety* (569 citations), *Process Safety and Environmental Protection* (406 citations), and *Safety Science* (401 citations). All of these top-5 cited journals are in the red cluster of the network of Fig. 8, which contains 16 items. This indicates these journals constitute the core journals for process safety research in China. The journal topics in this red cluster are related to safety, risk, accidents, and hazardous materials. The green cluster contains 13 items, and focuses on chemical engineering and processes. The top-3 journals in terms of number of citations in this cluster are *Computers & Chemical Engineering* (374 citations), *Industrial & Engineering Chemistry Research* (267 citations), and *AIChE Journal* (178 citations). The blue cluster, which contains 8 items, focuses on combustion and heat transfer. *International Journal of Hydrogen Energy* (257 citations), *Combustion and Flame* (182 citations), and *Fuel* (100 citations) are the top-3 most cited journals in the blue cluster. The yellow cluster, which also contains 8 items, relates to the optimization of transport routes of hazardous materials. The *European Journal of Operational Research* (215 citations), *Transportation Science* (156 citations), and *Computers & Operations Research* (4 citations) are the top-3 journals with respect to the number of citations. The smallest cluster is the purple cluster,

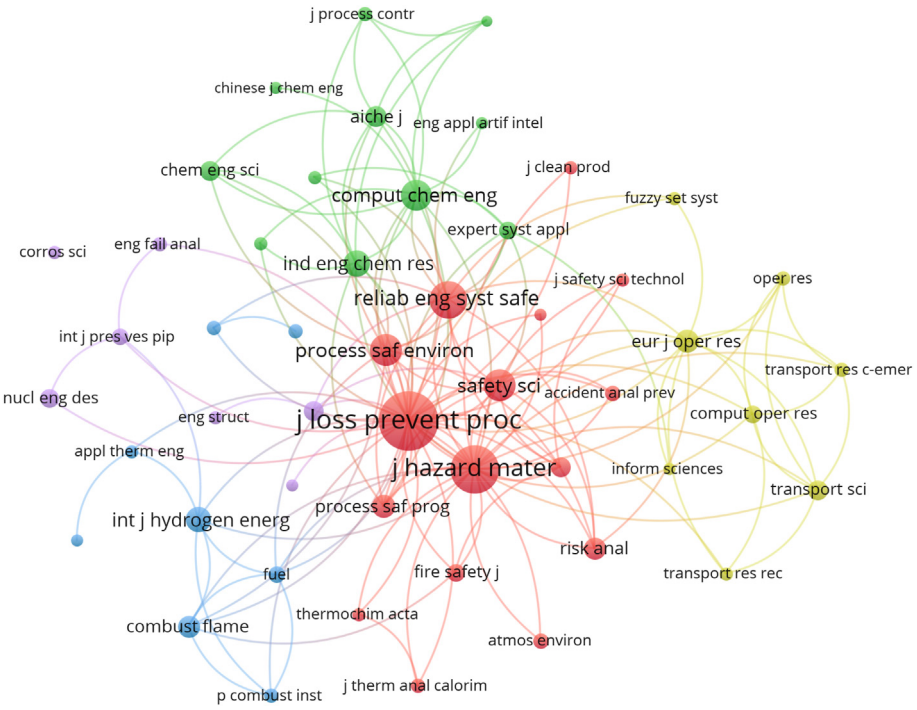

Fig. 8. Co-citation network of publication sources that were cited more than 50 times by Chinses scholars in the field of process safety. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

containing 7 journals, and focusing on process equipment failures. The top-3 most cited journals in this cluster are *Ocean engineering* (146 citations), *Nuclear Engineering and Design* (135 citations), and *International Journal of Pressure Vessels and Piping* (101 citations).

3.4. Research hot topics and tends

The text in keywords, titles, and abstracts can be used to infer the major focus topics and trends of a specific research field, using text mining techniques (Li et al., 2020). In the present work, a co-occurrence analysis of terms is carried out using VOSviewer. In this analysis, text strings are extracted from keywords, titles and abstracts of all publications in the database.

A total of 4850 terms were identified by VOSviewer from the 1285 retrieved articles. Among these, 969 terms appeared only once and 205 terms appeared more than 5 times. In order to identify hot topics of process safety research in China and evolution and trends in different periods, Table 7 summarizes the top 30 terms, which appeared most frequently in each period. Furthermore, Fig. 9 presents a heat map showing the density of the terms in the research domain, for different periods. In the density view, colors from blue to red indicate the occurrence frequency of the different terms, where the distance between two terms indicates the strength of association in the research articles.

Every five years, the Chinese government formulates a five-year plan for national economic and social development, and detailed five-year plans are issued for various fields (Wang et al., 2018a). The 13th five-year plan (2016–2020) for work safety was issued by the State Council of China on January 12, 2017, which lays down the main objectives and tasks in the field of work safety in China for this period. Through the funding mechanism used to implement these five-year plans, these have a significant impact on the development of the Chinese academic research in the field of industrial safety. Therefore, the division of the research periods in Fig. 9 is made consistent with these five-year plan periods in China. Thus, following temporal division is made: the 13th five-year period (2016–2020), the 12th five-year period (2011–2015), and before the 11th five-year period (before 2010).

The overall process safety research hotspots in China can be identified based on the occurrence frequency of the global terms in Table 7 and their distribution in Fig. 9(a). It is found that following major topics are addressed in the field of process safety research among Chinese scholars: risk assessment model and framework; risk-based design; optimization of hazardous materials transportation network; numerical simulation of fire (especially pool fire) and explosion accidents; safety management; domino effects in chemical industrial parks; fault diagnosis, reliability and uncertainty analysis of process equipment and systems; and hazard identification. In terms of analysis methods, HAZOP, numerical simulation, and Bayesian networks are widely applied by Chinese scholars working in the process safety field. The research areas focus primarily on hazardous materials, chemical processes and systems, chemical industrial parks, offshore platforms, oil and gas pipelines, and storage tanks.

In order to obtain insights in the evolution of major topics in the field of process safety in China, the distribution of research topics are analyzed for the 3 defined time periods. As seen in Fig. 9(b), in the first period (before 2010), a total of 993 terms from 292 articles were extracted by VOSviewer, of which 59 terms appeared more than three times.

Along with Table 7, Fig. 9(b) shows the primary focus topics in process safety research in China before 2010 concern models and frameworks for safety or risk assessment (societal risk and individual risk); optimization of transportation network for hazardous

Table 7
Distribution of top 30 terms of process safety research in China: Global and temporal analysis.

R	Global		Before 2010		2011–2015		2016–2019	
	Terms	F	Terms	F	Terms	F	Terms	F
1	Model	115	Model	19	Model	26	Model	69
2	System	88	Risk assessment	18	System	24	System	53
3	Risk assessment	72	Risk	13	Risk assessment	23	Risk assessment	30
4	Risk	54	Safety assessment	10	Risk	20	Optimization	27
5	Hazardous material	46	System	10	Hazardous material	18	Safety	26
6	Optimization	45	HMT	9	HMT	15	Explosion	25
7	Accident	43	Risk analysis	9	Accident	15	Design	25
8	Explosion	43	Chemical process	8	**Design**	14	Risk analysis	23
9	HMT	41	Hazardous material	8	**Management**	14	Simulation	23
10	Risk analysis	41	Offshore platform	7	Optimization	13	Prediction	23
11	Safety	41	Reliability	7	HAZOP	13	Accident	22
12	Design	39	HAZOP	6	Explosion	12	Management	21
13	Management	39	Accident	6	Reliability	12	Risk	21
14	Simulation	35	Explosion	6	Numerical simulation	12	Hazardous material	20
15	Prediction	34	Numerical simulation	6	**Network**	11	**Bayesian network**	19
16	Framework	30	BLEVE	5	**Algorithm**	11	**Oil**	19
17	Numerical simulation	30	Framework	5	**Fault diagnosis**	11	Transportation	17
18	Network	29	Overpressure	5	**Hazard**	10	HMT	16
19	Reliability	29	Domino effect	5	Domino effect	10	Framework	15
20	Transportation	29	Optimization	5	Framework	10	**Behavior**	15
21	Domino effect	27	Safety	5	CIP	10	Network	14
22	Bayesian network	26	Safety analysis	5	Safety	10	Uncertainty	13
23	Fault diagnosis	26	Chemical plant	4	Risk analysis	9	**Fire**	13
24	Algorithm	25	Sensor	4	**Transportation**	9	**China**	12
25	Oil	23	GIS	4	**Prediction**	9	Domino effect	12
26	HAZOP	23	Expert system	4	Safety assessment	9	**Flow**	11
27	Uncertainty	23	LPG	4	**Uncertainty**	8	Algorithm	11
28	Behavior	23	Identification	4	BLEVE	8	Fault diagnosis	11
29	Offshore platform	22	Corrosion	4	**Impact**	8	Numerical simulation	11
30	CIP	21	CIP	4	**Pool fire**	8	Offshore platform	11

Notes: R = Rank; F = Frequency of each term; CIP = Chemical industrial park; HMT = Hazardous material transportation. Bold terms represent emerging terms.

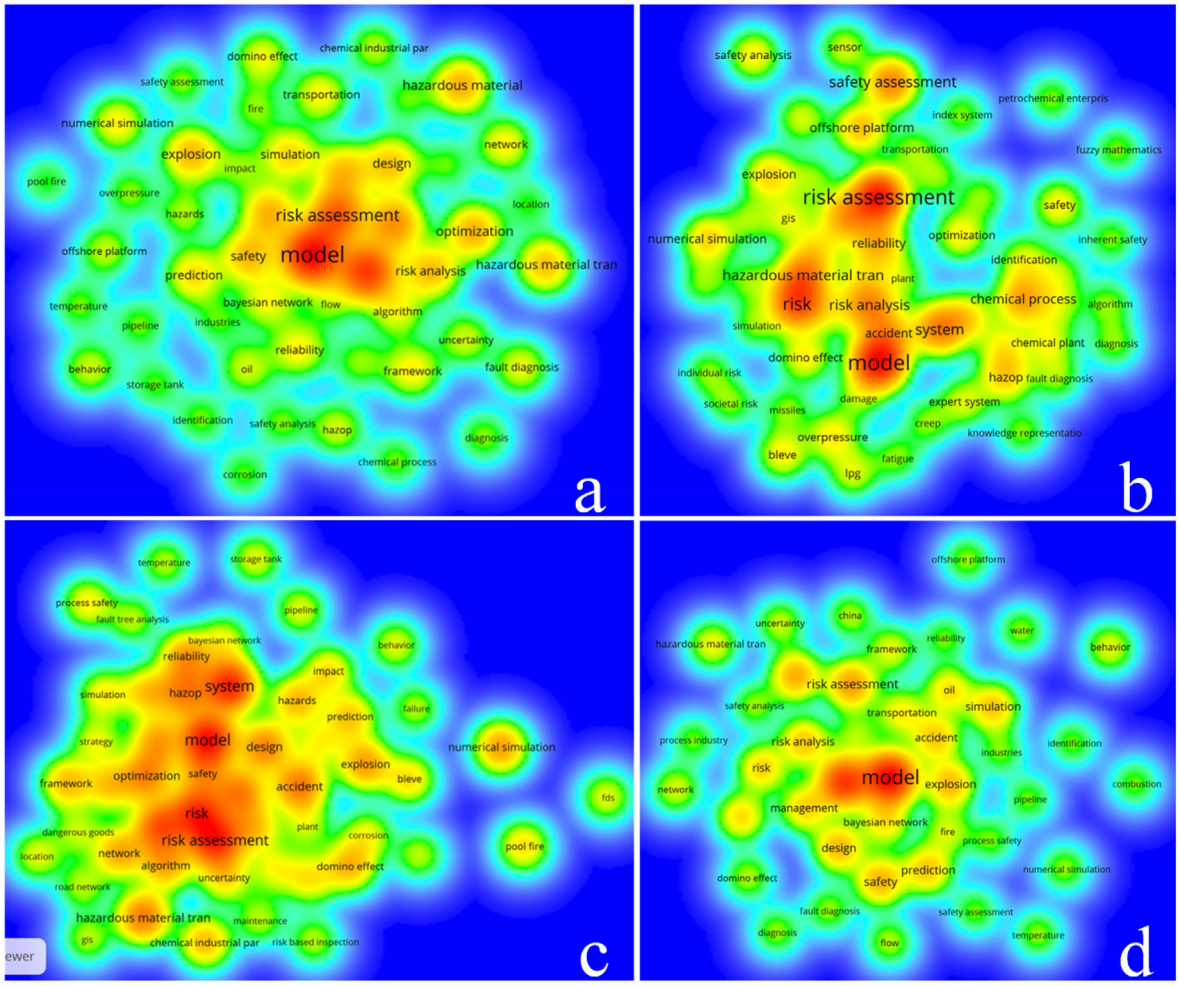

Fig. 9. Heat maps of terms in process safety research in China during different time periods. (a) All time; (b) before 2010; (c) 2011–2015; (d) 2016–2019. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

materials; domino effects in chemical industrial parks; safety assessment and analysis for offshore platforms; numerical simulation of explosions, especially BLEVE related to LPG; and fault diagnosis and reliability assessment for process equipment and systems. The main research methods include HAZOP, numerical simulation, GIS, inherent safety, and fuzzy mathematics.

During the 12th five-year period (2011–2015), a total of 478 articles contributed 1889 terms, 53 of which appeared more than 5 times, which are shown in Fig. 9(c). Table 7 and Fig. 9(c) show that in this period, risk or safety assessment models, optimization of hazardous materials transportation, numerical simulation of explosion (especially BLEVE) accidents, and domino effects in chemical industrial parks are still popular topics (Chen et al., 2018; Chen et al., 2019a; Chen et al., 2020a,b; Zhang et al., 2019; Zeng et al., 2020). In addition, a number of new topics and focus areas emerge in this period, including fault diagnosis and maintenance, hazard identification, numerical simulation of pool fires, fire dynamics simulation (FDS), fault tree analysis (FTA), and risk-based inspection.

In the 13th five-year period (2016–2019), a total of 515 papers contributed 2691 terms, among which 42 terms appear more than 10 times. These terms are shown in Fig. 9(d). It can be seen from Table 7 and Fig. 9(d) that the research focus topics in this period are mostly the same as in the previous two periods, i.e. this period signifies a continuation of the research areas previously initiated. Only few new research or intensifying research topics emerge in this period. Combustion behaviors of fires become a more significant area of activity, and Bayesian networks become a widely used technique in process safety among Chinese scholars during this period.

3.5. Funding for process safety research in China

The funding supporting the work done in research publications can reflect the areas of concern of the government, commercial enterprises, and other funding institutions supporting the development of the field. A total of 681 publications of the 1285 retrieved publications in the field of process safety in China contained funding information, accounting for 53.0% of the total. These covered a total of 1218 funding grants originating from 643 funding agencies.

The top 10 funding agencies with highest research yield in terms of number of publications are listed in Table 8. The analysis indicates that process safety research in China has received significant attention, with funding originating from the Chinese government, and from scientific funding bodies and programs it supports.

Funding from the National Natural Science Foundation of China (NSFC) supported the highest number of publications, with 356 funded publications accounting for 52.3% of the total. It is followed

Table 8
Top 10 productive funding agencies supporting the process safety research in China.

R	Funding agency	TFP	PTF
1	National Natural Science Foundation of China	356	52.3%
2	National Key Research and Development Program of China	84	12.3%
3	Fundamental Research Funds for the Central Universities	82	12.0%
4	National High Technology Research and Development Program of China (863 Program)	54	7.9%
5	National Basic Research Program of China (973 Program)	43	6.3%
6	Science Foundation of China University of Petroleum (Campus Beijing)	28	4.1%
7	China Postdoctoral Science Foundation	25	3.7%
8	China Scholarship Council	18	2.6%
9	Program for New Century Excellent Talents in University	16	2.3%
10	Beijing Natural Science Foundation	11	1.6%

Notes: TFP = Total number of funded publications; PTF = Percentage of the total number of funded publications.

by the National Key Research and Development Program of China (84 publications) and the Fundamental Research Funds for the Central Universities (82 publications). 8 of the top 10 funding agencies are national funding agencies, which indicates that by far most funding supporting the field of process safety was provided by the Chinese government. The other two funding agencies are province and university. The Beijing Natural Science Foundation is the most productive provincial funding agency with 11 publications, and the Science Foundation of China University of Petroleum (Beijing) is the most productive funding agency among all universities with 28 publications.

4. Synthesis and discussion

4.1. Publication trends

Before 2008, Chinese scholars published relatively few English articles in the field of process safety. However, this number has increased approximately linearly since then, and China is currently ranked third in the world in terms of the total number of publications. One factor contributing to the development of the field may be that a series of natural disasters and accidental disasters involving safety occurred in 2008, which caused the whole society to pay unprecedented attention to safety issues in various fields, as found by Jiang et al. (2019). Another plausible contributing factor is the fact that the State Administration of Work Safety (now called the Ministry of Emergency Management) (Wang and Wu, 2019a) designated 2008 as the "Potential Hazards Management Year for Work Safety in China", in response to deficiencies and poor safety performance in high risk industry enterprises prior to this (Wang and Wu, 2019a).

It is worth noting that before 2015, Chinese scholars published more conference papers than journal papers, but since 2015 the situation has reversed. This may indicated that Chinese scholars put more value in publishing journal papers instead of conference papers. A plausible reason for the fluctuating trend for the number of conference papers is that several influential conferences related to process safety are held every two or three years. The top 10 conferences in which Chinese scholars have been active in the field of process safety are listed in Table 9. As can be seen from that table, *International Symposium on Safety Science and Technology (ISSST)* is the international conference focusing on safety science and engineering with the largest number of conference papers in the field of process safety. The conference, held every two years in China since 1998, had attracted scholars from more than 30 countries around the world contributing 2781 papers in the field of safety science and engineering by 2012. More than 85% of its contributing scholars were from China due to the fact that the conference is held in China (Li et al., 2014), indicating that ISSST has become one of the most influential international conferences in the field of safety science and engineering in China and even in the world. Therefore, ISSST is a good platform for understanding the development of safety science and technology and communicating with Chinese scholars in China. It is followed by *ASME Pressure Vessels and Piping Conference (PVP)* and *International Conference on Ocean, Offshore and Arctic Engineering (OMAE)*, which are organized bi-annually and annually, respectively.

4.2. The influential authors, institutions, and areas

Considering the leading scholars in the field of process safety in China, Laibin Zhang from China University of Petroleum (Campus Beijing), Juncheng Jiang from Nanjing Tech University, and Guohua Chen from South China University of Technology are the top 3 most productive authors. China University of Petroleum, Nanjing Tech University and Tsinghua University are the top 3 most productive institutions. China's three largest oil companies, i.e. CNOOC, CNPC and SINOPEC, are the most productive industrial organizations. Beijing, Shandong and Jiangsu are the top 3 most productive provinces in China. The most productive authors, institutions, and provinces are located in economically developed coastal areas and in areas with more universities specializing in safety science and engineering in China. The collaboration between these institutions shows distinct geographical characteristics. This information can help Chinese students who are interested in process safety to find suitable universities to study and supervisors with whom to pursue a research degree. The results may also aid Chinese and international scholars or institutions to find highly performing institutions for collaboration, and help industry and academic partners to work together in the field of process safety.

As for the international cooperation on process safety research in China, the United States of America, Canada and Australia are the most cooperative countries with China. TU Delft (the Netherlands), University of Antwerp (Belgium) and Curtin University (Australia) are the most productive foreign institutions collaborating with Chinese institutions. China University of Petroleum, Tsinghua University, and Nanjing Tech University are the Chinese institutions from which most jointly authored articles with international partners originate. The most significant collaborating countries are economically developed countries or China's neighbors, and these countries have published a large number of important papers in this field (Amin et al., 2019).

Juncheng Jiang (Nanjing Tech University), Jianfeng Zhou (Guangdong University of Technology) and Laibin Zhang (China University of Petroleum, Campus Beijing) are the most productive Chinese authors in terms of internationally co-authored articles. Genserik Reniers (TU Delft, the Netherlands), Chi-Min Shu (National Yunlin University of Science & Technology, Taiwan) and Faisal Khan (Memorial University of Newfoundland, Canada) are the most productive foreign scholars working together with Chinese

Table 9
Top 10 most influential international conferences on process safety among Chinses scholars.

Conferences	TP	Frequency (year)
International Symposium on Safety Science and Technology	67	2
ASME Pressure Vessels and Piping Conference	32	2
International Conference on Ocean, Offshore and Arctic Engineering	18	1
International Conference on Nuclear Engineering	14	1
Asia Pacific Symposium on Safety	10	2
International Pipeline Conference	9	2
International Conference on Energy, Environment and Sustainable Development	8	1
International Conference on Pressure Vessel Technology	7	3
International Conference on Civil Engineering, Architecture and Building Materials	7	1
International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering	6	1

Note: TP = Total publications.

scholars. It is apparent that the main way of collaboration between China and foreign countries in the process safety field is through visiting scholars and visiting PhD students studying in foreign institutions funded by Chinese government, in particular through the China Scholarship Council (CSC).

Most of productive provinces are economically developed eastern coastal areas or provinces with more safety science and engineering research institutes, as also indicated by Wang et al. (2020). Duan et al. (2011) show the number of petrochemical industrial organizations and the Gross Domestic Product (GDP) per province, showing that the coastal areas are more economically developed and have higher concentrations of petrochemical facilities. Accident statistics and analyses furthermore show that there have been several chemical accidents in these coastal areas of China, several of which leading to serious consequences (Duan et al., 2011; Wang et al., 2018b). These factors may explain why there are more research institutes working on process safety in these provinces, and hence why those are more scientifically productive. In addition, the regional areas in China with developed safety science and engineering education resources, such as Liaoning, Hebei, Sichuan, Shaanxi, and Hubei also exhibit elevated levels of research activity on process safety (Wang et al., 2020).

4.3. Citation and co-citation analysis

The citation analysis shows that the citation rate of Chinese scholars in the process safety field is comparatively low, with nearly half of the articles never having been cited. Furthermore, nearly 60% of the citations were received from other Chinese scholars, showing that Chinese process safety research currently still has a relatively limited international impact.

According to co-citation analysis, process safety research in China primarily focuses on three aspects: domino effects and fire and explosion accidents, transportation of hazardous chemicals, and research on method development for process safety analysis, such as Bayesian networks, dynamic risk analysis, bow-tie, fuzzy set, and fault tree.

Following journals are the most important in terms of number of publications contributed by Chinese scholars and with respect to citation-related impacts: *Journal of Loss Prevention in the Process Industries, Process Safety and Environmental Protection, Process Safety Progress, Safety Science, Journal of Hazardous Materials,* and *Reliability engineering and System Safety* (Li and Hale, 2015; Reniers and Anthone, 2012; Amin et al., 2019).

Through the co-citation analysis of the cited journals, it is observed that there are five major narrative clusters to which Chinese scholars working with process safety contribute: i) safety, risk, accidents, and hazardous materials; ii) chemical engineering and processes; iii) combustion and heat transfer; iv) optimization of hazardous materials transport routes; and v) process equipment failures.

4.4. Research hot topics and future directions

The analysis of hot topics in process safety research in China shows that risk assessment modeling and frameworks; risk-based design; optimization of hazardous materials transportation network; numerical simulation of fire (especially pool fire) and explosion accidents; safety management; domino effects in chemical industrial parks; fault diagnosis, reliability and uncertainty analysis of process equipment and system; and hazard identification. During the 13th five-year period (2016–2019) of the Chinese government, there were few new emerging topics in the Chinese research community. This indicates that although Chinese scholars have contributed a significant body of literature in the field of process safety research and have published thousands of English-language articles covering a wide range of topics, there currently are very few new methods or research topics introduced, or at least these are not very impactful. There is still significant room for the Chinese research community to improve in some subdomains of the research field, and catch up with progress made in other areas in the world.

Considering this, future directions for process safety research in China are identified taking the latest global progress in process safety research as a guide. Based on the priority research topics outlined in the Process Safety Research Agenda for the 21st Century, which is a policy document developed by leading representatives of the global process safety research community (Alkhawaldeh and Kožuh, 2011), Chinese scholars could in the future give further attention to following research topics: critical infrastructure protection, failure of complex systems, integration of process safety with occupational safety, import process safety into emerging technologies, standardization of process safety methods that are easy to implement in industries, natural hazards triggering technological disasters (Natech events) (Yang et al., 2018, 2020; Huang et al., 2020), safety culture, and human and organizational factors of safety. Furthermore, dynamic risk assessment, which has been proposed as the basis for the next generation of risk and management approaches (Khan et al., 2016; Chen et al., 2020), process safety education (Mkpat et al., 2018), process safety indicators (Swuste et al., 2016), safety barriers (Bubbico et al., 2020), safety triad (a framework for risk assessment) (O'Connor et al., 2019) safety-related intelligence (Wang and Wu, 2019b) are also emerging research topics in the global community. In terms of methods, following research areas can be recommended based on global developments: Bowtie (de Ruijter and Guldenmund, 2016), Dynamic Bayesian Network (Khakzad, 2015; Khakzad et al., 2017), Dynamic Fault Tree Analysis (Codetta-Raiteri, 2011) and Computer-aided Fault Tree Analysis (Ferdous et al., 2009; Xue et al., 2019). The above new future directions can contribute to providing a safer and

cleaner production environment for human activities in the chemical industries in China, which further will enable the sustainability of social economic development.

4.5. Funding agencies

In terms of funding, more than half of the articles authored by Chinese scholars were funded by 1218 funding grants from 643 funding agencies, mostly obtained from the Chinese government. The National Natural Science Foundation of China (NSFC) is the most influential funding agency, leading to a high research productivity. It was established in 1986 and aims to support basic research, foster talented researchers, develop international cooperation, ultimately aiming to promote social and economic development in China. A total funding of 168 billion CNY was funded by the NSFC from 2011 to 2018 (Liu et al., 2019). The above discussion/data indicate that research in the field of process safety has been given a lot of attention by the Chinese government, probably much more than the average in the rest of the world. Actually, global funding on process safety, has been found to be more difficult to obtain (Alkhawaldeh and Kožuh, 2011).

4.6. Limitations

Despite the insights obtained from the work, the present work has some limitations due to the limitations of the publication retrieval process and the applied analysis methods. First, only Web of Science database was selected in this article due to different data standards and incompatibility with other databases such as Scopus and Compendex. This may result in missing some papers related to process safety in China, and hence bias some results or miss some patterns or developments. Second, in order to allow the global research community on process safety to better understand the structure and development of process safety research in China, the language of the articles is limited to English, the most widely used academic language. However, most Chinese-authored articles on process safety are published in Chinese journals in the Chinese language. These are not available in Web of Science, which may also have an impact on the results.

5. Conclusions

In this paper, 1285 publications on process safety research in China were retrieved from the Web of Science database. A bibliometric analysis of this research domain was carried out to identify a detailed overview of the leading contribution of process safety research. Publication trends, influential authors, institutions, provinces, articles, journals and conferences, and funding agencies in China were identified and discussed. In addition, international collaboration of process safety research in China was also analyzed from the perspective of countries, institutions and authors. Finally, by analyzing frequently occurring terms in process safety research in China, hot topics and emerging research trends were identified. The evolution of focus topics in different periods was presented and future directions for process safety research in China are proposed.

Visualizations of co-authorship networks of countries and institutions, co-citation networks of publications and journals, and density maps of focus topics are provided. Hence, it is shown that bibliometric analysis is a useful method for obtaining insights into the development of process safety research in China. The results can contribute to the understanding the overall structure and progression of this research field, and can help prospective students and researchers identify impactful institutions, scholars, and funding agencies for education and international collaboration. Based on the above information, Chinese scholars can recognize the overall situation and shortcomings of current research, and scholars outside China can look for potential Chinese partners in education and research in the field of process safety, which may be beneficial to the sustainable development of China's chemical industry, and even to the world's related industrial activities.

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.

Acknowledgement

This study was supported by the National Key R&D Program of China (2017YFC0804700), the National Natural Science Foundation of China (21878102, 21576102), and the China Scholarship Council (201806150064). The contributions by the last author were supported by the Canada Research Chairs Program, through a grant by the Natural Sciences and Engineering Research Council (NSERC). This support is gratefully acknowledged. The authors are indebted to two anonymous reviewers, whose thoughtful comments have contributed to improving an earlier version of this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.121433.

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