Chinese international process safety research

Collaborations, research trends, and intellectual basis

Li, Jie; Goerlandt, Floris; Reniers, Genserik; Feng, Changgen; Liu, Yi

DOI
10.1016/j.jlp.2021.104657

Publication date
2022

Document Version
Final published version

Published in
Journal of Loss Prevention in the Process Industries

Citation (APA)
Li, J., Goerlandt, F., Reniers, G., Feng, C., & Liu, Y. (2022). Chinese international process safety research: Collaborations, research trends, and intellectual basis. *Journal of Loss Prevention in the Process Industries*, *74*, Article 104657. https://doi.org/10.1016/j.jlp.2021.104657

Journal of Loss Prevention in the Process Industries 74 (2022) 104657

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

Chinese international process safety research: Collaborations, research trends, and intellectual basis

Jie Li [a,b,c], Floris Goerlandt [d], Genserik Reniers [e,f,g,*], Changgen Feng [b], Yi Liu [h]

[a] National Science Library, Chinese Academy of Sciences, Beijing, China
[b] State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, China
[c] College of Safety Science & Engineering, Liaoning Technical University, Huludao, Liaoning, China
[d] Dalhousie University, Department of Industrial Engineering, Halifax, NS B3H 4R2, Canada
[e] Safety and Security Science, Faculty of Technology, Policy and Management, Delft University of Technology, the Netherlands
[f] Antwerp Research Group on Safety and Security (ARGoSS), Faculty of Applied Economics, University of Antwerp, Belgium
[g] CEDON, KU Leuven, 1000, Brussels, Belgium
[h] Department of Environmental and Safety Engineering, China University of Petroleum (Huadong), China

ARTICLE INFO

Keywords:
Scientometrics
Chinese process safety research
Bibliometrics
Bibliometric mapping
Process safety
Scientific collaboration

ABSTRACT

This article presents a bibliometric analysis and mapping of the Chinese process safety research, focusing on the contributions made in core process safety journals and on the influences of international collaborations and knowledge sources on the developments of this research domain. Collaboration networks, term co-occurrence networks, and co-citation network were analyzed to identify trends, patterns, and the knowledge distribution of the Chinese research on process safety. Work to data has been clustered mainly on safety of chemical processes, fire and explosion, and risk management and accidents. Chinese research contributions are concentrated in only few journals, while the corresponding intellectual base draws on the wider literature focused on understanding and modeling phenomena, and on the broader risk research literature, although to a lesser extent. While various foreign authors are highly cited by Chinese authors, only very few direct collaborations with international scholars are identified. The results are used as a basis for a discussion on future research directions and developments for the community. Increased focus on uncertainty treatment and handling of black swan events, risk evaluation and economic aspects of safety decisions, interorganizational risk management, road and maritime transport of hazardous substances, risk perception and communication, and integrated safety and security assessment, are highlighted as fruitful directions for future scholarship. It is hoped that the insights obtained from this work can facilitate new and consolidated collaborations, as well as further invigorate the Chinese process safety domain, ultimately contributing to improved safety performance of process industries in China and elsewhere.

1. Introduction

Process industries are an important sector in the global economic landscape and provide the backbone for economic and social development in many areas where industrial facilities are located. Nevertheless, process plants are hazardous facilities, which can lead to significant negative safety and environmental impacts and are thus of high societal concern. In support of its economic development, the scale, production output, and revenue of process industries has grown very fast in China (Yang et al., 2019a). Simultaneously, due to the above-mentioned safety and environmental concerns, process safety has gained increasing attention in Chinese industrial, government, and academic contexts. This has led to a steady improvement in safety performance of the Chinese chemical industries (Zhao et al., 2014). Nevertheless, accidents and serious high-consequence loss events still occur relatively frequently, e.g. the explosions in Dalian Port (2010-7-16), Qingdao (2013-11-22), Tianjin Port (2015-8-12), and Xiang-Shui (2019-3-21). Various authors have performed research focusing on these and other accidents (Chen and Wang, 2012; Chen et al., 2019; Zhang et al., 2019; Zhao, 2014), indicating that scientific research is important for improving process safety in China.

Several authors have highlighted aspects of process safety in China.

* Corresponding author. Antwerp Research Group on Safety and Security (ARGoSS), Faculty of Applied Economics, University of Antwerp, Belgium.
E-mail address: G.L.L.M.E.Reniers@tudelft.nl (G. Reniers).

https://doi.org/10.1016/j.jlp.2021.104657
Received 26 April 2020; Received in revised form 30 September 2021; Accepted 6 October 2021
Available online 16 October 2021

Some authors focus on describing the characteristics of these accidents. For instance (Duan et al., 2011), made an analysis of hazardous chemical accidents in China between in the period 2000–2006, finding a fatality rate between 220 and 1100 people per year (Zhang and Zheng, 2012). presented a statistical of characteristics of chemical process accidents in China, providing insights in the associated time volatility, location, accident type, injuries and deaths, assigned causes, and industry type (Zhao et al., 2018). present an updated analysis of the chemical accidents in China in the period 2006 to 2017, providing insights in the time evolution, accident types, and assigned causes of these accidents. Other authors provide insights in aspects of process safety in China, with for instance several authors describing challenges for process safety for SMEs in China (Zhao et al., 2013), lessons learned for process safety management in China (Zhao et al., 2014), or describe core elements and control measures for process safety management in China (Zhou et al., 2017). (Besserman and Mentzer, 2017) reviewed global process regulations, comparing regulation in China with that of the European Union, India, the United Kingdom, and the United States (Wang et al., 2018a). provided an overview of work safety in China's thirteenth five-year plan for the period 2016–2020, highlighting various challenges and tasks related to chemical process safety (Wang et al., 2018b). described problems, challenges and opportunities for process safety in China, while (Chen and Reniers, 2020) provides a recent overview of the status of the chemical industry in China, safety-related problems, and pathways to sustainable development.

Reviews and retrospective analyses are important catalysts to focus attention on the developments in a research domain. Several descriptive accounts of the history of process safety or one of its subdomains have been presented. For instance (Khan et al., 2015), provide an overview of methods and models in process safety and risk management (Swuste et al., 2016). review the literature on process safety indicators (Mkpat et al., 2018), on process safety education, and (Gao et al., 2020) and (Park et al., 2020) address inherent safety in chemical processes and during the conceptual design process, respectively.

Given the very large body of research on process safety which has accumulated over the years, narrative reviews are of limited use to provide insights in the overall developments of the research domain. Narrative reviews are very useful and important for gaining understanding of specific aspects of a research topic, but become cumbersome and unwieldy for obtaining insights in larger domains of research (Grant and Booth, 2009). For such purposes, bibliometric analyses are more suited as a review methodology, as these techniques can provide quantitative insights in the contents, structure, patterns, and developments of a research domain (Li et al., 2020a, 2020b, 2020c, 2021).

Various such scientometric analyses have been presented for process safety research (Li et al., 2017). made a bibliometric analysis focusing on domino effects in the process industry, describing temporal evolutions, collaborations between countries, organizations and authors, and co-citation clusters providing insights in important clusters of research contributions (Gobbo et al., 2018). performed a bibliometric mapping analysis linking process safety to environmental protection and industry 4.0 (Amin et al., 2019). present a scientometric analysis of all process safety related research, focusing inter alia on active countries, key areas, leading authors, publication sources, and focus topics (Li et al., 2020a, 2020b, 2020c, 2021). present a scientometric overview of the research contributions by Dr. Sam Mannan, one of the process safety pioneers who was active and highly impactful in several of its research subdomains. A comparative analysis of the publication trends, focus topic areas, collaboration networks and core co-citation clusters of three core process safety related journals (*Journal of Loss Prevention in the Process Industries* (JLPPI), *Process Safety and Environmental Protection* (PSEP), and *Process Safety Progress* (PSP)), is presented by Li et al. (2020a). Yang et al. (2020) present a bibliometric analysis of process safety in China from a sustainability perspective, highlighting provinces of high research activity, collaboration networks, hot topics, influential contributions, and international collaborations.

In the current article, compared to Yang et al. (2020), a complementary and more detailed analysis is made of the Chinese process safety research, focusing especially on the international collaboration of Chinese scholars, and on the influence of research originating from outside China on the Chinese process safety research. In this analysis, the focus is furthermore on research of Chinese origin published in the three core process safety journals analyzed in Li et al. (2020a): JLPPI, PSEP, and PSP. To provide further insights in the developments of process safety research in China, answers to following research questions are sought:

RQ1. In what international geographic collaboration networks are Chinese process safety researchers and institutions active?

RQ2. What are the dominant narrative clusters and focus topics in Chinese process safety research, and what trends can be identified in these clusters?

RQ3. For what topics does the international collaboration drive the progress in Chinese process safety research?

RQ4. What research from which international (non-Chinese) authors has had a significant impact on the development of Chinese scholarship on process safety?

The aim of the current research is thus to provide further insights in the status and development of Chinese process safety research. A subsequent discussion will further contextualize the outputs of the Chinese process safety research community, focusing on selected future research directions considering recent trends in the wider process safety research community.

The remainder of this article is organized as follows. In Section 2, the data collection process is described and the applied scientometric methods briefly outlined. Section 3 presents the analysis results, providing answers to the above stated questions. In Section 4, a discussion on the results is given, while Section 5 concludes.

2. Data and methods

2.1. Data source and construction of datasets for analysis

The article data sample of Chinese international process safety (CIPS) research were searched in Web of Science (WoS) and downloaded on February 6, 2020. The Web of Science Core Collections (WoSCC) (SCI/SSCI) from Clarivate Analytics was selected as the source database, as this is known to comprehensively cover most academic disciplines with a high data quality (Li et al., 2020a, 2020b, 2020c, 2021). The time span of the search strategy was set from 1900 to 2019.

To obtain the Chinese international process safety papers, the steps shown in Fig. 1 were taken in the search process. First, articles originating from China in the core process safety journals (JLPPI, PSEP, and PSP) are downloaded as dataset #1. These journals are selected because earlier work has indicated that these are the 'core' process safety journals, see Li et al. (2020a). By construction, all papers in this dataset will have at least one Chinese researcher as author. This dataset contains 1,148 records. Second, a title-based search strategy is used, with the search term "process safety" and country of origin of the document set as China. This search leads to dataset #2, containing 97 publications. Third, these two datasets (dataset #1 and dataset #2) are combined to dataset #3 using the "OR"-logic operator. This dataset contains 1,214 records, indicating there is an overlap of 31 documents between the two datasets. In Table 1, some characteristics of this dataset are shown. For further use in the remainder of this article, this dataset is labeled '*Dataset TP*' (for '*Total Publications*') and contains all the articles focusing on process safety originating from China.

To distinguish the domestic Chinese articles (i.e. articles originating from China without international collaboration) from internationally co-authored articles originating from China, an additional operation is performed using the WoS search platform. As shown in Table 1, in '*Dataset DP*' (for '*Domestic Publications*'), 931 records are retained by excluding articles which are recorded in the WoSCC database as

Set	Results	Save History / Create Alert / Open Saved History
# 5	283	#2 OR #1 **Refined by: COUNTRIES/REGIONS:** (USA OR AUSTRALIA OR CANADA OR TAIWAN OR JAPAN OR ENGLAND OR FRANCE OR NORWAY OR NETHERLANDS OR BELGIUM OR PAKISTAN OR GERMANY OR INDIA OR FINLAND OR MALAYSIA OR SINGAPORE OR SOUTH KOREA OR DENMARK OR IRAN OR ITALY OR POLAND OR RUSSIA OR THAILAND OR EGYPT) *Indexes=SCI-EXPANDED, SSCI Timespan=1900-2019*
# 4	931	#2 OR #1 **Refined by:** [excluding] **COUNTRIES/REGIONS:** (USA OR AUSTRALIA OR CANADA OR TAIWAN OR JAPAN OR ENGLAND OR FRANCE OR NORWAY OR NETHERLANDS OR BELGIUM OR PAKISTAN OR GERMANY OR INDIA OR FINLAND OR MALAYSIA OR SINGAPORE OR SOUTH KOREA OR DENMARK OR IRAN OR ITALY OR POLAND OR RUSSIA OR THAILAND OR EGYPT) *Indexes=SCI-EXPANDED, SSCI Timespan=1900-2019*
# 3	1,214	#2 OR #1 *Indexes=SCI-EXPANDED, SSCI Timespan=1900-2019*
# 2	97	TS=("process safety") AND CU=(Peoples R China) *Indexes=SCI-EXPANDED, SSCI Timespan=1900-2019*
# 1	1,148	SO=("Journal of Loss Prevention in the Process Industries" OR "Process Safety and Environmental Protection" OR "Process Safety Progress") AND CU=(Peoples R China) *Indexes=SCI-EXPANDED, SSCI Timespan=1900-2019*

Fig. 1. Data search strategy of Chinese international process safety papers, Set #3, #4, and #5 correspond to datasets TP, DP, and ICP in Table 1.

Table 1
Bibliometric indicators of three datasets.

Dataset	Number of records	H-index	ACPI	STC	WSC	Timespan
DP	931	38	10.28	9574	8669	1995–2019
ICP	283	24	8.36	2365	2235	1996–2019
TP	1,214	40	9.83	11,939	10,490	1995–2019

Note : ACPI = Average citations per item | STC = Sum of Times Cited | WSC = Without self-citations | TP = total publications | DP = domestic publications | ICP = international co-authored publications.

originating from the countries or regions indicated in Fig. 1. Conversely, the '*Dataset ICP*' (for '*Internationally Co-authored Publications*') contains 283 documents, and is obtained by including the countries with which Chinese authors have collaborated in the search strategy (Li et al., 2020a, 2020b, 2020c, 2021).[1] Table 1 lists selected characteristics of this dataset.

Fig. 2 and Table 1 show several bibliometric indicators and summary statistics of the finally obtained datasets DP, ICP, and TP. Fig. 2(a) shows that 283 (23.31%) of the papers have at least one co-author from other countries/regions than China, while 931 (76.69%) are domestically Chinese articles. With an overall international collaboration rate of just 0.23, there appears significant room for increased internationalization of Chinese process safety research. Apart from the benefit of international collaboration to address complex challenges (Sonnenwald, 2007), this can increase productivity (Beaver, 2001) and may lead to increased acceptance of research contributions, especially when co-authorships are established with high-visibility scholars (Chinchilla-Rodríguez et al., 2018).

Fig. 2(b) shows that the main sources of Chinese international process safety research were published in *Journal of Loss Prevention in The Process Industries* (571, 47.0%), *Process Safety and Environmental Protection* (489, 40.3%) and *Process Safety Progress* (88, 7.3%), with these top three journals accounting for 94.6% of the total papers in the TP dataset. This confirms that indeed, these three journals can be regarded as 'core' process safety journals, which supports the data selection strategy outlined above. The results of Li et al. (2020a) indicate that JLPPI, PSEP, and PSP have in the period 1999–2019 together published 5295 articles, where these respectively account for 45.4%, 35.7%, and

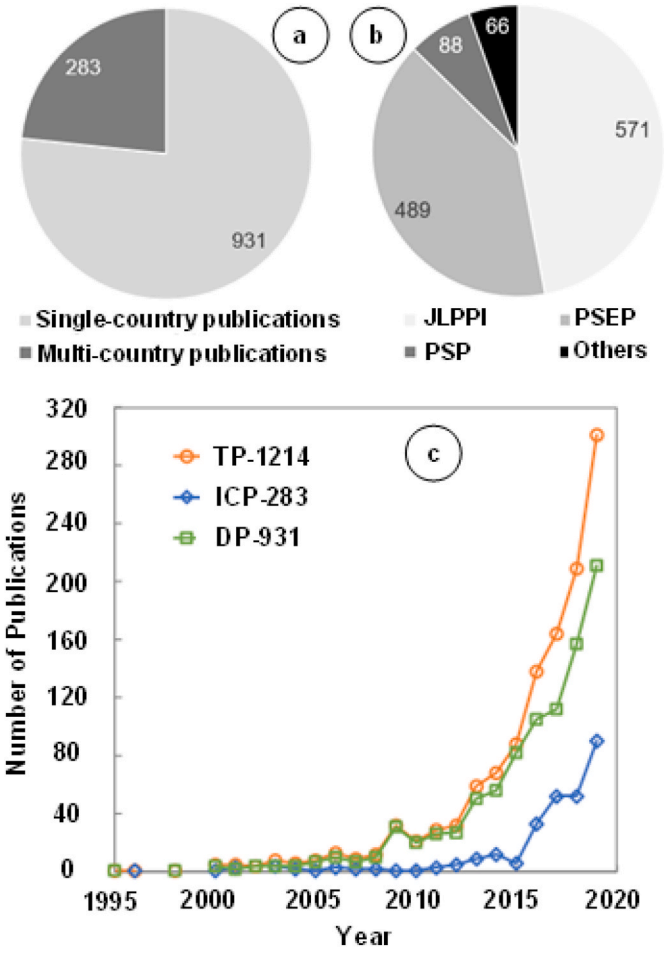


Fig. 2. Publications distribution of Chinese international process safety articles, (a) Domestic and internationally co-authored publications, (b) Journals distribution, (c) Annual publication trends of TP, DP, and ICP datasets as identified in Table 1.

18.9% of this total. This indicates that PSP is less frequently chosen as a publication outlet by Chinese scholars than JLPPI or PSEP, when compared with the overall publication trends in these journals.

The annual trend of each dataset is shown in Fig. 2(c). It is seen that Chinese international process safety research started in 1995, with the first internationally co-authored article appearing soon after in 1996.

[1] The countries listed in the search restrictions for set #4 and #5 in Fig. 1 are determined by a pre-analysis of the collaborating countries represented in set #3. As explained in Li et al. (2020a, 2020b, 2020c, 2021), an initial analysis of the obtained dataset(s) is commonly made to refine the finally used dataset(s) in the envisaged scientometric analysis.

Compared to the overall process safety research domain, which research efforts initiated in the late 1960s (Amin et al., 2019) and intensified in the 1970s and 1980s through the efforts of influential process safety pioneers such as Lawley (1974), Gibson (1976), and Kletz (2012), Chinese scholarly contributions appeared relatively late. From about the mid-2000s and especially since 2010, a very fast increasing publication output is however clearly apparent. It is seen that domestic publications are characterized by an exponential trend, while the trend of internationally co-authored publications shows a polynomial trend. In the past five years (2015–2019), the growth of domestic and internationally authored co-publications can both be well approximated with linear trends, where the rate of increase of the latter is higher than that of the former. Thus, while the growth speed of domestic Chinese process safety research is higher than that of internationally co-authored Chinese process safety research, in recent years there appears to be an increased focus on internationalization of the research efforts.

2.2. Bibliometric analysis and mapping methods and tools

Various bibliometric mapping analysis methods are applied in the current research to obtain answers for the research questions stated in Section 1. Bibliometrics is a scientific area and is defined as the application of the mathematics and statistics to analyze the journals, books and other media in a quantitative way (Pritchard, 1969). Bibliometric mapping refers to the combination of visualization techniques with the statistical methods of the bibliometric analysis, which are thus used to visually represent the results to facilitate interpretation (Small, 1999).

In recent years, bibliometrics research has seen a fast growth as a subdomain of information and science studies, and its methods and tools have been increasingly applied in diverse domains of science. Currently, a wide variety of tools has been developed, which has led to increased interest in performing scientometric analyses across scientific domains (Moral-Muñoz et al., 2020). Within the safety science community, bibliometric mapping has to date primarily applied to identify networks of author, organization, or country collaboration, to identify patterns in journals as knowledge sources, and to construct topic maps of frequently occurring terms (Li et al., 2020a, 2020b, 2020c, 2021). Examples of application of scientometric methods to obtain high-level insights in the development of safety science include the identification and knowledge flows between core safety related journals (Li and Hale, 2015, 2016), and the evolution of the *Safety Science* journal (Merigó et al., 2019) and of the three core process safety journals JLPPI, PSEP, and PSP (Li et al., 2020a). Furthermore, several aspects, topics or specific subdomains of safety research have been analyzed using bibliometric mapping, for instance safety culture (van Nunen et al., 2018), human reliability analysis (Tao et al., 2020), laboratory safety in universities (Yang et al., 2019b), construction safety (Akram et al., 2019; Jin et al., 2019), and maritime safety (Luo and Shin, 2019; Gil et al., 2020).

There are several methods for bibliometric mapping analysis, each designed for a specific research purpose. In this paper, three types of bibliometric maps are created to answer the research questions listed in Section 1: collaboration network, terms network and co-citation network. Further details of the applied scientometric mapping methods and tools are given in Table 2.

To answer research question RQ1, co-authorship mapping is used to detect the collaborations within Chinese international process safety research. Collaborations are identified and counted first at the document level, which is then further aggregated to the level of authors, institutions, cities, or countries/regions (Leydesdorff and Wagner, 2008). Co-authorship mapping is useful to represent the relative significance of contributors to the scientific domain and displays the social networks and the structure of collaboration in the Chinese international process safety research community. For this analysis, dataset TP of Table 1 is applied, with results shown in Section 3.1.

For answering research questions RQ2 and RQ3, terms co-occurrence maps are created. Terms and term phrases occurring in specific research domains provide insights in the narratives of those domains, where frequently co-occurring terms can be used to obtain insights in the important narrative patterns in the research area (Van Eck et al., 2010b). Frequently occurring terms are furthermore considered to indicate hot topics in the research domain. In this paper, noun phrases of the Chinese international process safety research are identified, extracted, selected, and visualized. Referring to Table 1, dataset TP is used for answering RQ2, while datasets DP and ICP are used to answer RQ3. Results are presented in Section 3.2.

Table 2
Interpretation of the different types of bibliometric maps applied to answer research questions RQ1 to RQ4, presented in Section 1.

Research question (s)	Type of map	Interpretation of the elements in the bibliometric map		
		Nodes	Links	Clusters
RQ1	Co-authorship	• Represent countries/ regions, cities, institutions, or authors • Size indicates the number of publications found for the item	Represent co-authorship or collaboration	Represent subgroups in the scientific community
RQ2, RQ3	Co-occurrence	• Represent terms extracted from the titles and abstract of the paper • Size indicates the term's occurrence frequency	Represent co-occurrence of the terms in articles	Represent narrative patterns and research themes
RQ4	Co-citation	• Represent the cited references, authors, or sources • Size indicates the number of citations of an item	Represent co-citation of references in articles	Represent intellectual basis and influential research domains

Note:
Colors in the bibliometric maps normally indicate the cluster to which an item is assigned.
Color schemes can also be used as an overlay to highlight e.g. the temporal evolution or scientific impact associated with specific items in the map.

For research RQ4, co-citation maps are constructed, focusing on journals co-citation, authors co-citation, and references co-citation of Chinese international process safety research. Co-citation analysis of references was first introduced by Small (1973), where the basic idea is that if two references are cited together (i.e. are co-cited), there is a certain relation between them. When references are frequently cited together, this indicates a high degree of similarity between them in some way, for instance as they address the same topic or build on the same ideas. Building on Small's original ideas, authors co-citation analysis (White and Griffith, 1981) and journals co-citation analysis (Ding et al., 2000; McCain, 1991) were also developed, using the same notion of similarity of the co-cited information units. For this research question, dataset TP of Table 1 is applied, with results shown in Section 3.3.

In the current research, the bibliometric maps of Chinese international process safety research are constructed using the VOSviewer software (van Eck and Waltman, 2010). VOSviewer is well known in bibliometric mapping analysis and has been widely used in scientific communities, also in safety related topics (Li et al., 2020a, 2020b, 2020c, 2021). The VOSviewer tool implements the visualization of similarities method, which determines the strength of relation between objects using mathematical formulations (van Eck and Waltman, 2007).

There are three main techniques implemented in VOSviewer to construct the bibliometric map: co-occurrence matrix normalization (van Eck and Waltman, 2010; van Eck et al., 2010a), VOS mapping technique (van Eck and Waltman, 2010), and VOS clustering technique (Waltman and van Eck, 2013; Waltman et al., 2010). For further technical details, the reader is referred to these publications.

3. Results

In this Section, the results of the various bibliometric analyses are shown, where the bibliometric maps created as described in Section 2.2 for the datasets described in Section 2.1 are used as central aspects of providing the answers to the research questions of Section 1. In Section 3.1, collaboration networks of the Chinese international process safety are shown, answering RQ1. Section 3.2 shows the results of the terms co-occurrence network analyses, answering RQ2 and RQ3. Finally, in Section 3.3 the results of the co-citation analyses are shown, answering RQ4.

3.1. Collaboration analysis of Chinese international process safety research

3.1.1. Countries/regions and cities collaboration network

Fig. 3 shows the collaboration network of Chinese researchers detected in the Chinese international process safety research, using dataset TP of Table 1. Of the 1,214 records in this dataset, 93.29% were geocoded successfully, i.e. 1,133 records. The remaining 6.71% of the records (81 items) could not be geocoded and are hence not represented in the results.

The geographic distribution map shows that more than 40 countries/regions have established co-authorship relations with China. Among these countries/regions, the United States of America (65, 5.74%), Australia (49, 4.32%), Canada (31, 2.74%), Taiwan (30, 2.65%), Japan (25, 2.21%), the United Kingdom (23, 2.03%), France (16, 1.41%), Norway (15, 1.32%), Netherlands (14, 1.24%) and Belgium (12, 1.06%) are the top 10 countries/regions having the most intense research collaboration with China in regards to process safety.

There are 206 cities mapped on the world map, where apart from many Chinese cities, cities in the northeastern United States and Canada, western and northern Europe, and southern Australia are most strongly represented. The geographic outputs of the cities in China correspond well to the areas of higher population density (She, 1998), with the central and eastern regions of China dominating the research intensity. Within China, the top 10 productive cities are Beijing (461, 40.69%), Nanjing (326, 28.77%), Shanghai (138, 12.18%), Guangzhou (122, 10.77%), Jinan (112, 9.89%), Hefei (110, 9.71%), Qingdao (105, 9.27%), Tianjin (75, 6.62%), Shenyang (69, 6.09%), and Chongqing (63, 5.56%).

3.1.2. Institutions and authors collaboration network

There are 699 institutions identified from the addresses provided in the publications. For the analysis, institutions with 10 or more publications are extracted from the cleaned dataset TP of Table 1, with in total 55 institutions meeting this threshold. Finally, the collaboration network of these 55 institutions in Chinese international process safety is constructed and shown in Fig. 4. As explained in Table 2, the node and label sizes indicate the number of publications of an institution, where the width of the links between each node pair represents the strength of research collaboration between the two institutions. The colors represent clusters of institutions with a comparatively high degree of joint research activities.

Given the adopted search strategy of Section 2.1, it is self-evident that almost all institutions are from China. China University of Mining and Technology from Jiangsu province has published 109 articles of the total of 1,214 (8.98%). It is followed by China University of Petroleum (86, 7.33%), Nanjing Tech University (83, 6.84%), Beijing Institute of Technology (63, 5.19%), University of Science and Technology of China (53, 4.37%), and Tsinghua University (51, 4.20%). Among these highly productive institutions, the average publication year (APY) is used to determine which institutions have become active in recent years. It is found that Shandong University of Science and Technology (APY = 2018.19), National Yunlin University of Science and Technology (APY = 2017.87), China University of Mining and Technology Beijing (APY = 2017.70), China University of Petroleum East China (APY = 2017.39) and China University of Mining and Technology (APY = 2017.08) have become recently active in the research domain compared to other institutions.

The total links (TL) of the institutions is selected as an indicator to

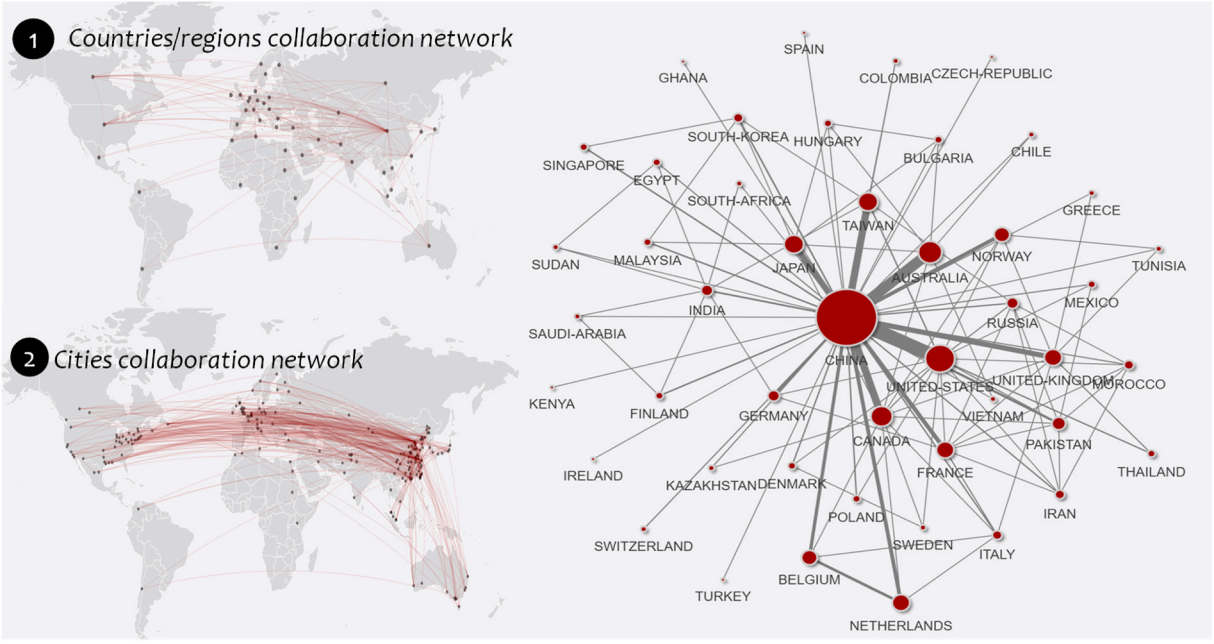


Fig. 3. Geographic distributions of collaboration network in Chinese international process safety publications, visualized using the approach by Maisonobe et al. (2019).

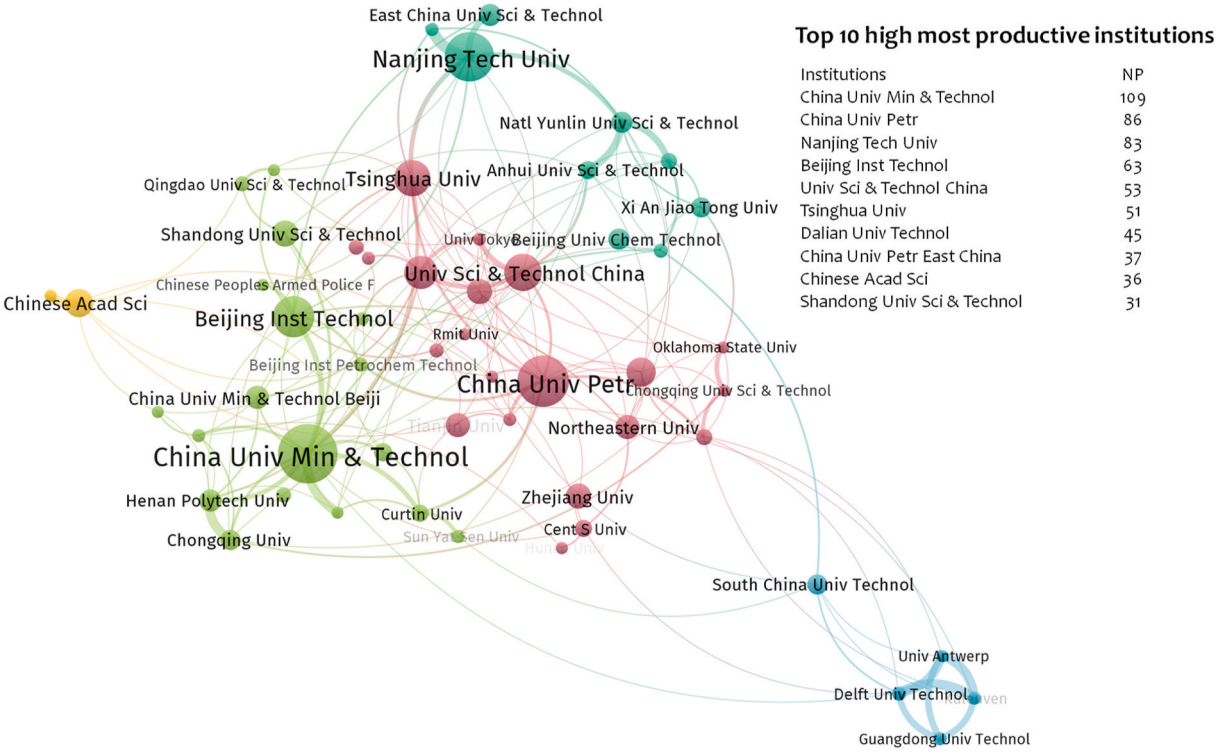


Fig. 4. Institutions collaboration network of Chinese international process safety papers, (Nodes = 55, links = 172), visualized using VOSviewer (van Eck and Waltman, 2010).

measure the degree to which institutions are open to and active in inter-organizational collaboration. The TL is equal to the number of links of a node, and thus measures the number of organizations with which a given institution has collaborated. Among the Chinese institutions in the network, China University of Mining and Technology has linked with 17 institutions, having the largest collaboration network among all organizations in the dataset. It is followed by Tsinghua University (TL = 16), University of Science and Technology China (TL = 14), Beijing Institute of Technology (TL = 13), China University of Petroleum (TL = 12), Dalian University of Technology (TL = 12), and Northeastern University (TL = 10).

Fig. 5 shows the authors collaboration network of Chinese international process safety research. Professor Jiang, Juncheng from Changzhou University (the former vice-president of Nanjing Tech University) has published 66 papers, followed by Wang, Zhirong (from Nanjing Tech University, a former PhD student of Prof. Jiang), Zhang, Laibin (China University of Petroleum, Beijing), Chen, Guoming (China University of Petroleum East China), and Wang, Kai (China University of Mining and Technology). The author collaboration is also further divided into different communities based on their collaboration strength, as indicated by the clusters marked in different colors. In Fig. 5, authors in the same cluster are usually from the same institute. For example, Jiang, Juncheng (Nanjing Tech University), Zhang, Liabing (China University of Petroleum), Chen, Guoming (China University of Petroleum East China), Gao, Wei (Dalian University of Technology), Wang, Kai (China University of Mining and Technology), Yu, Minggao (Henan Polytechnic University), and Shu, Chimin (National Yunlin University of Science and Technology) are leading researchers in their group. Among these, the groups of Chen, Guoming, Shu, Chimin, and Wang Kai have become more active in recent years, as indicated by their average publication years, which are 2017.84, 2017.9, and 2017.33, respectively.

Based on the authors and institutions collaboration network, it is found that some of the research groups have established collaborations with selected influential international scholars. These include Khan, Faisal (Memorial University of Newfoundland), Reniers, Genserik (Delft University of Technology, University of Antwerp, and KU Leuven), Amyotte, Paul (Dalhousie University), Mannan, M. Sam (Texas A&M University), Mebarki, Ahmed (Université Paris Est), and Dobashi, Ritsu (The University of Tokyo).

3.2. Narrative clusters and focus topics in Chinese international process safety research, and topics driven by international collaboration

Terms appearing in the title and abstract of scientific articles are important descriptors of their key content. In this Section, terms appearing in Chinese international process safety research are extracted from the titles and abstracts of the scientific publications of the TP dataset of Table 1. This is done using the automatic term identification method (Van Eck et al., 2010b), with the terms map was visualized by VOSviewer (van Eck and Waltman, 2010).

Fig. 6 shows the terms co-occurrence map. Adopting a threshold so that only terms occurring at least in 10 different articles are shown, a total of 314 terms are identified and visualized. A simple descriptive statistical analysis indicates that the term occurrence frequency distribution is very unbalanced, with only a few terms occurring very frequently and many terms only comparatively seldom. For example, there are only 13 terms which occur at least 100 times in the considered dataset. These terms are *'concentration'* (232 occurrences), *'accident'* (198), *'experimental study'* (191), *'pressure'* (187), *'increase'* (181), *'approach'* (177), *'risk'* (161), *'safety'* (128), *'mixture'* (120), *'China'* (103), *'case study'* (102), *'property'* (102), and *'reaction'* (101). While these terms are indeed clearly associated with the general topic of process safety research in China, they are very generic and provide little insight in the specific narratives and focus topics in the considered research domain.

To provide further insights in the narrative patterns and the focus topics in the research domain, a terms cluster analysis is conducted, which analyzes the terms in pairs and groups. As outlined in Section 2.2, two terms are considered to co-occur these appear together in the same paper. Co-occurrence relations give insights in the semantic links in the

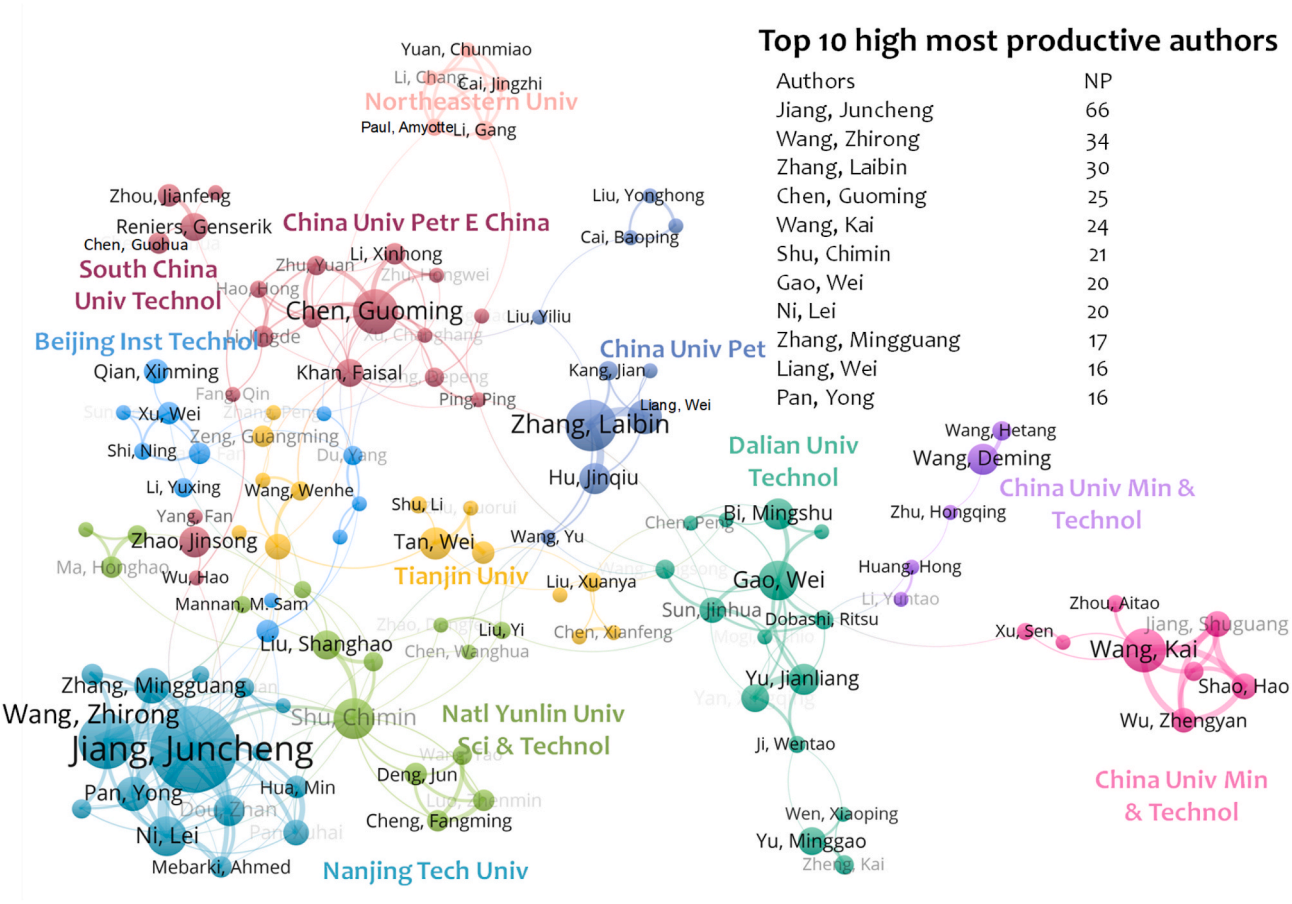


Fig. 5. Authors collaboration network of Chinese international process safety publications, (Nodes = 119, links = 273), visualized using VOSviewer (van Eck and Waltman, 2010).

dataset, more easily allowing interpretation of the dominant narrative patterns in the research domain. A further clustering of the terms based on their co-occurrence strength provides insights in the main research areas. Using the VOS clustering technique (Waltman and van Eck, 2013; Waltman et al., 2010), three clusters are detected and shown in Fig. 6: Cluster #1 *'Process safety risk management'* (including 120 terms), Cluster #2 *'Fire and explosion process safety'* (105 terms) and Cluster #3 *'Chemical process safety'* (89 terms). It is apparent that these are the same main research areas as those associated with all research published in the core process safety journals JLPPI, PSEP, and PSP, see (Li et al., 2020a). The labels of these clusters are judgments by the authors, based on the frequently occurring terms in each cluster.

To obtain further insights in the evolution and influence of the research topics in Chinese international process safety research, visual overlays are applied to the term co-occurrence map of Fig. 6. The results are shown in Fig. 7, with (a) depicting the average publication year in which the terms appear, and (b) the average citations of the terms. The overall average publication years of each cluster are very close to one another: Cluster #2 is 2015.876, Cluster #1 is 2015.997, and Cluster #3 is 2016.109. However, the standard deviation of the publication years of the terms are rather different, with Cluster #3 having the highest deviation (0.972). This indicates that while chemical process safety is well-established as a research area within Chinese international process safety research, it also has some significant emerging research focus topics. In Cluster #1, the terms *'risk'*, *'assessment'*, *'risk analysis'*, *'Bayesian network'*, *'uncertainty'*, and *'disaster'* have the highest average publication year, indicating that these topics are more recent. Within Cluster #2, the recently appearing topics are *'dust'*, *'explosion pressure'*, and *'explosion parameter'*. Finally, in Cluster #3 the terms *'coal'*, *'spontaneous combustion'*, and *'FTIR'* (Fourier Transform Infrared) are more recent.

In the co-occurrence map with overlay of the average number of citations, shown in Fig. 7(b), it is seen that the terms with the highest impact are primarily located in Cluster #3. Within this cluster, the term *'removal'* has the highest average number of citations. Other impactful terms include *'pollutant'*, *'aqueous solution'*, *'reaction temperature'*, *'coal oxidation'*, *'adsorption process'*, *'response surface methodology'*, and *'chemical oxygen demand'*. In Cluster #2, terms related to *'dust'*, including e.g. also *'dust explosion'*, *'dust cloud'*, and *'particle'* are comparatively more impactful than other terms in the cluster. Finally, in Cluster #1, terms related to quantitative risk analysis, such as *'fault tree'*, *'failure probability'*, as well as *'gas pipeline'* and *'construction'* are highly impactful.

Fig. 8 shows another overlay analysis of the term co-occurrence map of Fig. 6, indicating the ratio of the terms appearing in respectively the domestic and internationally co-authored Chinese process safety research. It is seen that the domestic papers primarily appear in Cluster #2 *'Fire and explosion process safety'*, whereas internationally co-authored topics are mostly associated with Cluster #1 *'Process safety risk management'*. As it is well understood that only scientific, technical, or engineering knowledge is insufficient to effectively manage risks and reduce the number of occurrences of process safety accidents (Meyer and Reniers, 2016), the comparative lack of specific knowledge of safety and risk management can be seen as a shortcoming of the Chinese process safety research community. Considering that international collaboration can improve the capacity to address complex challenges and facilitate knowledge exchange (Sonnenwald, 2007), it is apparent that various Chines researchers have established collaboration networks

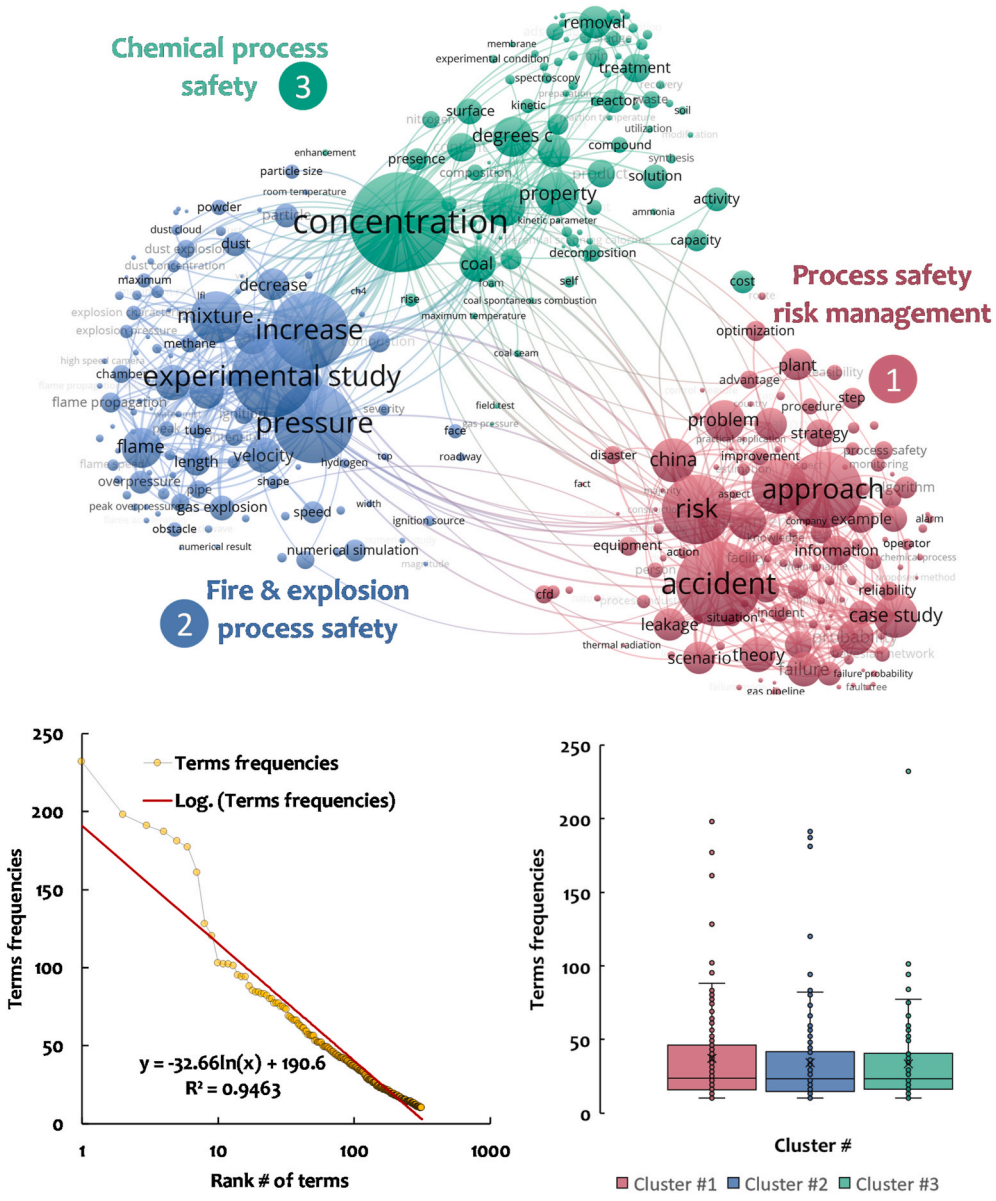


Fig. 6. Clustered term co-occurrence map of Chinese international process safety research and selected summary statistics, visualized using VOSviewer (van Eck and Waltman, 2010).

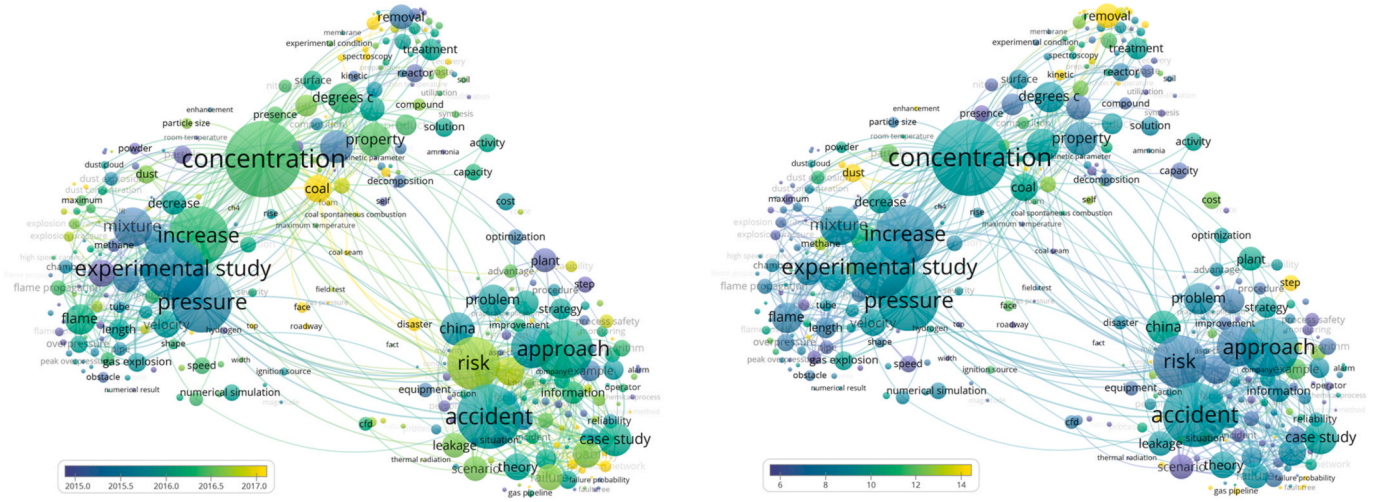
as indicated in Section 3.1.2, in particular to enhance China's capacity to work on safety and risk management related topics.

3.3. Intellectual basis: journals, authors, and impactful references

3.3.1. Cited journals and authors analysis

Highly cited journals are journals from which articles are frequently cited by Chinese process safety researchers. Hence, these journals can be regarded as influential knowledge sources in the Chinese process safety research community. Fig. 9 shows the journals co-citation network of Chinese international process safety articles. In this network, *Journal of Loss Prevention in the Process Industries* (3124), *Journal of Hazardous Materials* (1694), *Process Safety and Environmental Protection* (1102), *Fuel* (836), *Combustion and Flame* (737), *Safety Science* (582) and *Reliability Engineering and System Safety* (513) are highly cited journals, each having received more than 500 citations from the Chinese international papers in process safety. The structure of the intellectual basis at the journal level is clustered in five groups: Cluster #1 *'Environmental technology'* (red in Fig. 9), Cluster #2 *'Process safety and risk'* (green), Cluster #3 *'Fuel and mining'* (blue), Cluster #4 *'Chemical science and engineering'* (purple), and Cluster #5 *'Energy'* (yellow). The dominant cluster clearly is Cluster #2 *'Process safety and risk'*, showing the central importance of knowledge about safety, reliability, and risk aspects in implementing process safety. It is noteworthy that although JLPPI, PSEP, and PSP are core knowledge carriers for process safety research (Amin et al., 2019; Li et al., 2020a), PSP contributes comparatively less to the knowledge base for Chinese process safety researchers than the other core process safety journals, and even less than more generic safety and risk related journals.

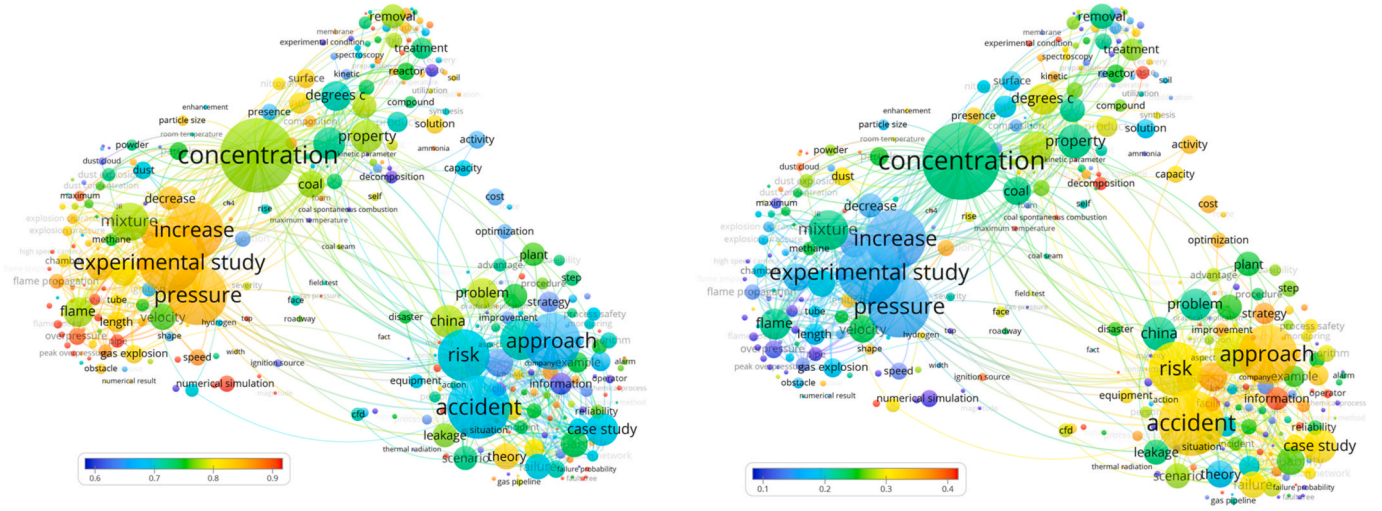
Cluster #2 also contains a subset of journals related to fire and combustion, which are related as well to the fuel-related knowledge carriers in Cluster #3. In terms of application domains of the Chinese process safety research, it is apparent that *'Environmental technology'* and *'Fuel and mining'* related knowledge is comparatively more relevant for the Chinese process safety research community, which confirms the findings of Section 3.2 that related topics provide important narratives in the research domain. Knowledge carriers related to *'Chemical science and engineering'* and *'Energy'* are also important, although comparatively



(a) Average publication year of the topics of CIPS, dataset TP of Table 1

(b) Average citations of the topics of CIPS, dataset TP of Table 1

Fig. 7. Term co-occurrence maps of Chinese international process safety research, with overlays of average publication year (a) and average citations (b), visualized using VOSviewer (van Eck and Waltman, 2010).



(a) Terms from only Chinese local communities, datasets DP and TP of Table 1

(b) Terms from the international collaboration, datasets ICP and TP of Table 1

Fig. 8. Term co-occurrence maps of Chinese international process safety research, with overlays of average publication year, visualized using VOSviewer (van Eck and Waltman, 2010).

less than the above-mentioned application domains.

Highly cited authors by the Chinese process safety research community show that articles by these authors are influential to the development of the Chinese process safety research. In this paper, particular interest goes to the scholars from other countries/regions, who have been highly cited by Chinese researchers. A co-citation map of the authors of the cited journals, presented in Fig. 10, shows that Khan FI (129), Khakzad N (97), Amyotte PR (91), Eckhoff RK (85), Cashdolloar KL (69), Cozzani V (67), Di Sarli V (62), Mebarki A (58), Baum MR (55), Razus D (55), and Reniers G (51) are highly cited international authors. These authors all have received more than 50 citations from the Chinese process safety research community.

As shown in Fig. 5, among these authors, Khan FI, Amyotte PR, Mebarki A, and Reniers G already have established collaborations with Chinese colleagues, which may be among the reasons that their work has been more frequently cited than that of other international process safety scholars. Notwithstanding the value of the knowledge dissemination through collaboration with these above-mentioned international scholars, it may be fruitful for the development of Chinese process safety research, and ultimately for enhancing the safety performance of the Chinese process industries, to further diversify its international collaborations.

In Fig. 10, the cited authors are furthermore clustered based on their co-citation strength. The clusters show that the intellectual basis of from other countries/regions on which the Chinese process safety research community relies is mainly focused on four aspects. In Cluster #1 '*Explosion and pressure*', the key authors are Di Sarli V, Razus D, and Lee JHS. Cozzani V, Mebarki A, and Baum MR are distinguished authors in

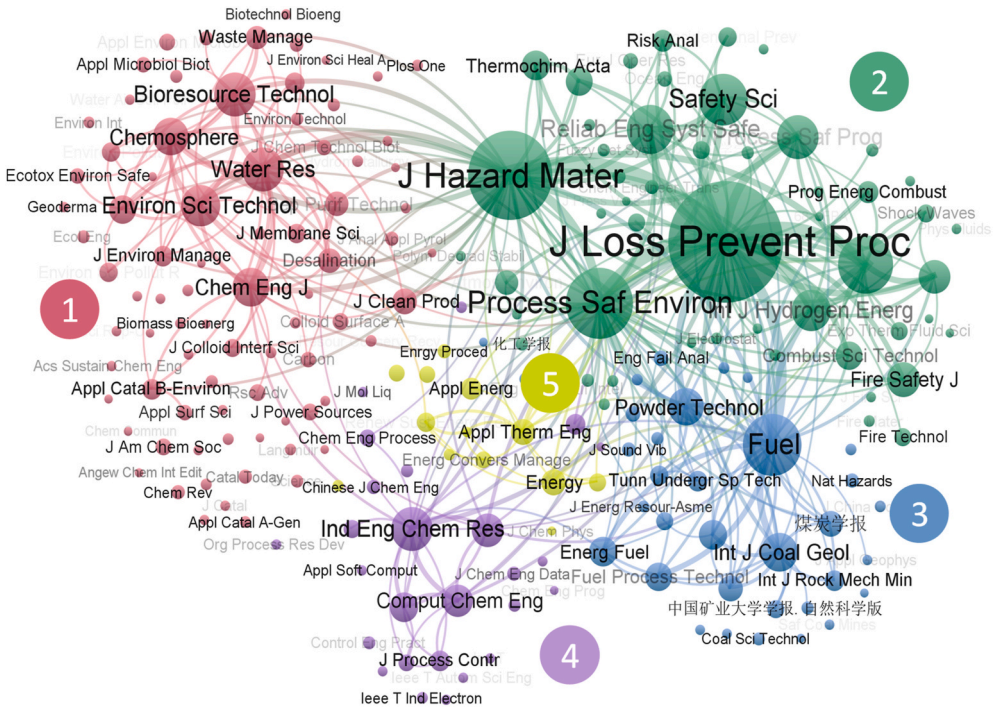


Fig. 9. Co-citation network of high cited journals in Chinese international process safety research, visualized using VOSviewer (van Eck and Waltman, 2010).

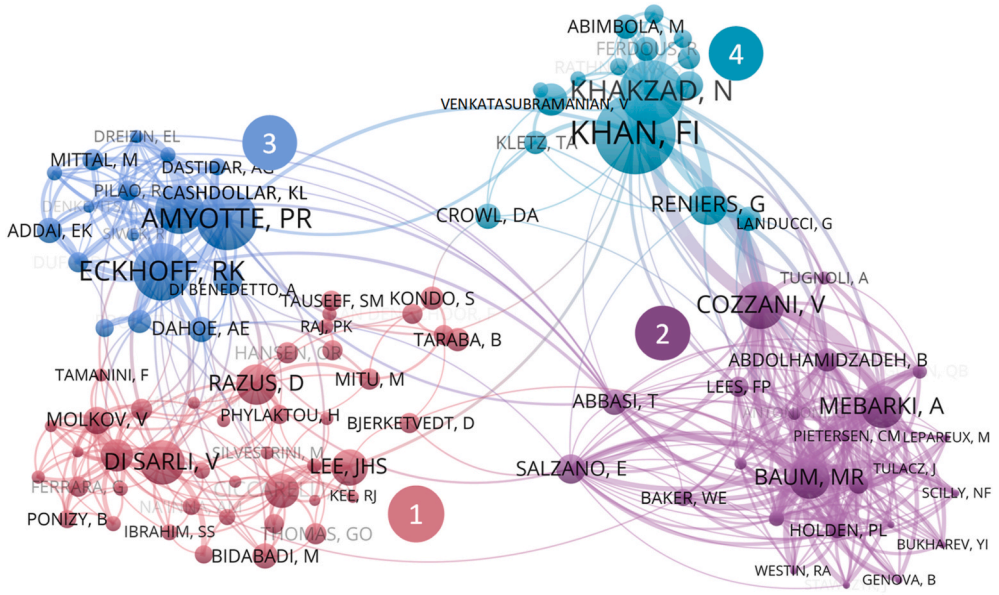


Fig. 10. Clustered co-citation network of highly cited foreign authors in Chinese international process safety research, visualized using VOSviewer (van Eck and Waltman, 2010).

Cluster #2 '*Domino effects*', with Cozzani V having strong co-citation links with Khan FI and Reniers G, who are primarily active in Cluster #4 '*Process safety and risk analysis*', but also are important contributors to domino effects (Li et al., 2017). In Cluster #3 '*Explosions*', the key authors are Amyotte PR, Eckhoff RK, and Cashdollar KL. Finally, in the Cluster #4, apart from the already mentioned Khan FI and Reniers G, Khakzad N is a key scholar.

3.3.2. Cited documents analysis

Highly cited references signify publications which have been frequently used as a basis for new research developments. Hence, such articles can be regarded as the immediate intellectual basis of the Chinese international process safety research domain. In total, 80 references with more than 10 citations are identified and extracted to construct the reference co-citation network. Fig. 11 shows the distribution of these publications, indicating that these originate from 22 different sources, in the period 1965–2018. Among these sources, *Journal of Loss Prevention in the Process Industries* accounts for 30 out of 80 publications, showing its key role in advancing the knowledge basis of Chinese process safety research. It is followed by *Journal of Hazardous Materials* (14 of 80 highly cited references), whereas *Process Safety and Environmental Protection* and other journals are significantly less influential. It is noteworthy that *Process Safety Progress*, although a key process safety journal, is not represented in the list. In terms of total

Journals/Years	1965	1980	1986	1987	1993	1994	1996	1997	1999	2000	2001	2002	2003	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total
J Loss Prevent Proc	0	0	0	0	0	0	2	0	1	2	2	0	0	1	4	1	0	3	1	2	3	2	2	3	0	1	0	30
J Hazard Mater	0	0	0	0	0	0	0	1	0	0	0	1	0	1	3	2	1	1	3	1	0	0	0	0	0	0	0	14
Process Saf Environ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	5
Fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	0	0	1	0	4
Combust Flame	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	3
Combust Sci Technol	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2
Comput Chem Eng	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Int J Coal Geol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	2
Powder Technol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	2
Prog Energ Combust	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2
Reliab Eng Syst Safe	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2
Safety Sci	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	2
Adv Eng Softw	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Adv Powder Technol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Chem Eng Sci	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
Dust Explosions Proc	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Guid Ev Char Vap Clo	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Inform Control	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Int J Hydrogen Energ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
P Combust Inst	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Thermal Safety Chem	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
Thermochim Acta	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Total	1	1	1	1	1	1	2	1	1	2	3	1	3	2	9	3	4	8	5	6	4	5	5	5	1	3	1	80

Fig. 11. Year and source of the highly cited references in Chinese international process safety research.

citations, a very similar result is found, with *Journal of Loss Prevention in the Process Industries* (3124) and *Journal of Hazardous Materials* (1694) receiving the highest number of citations. In the period 1965–2018, is can furthermore be seen that 2006 and 2009 are special years, during which respectively nine and eight highly cited articles were published.

The clusters of highly cited references in Chinese international process safety research are analyzed through a documents co-citations network, which provides insights in the intellectual structure of Chinese process safety research. The resulting clustered co-citation map is shown in Fig. 12. It contains six clusters, with the top 3 most frequently cited publications listed in Table 3. The labels of these clusters are judgments by the authors, based on the titles and abstracts of the top-3 cited articles in each cluster. The research in cluster #1 is mostly related to gas explosions; cluster #2 focuses on the application of Bayesian network models for process safety and risk analysis; cluster #3 concerns domino effects; cluster #4 relates to dust explosion; cluster #5 focuses on spontaneous heating of coal; while cluster #6 focuses on pressure and explosions. While clusters #2, #3, and #5 appear more peripheral in the figure and are rather disjoint from other clusters in the co-citation network, the clusters #1, #4, and #6 are located more closely to each other, and show stronger linkages between them. This is understandable as they all relate to various aspects of explosion, which is one of the key research areas within Chinese international process safety research, as found also e.g. in Fig. 6.

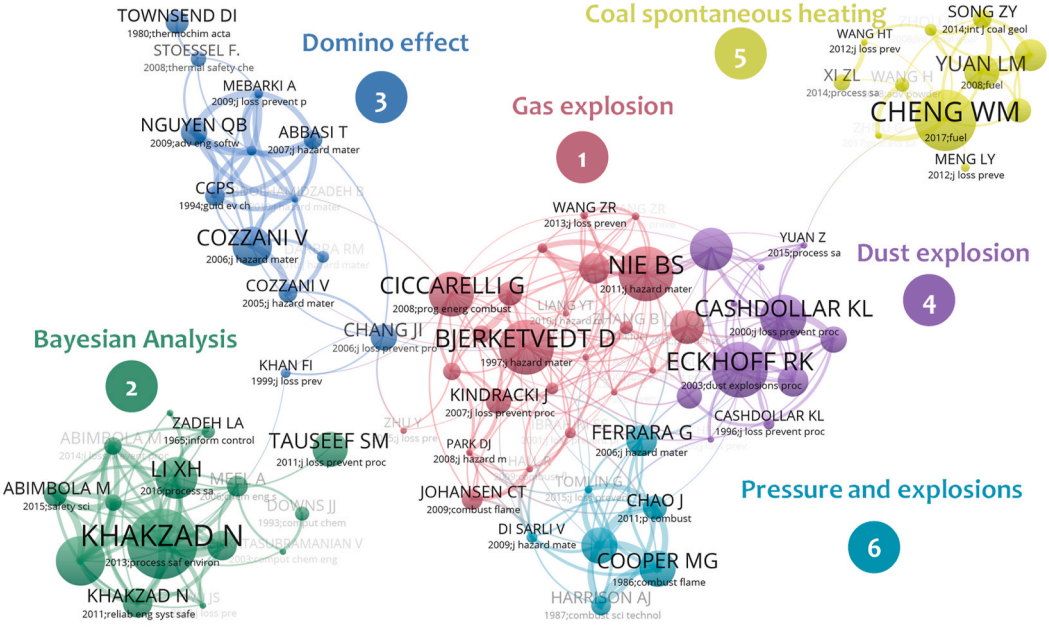


Fig. 12. Clustered co-citation network highly cited references in Chinese international process safety research, visualized using VOSviewer (van Eck and Waltman, 2010), (Nodes = 80, co-citation links = 478, sublabel indicates publication year and source).

Table 3
Top 3 high cited references in each cluster of the reference's co-citation network.

No.	First Author	Title	Cluster	NC	ACP	Reference
1	Bjerketvedt D	Gas explosion handbook	1	21	0.91	Bjerketvedt et al. (1997)
2	Nie BS	The roles of foam ceramics in suppression of gas explosion overpressure and quenching of flame propagation	1	21	2.33	Nie et al. (2011)
3	Ciccarelli G	Flame acceleration and transition to detonation in ducts	1	18	1.50	Ciccarelli and Dorofeev (2008)
4	Khakzad N	Dynamic safety analysis of process systems by mapping bow-tie into Bayesian network	2	26	3.71	Khakzad et al. (2013)
5	Bhandari J	Risk analysis of deepwater drilling operations using Bayesian network	2	19	3.80	Bhandari et al. (2015)
6	Li XH	Quantitative risk analysis on leakage failure of submarine oil and gas pipelines using Bayesian network	2	17	4.25	Li et al. (2016)
7	Cozzani V	Escalation thresholds in the assessment of domino accidental events	3	16	1.14	Cozzani et al. (2006)
8	Chang JI	A study of storage tank accidents	3	13	0.93	Chang and Lin (2006)
9	Nguyen QB	Integrated probabilistic framework for domino effect and risk analysis	3	13	1.18	Nguyen et al. (2009)
10	Townsend DI	Thermal hazard evaluation by an accelerating rate calorimeter	3	13	0.33	Townsend and Tou (1980)
11	Eckhoff RK	Dust explosions in the process industries [BOOK]	4	21	1.24	Eckhoff (2003)
12	Cashdollar KL	Overview of dust explosibility characteristics	4	18	0.90	Cashdollar (2000)
13	Amyotte PR	Solid inertants and their use in dust explosion prevention and mitigation	4	17	1.21	Amyotte (2006)
14	Cheng WM	An intelligent gel designed to control the spontaneous combustion of coal: Fire prevention and extinguishing properties	5	23	7.67	Cheng et al. (2017)
15	Yuan LM	Numerical study on effects of coal properties on spontaneous heating in longwall gob areas	5	15	1.25	Yuan and Smith (2008)
16	Taraba B	Effect of longwall face advance rate on spontaneous heating process in the gob area – CFD modeling	5	14	1.56	Taraba and Michalec (2011)
17	Bauwens CR	Effect of ignition location, vent Size, and obstacles on vented explosion overpressures in propane-air mixtures	6	15	1.50	Bauwens et al. (2010)
18	Cooper MG	On the mechanisms of pressure generation in vented explosions	6	15	0.44	Cooper et al. (1986)
19	Ferrara G	CFD analysis of gas explosions vented through relief pipes	6	14	1.00	Ferrara et al. (2006)

Note: NC = number of citations | ACP = average number of citations per year.

4. Discussion

4.1. Interpretation and future research directions

The analyses of the Chinese international process safety research show that the overall research community has made a fast-paced increase in research productivity especially during the last 15 years. Whereas compared to other industrialized regions such as western Europe and eastern United States, the developments in Chinese process safety research came with a delay, there currently is a large and active community advancing this knowledge domain in support of safer and more environmentally sustainable process industries.

Despite the significant number of countries and institutions with which Chinese scholars have contributed as seen in Fig. 3, there are relatively few internationally leading scholars who have established extensive collaborations with Chinese authors, as can be seen from Figs. 4 and 5. Wagner and Leydesdorff (2005) found that international collaborations are preferably sought with high-impact international scholars. Evidence suggests that international collaboration and researcher mobility is associated with increased productivity (Beaver, 2001), higher quality (Abramo et al., 2011), higher citation rates (Gazni et al., 2012), and increased acceptance of the research outputs (Chinchilla-Rodríguez et al., 2018). Further developing such collaborations, e.g. through international mobility efforts, can help to further advance the Chinese process safety community. Hence, both international leading experts in process safety as well as Chinese scholars can mutually benefit from establishing further collaborations. A further diversification of the internationalization of Chinese process safety research may moreover be beneficial to widen the intellectual basis of the research contributions. As seen in the co-citation analyses of Figs. 10 and 12, many of the most frequently cited authors by the Chinese process research community are also those with which collaborations have been established, see also Section 3.1.2. As there likely is a causal connection between these observations in that authors may preferentially adopt knowledge from their collaborators, this suggests that a further differentiation of the international collaboration may benefit the development of process safety research in China.

From Fig. 11, it is noteworthy that many of the highly cited articles in the Chinese process safety research literature are published relatively recently, with especially the period after 2005 representing a significant impact. This may be related to finding that the Chinese process safety research community itself became more active from around approximately that time, see Fig. 2. Considering that even very impactful articles receive fewer citations over time due to memory of ageing effects (Ponomarev et al., 2012), it is likely that earlier published process safety research has not received much explicit scholarly attention in China, whereas those sources may still spark new ideas. Therefore, it may be worthwhile for Chinese process safety scholars to trace back other impactful process safety literature from before the Chinese research community itself became increasingly active. Retrospective analyses such as those by Amin et al. (2019), Li et al. (2020a, 2020b, 2020c, 2021), and Khan et al. (2015), and viewpoints and analyses of the legacy of safety pioneers such as Dr. Trevor Kletz (Mannan, 2012; Pasman et al., 2012; Vaughen, 2012) can be instrumental in this regard. It is also noteworthy that the work Dr. Sam Mannan, even though he was one of the most influential scholars in process safety (Sanders, 2018), and despite being somewhat linked to the Chinese process safety research community as observed from Fig. 5, is apparently not very well known in this community. At least, his works are (to date) not as impactful as that of other internationally leading process safety scholars. In this regard, it may be instrumental for the Chinese process safety researchers to get more acquainted with his work, and that of his collaborators, for which a recent retrospective analysis of this publications may be helpful (Li et al., 2020a, 2020b, 2020c, 2021).

Considering the scope of the datasets as described it Section 2.1, where the focus of the current work is on Chinese process safety research published in the three core process safety journals JLPPI, PSEP, and PSP, it is also useful to make comparisons with the overall publication trends in those journals. This can provide insights especially in topics which are important in the wider process safety research community compared to those addressed in China. Considering the research areas identified in the clustered terms co-occurrence map of Fig. 6 in light of the results obtained by Li et al. (2020a),[2] it is evident that the same three main areas are found. Compared to the terms in Cluster #1 '*Process safety risk management*', the wider process safety research community has comparatively more focus on occupational safety, safety management, learning from incidents, and resilience than the Chinese community. Such topics can therefore be fruitful areas for Chinese process safety scholarship, where knowledge can be obtained from international process safety scholars. Within Cluster #2 '*Fire & explosion process safety*', the topics of the Chinese and international research communities are largely similar, but in international research there is comparatively more focus on vapor cloud explosions, dispersion models, and bleve (boiling liquid expanding vapor explosion), and blast waves. Considering Cluster #3 '*Chemical process safety*', the Chinese research is comparatively more focused on coal than the international research, which focuses on various other substances such as methanol, hexane, H_2O_2 (hydrogen peroxide), as well as biomass. On the other hand, recently emerging and impactful topics related to adsorption, aqueous solutions as removal and treatment approaches appear both in the international as in the Chinese process safety community, indicating that the Chinese community keeps abreast of and helps drive this line of research.

Based on the above insights, focusing on the fact that international collaboration appears to be most beneficial to drive the work in research area #1 '*Process safety risk management*', selected further directions for further research activity by Chinese scholars are given. Several future research directions are given also in the complementary work to this research, by Yang et al. (2020). The ideas presented there are not repeated here. Instead, the research directions are elaborated based on what the authors consider to be the main upcoming areas in the field of process safety research, based on the presented analysis. As quantification of risks and probabilistic analyses appear to be an important focus, future work may more widely focus on the treatment and communication of uncertainties in risk analysis, see e.g. Milazzo and Aven (2012) and Goerlandt and Reniers (2016) for insights on these topics. The related topics of risk evaluation, risk acceptability, and economic aspects of safety decision-making (Ale, 2005; Reniers and Van Erp, 2016) also present fruitful avenues for future research. Further issues related to risk assessment concerns how to identify and manage risks related to black swan events (Paté-Cornell, 2012), which are also an important aspect of Sam Mannan's safety triad for process safety (O'Connor et al., 2019). An issue needing more scientific attention is interorganizational accident risk management (Milch and Laumann, 2016), which has received little attention in the wider process safety research community and appears lacking in a Chinese context. This may for instance be relevant for risks related to the transport of hazardous materials (Torretta et al., 2017), or the storing and/or bunkering of LNG at ports, see e.g. (Aneziris et al., 2020). While some research has addressed public risk perception and communication related to process industries (Huang et al., 2013), this also appears to be an under-researched area. Furthermore, with increasing connectivity and digitalization, and with heightened awareness of terrorist threats, focus on the development of effective security risk management approaches is important, see e.g. Baybutt (2017). In this context, considering the similarities and the differences between safety and security concepts and on the different knowledge domains on which these build (Li et al., 2020b), is important for developing integrated safety and security risk management strategies. Finally, while resilience engineering is a topic of rising importance in the broader safety and risk communities, only scant work in this direction is found in our analysis. Leading researchers such as Sam Mannan have made contributions towards such novel conceptualizations of ensuring safety, see e.g. Li et al. (2020a, 2020b, 2020c, 2021), but further focus on this emerging area appears warranted.

4.2. Limitations of the work

As in any study, it is important to be aware of the limitations of the work. A first issue concerns the search strategy. As described in Section 2.1, a focused search is made in the three core process safety research journals for Chinese contributions, augmented by Chinese contributions specifically addressing process safety as a topic. This approach differs from the search strategy by Yang et al. (2020). Focusing on core journals of a research domain, as in Li et al. (2020a), is a suitable approach to identify the activity in driving knowledge carriers of a research domain (Li and Hale, 2015), and allows identification of the core authors, institutions, narrative clusters and intellectual basis in a given domain. Nevertheless, with a somewhat different search strategy, or by using other citation databases such as Scopus or SciFinder somewhat different results may be found. It is stressed as well that our current focus is only on process safety, i.e. work related to unintentional incidents and accidents. While the security of process installations (i.e. intentional events) clearly is immensely important as well, and work in that area has significantly developed as well in recent years, we have excluded security from our current scope.

An important issue in scientometric analyses is the interpretation of quantitative metrics such as number of citations and number of documents, which lay at the basis of the co-authorship, co-occurrence, and co-citation analyses as presented in Section 3. In scientometric analyses and scientometric mapping, citation metrics are used as a kind of proxy for the impact and significance of research contributions. This has however been much debated, see e.g. Garfield (1979) and Lynch (2015). These metrics should not be understood as quality measures or

[2] In particular, the reader is referred to Figs. 8 and 9 of Li et al. (2020a, 2020b, 2020c, 2021), which show term co-occurrence clusters of the publications in the journals *Loss Prevention in the Process Industries*, *Process Safety and Environmental Protection*, and *Process Safety Progress*.

endorsements of the research outputs, but rather as indicators providing high-level insights in the content, structure, and evolution of a research domain. Highly cited references indicate that these significantly contribute to the development of the research domain, but as such their high citation rate does not imply correctness or impact beyond the academic context. In this context, it is noted also that as our focus is on the contents and evolution of the Chinese-authored process research field, we have not analyzed journal-specific indicators such as the journal impact factors, as this is only tangentially related to the development of the field itself.

Finally, it should be borne in mind that due to the lifecycle of research articles, for which citations accumulate over time (Ponomarev et al., 2012), the focus on number of citations in scientometrics can lead to an underappreciation of significant emerging research topics or authors. This is because more recently published articles have not yet had the time to accumulate a high number of citations, which may bias the analyses somewhat in favor of research published a longer time ago.

5. Conclusions

In this paper, a bibliometric mapping analysis is performed of the Chinese international process safety literature, focusing on the contributions in three core process safety journals. It is found that the earliest international academic contributions from China appeared in the mid-1990s, with the research community becoming increasingly active since approximately the mid-2000s, with a fast-increasing publication output since then.

The results of the collaboration analyses indicate that while Chinese researchers and institutions have collaborated with many international scholars located mostly in western Europe, northeastern USA, southern Australia, and Japan, by far most of the collaborations occur within China. Only with a few leading international scholars have more enduring collaborations been established, whereas the terms co-occurrence analysis indicates that these international collaborations primarily contribute to advance the knowledge in aspects related to process safety risk management. In contrast, Chinese researchers are mostly working domestically on aspects related to fire and explosion process safety, and chemical process safety. Within those research areas, while there are some differences in focus topics compared to the complete international process safety research community, the Chinese research community is well established. For the process safety risk management related research, the focus in Chinese contributions is on quantitative risk analysis, probabilistic analyses, and process accidents. A clustered co-citation analysis further indicates that especially the use of Bayesian network models and is an important influence from international authors, as well as approaches to understand and analyze domino effects. In terms of journals focusing on safety and risk management, Chinese scholars rely on knowledge from *Journal of Loss Prevention in the Process Industries*, *Journal of Hazardous Materials*, *Process Safety and Environmental Protection*, *Safety Science*, and *Reliability Engineering and System Safety*. Interestingly, while being a core process safety journal, Chinese researchers rely comparatively less on knowledge disseminated in *Process Safety Progress*. Compared to the international process safety community, and the wider safety and risk scholarly community the terms co-occurrence and co-citation analyses indicate that the Chinese research community has paid less attention to issues such as occupational safety, safety management, learning from incidents, and resilience.

Based on the findings, several suggestions for future research directions are formulated. These include increased focus on the treatment and communication of uncertainties in risk analysis, economic aspects of safety decisions and safety economics, black swan events, resilience engineering and systems approaches, interorganizational accident risk management, road and maritime transport of hazardous substances, process safety risk perception and communication, and integrated process safety and security. While scientometric methods can only provide a high-level overview of the Chinese process safety research domain, it is also recommended that further narrative literature reviews of its research domains are conducted, to obtain more detailed insights in the developments and knowledge gaps. The trends, patterns, developments, gaps, and research directions identified using the presented analyses could serve as a fruitful basis for this.

It is hoped that the insights obtained from the presented analysis can be used by Chinese researchers and international scholars to identify possible areas of future collaboration. This can invigorate the research domain, bring in new ideas, concepts, and methods, and may lead to higher productivity, strengthen the quality and acceptance of solutions for the various complex challenges facing the research domain, and ultimately help to further improve the safety performance of the process industries in China and elsewhere.

Author contribution statement

The authors hereby confirm that they all have had a role and impact in the conceptualization, development, structuring and/or writing of the paper.

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.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (NO. 51874042 and 51904185) and discipline innovation team of Liaoning Technical University (LNTU20TD-04). The contributions by the second author were supported through the Canada Research Chairs Program, through a grant by the Natural Sciences and Engineering Research Council (NSERC).

References

Abramo, G., D'Angelo, C.A., Solazzi, M., 2011. The relationship between scientists' research performance and the degree of internationalization of their research. Scientometrics 86, 629–643.
Akram, R., Thaheem, M.J., Nasir, A.R., Ali, T.H., Khan, S., 2019. Exploring the role of building information modeling in construction safety through science mapping. Saf. Sci. 120, 456–470.
Ale, B.J.M., 2005. Tolerable or acceptable: a comparison of risk regulation in the United Kingdom and in The Netherlands. Risk Anal. 25, 231–241.
Amin, M.T., Khan, F., Amyotte, P., 2019. A bibliometric review of process safety and risk analysis. Process Saf. Environ. Protect. 126, 366–381.
Amyotte, P.R., 2006. Solid inertants and their use in dust explosion prevention and mitigation. J. Loss Prev. Process. Ind. 19, 161–173.
Aneziris, O., Koromila, I., Nivolianitou, Z., 2020. A systematic literature review on LNG safety at ports. Saf. Sci. 124, 104595.
Bauwens, C.R., Chaffee, J., Dorofeev, S., 2010. Effect of ignition location, vent size, and obstacles on vented explosion overpressures in propane-air mixtures. Combust. Sci. Technol. 182, 1915–1932.
Baybutt, P., 2017. Issues for security risk assessment in the process industries. J. Loss Prev. Process. Ind. 49, 509–518.
Beaver, D.D., 2001. Reflections on scientific collaboration (and its study): past, present, and future. Scientometrics 52, 365–377.
Besserman, J., Mentzer, R.A., 2017. Review of global process safety regulations: United States, European Union, United Kingdom, China, India. J. Loss Prev. Process. Ind. 50, 165–183.
Bhandari, J., Abbassi, R., Garaniya, V., Khan, F., 2015. Risk analysis of deepwater drilling operations using Bayesian network. J. Loss Prev. Process. Ind. 38, 11–23.
Bjerketvedt, D., Bakke, J.R., Van Wingerden, K., 1997. Gas explosion handbook. J. Hazard. Mater. 52, 1–150.
Cashdollar, K.L., 2000. Overview of dust explosibility characteristics. J. Loss Prev. Process. Ind. 13, 183–199.
Chang, J.I., Lin, C.-C., 2006. A study of storage tank accidents. J. Loss Prev. Process. Ind. 19, 51–59.
Chen, C., Reniers, G., 2020. Chemical industry in China: the current status, safety problems, and pathways for future sustainable development. Saf. Sci. 128, 104741.

Chen, M., Wang, X., 2012. Lessons learned from Dalian tank farm accident. In: 2012 AIChE Spring Meeting and 8th Global Congress on Process Safety 2012, Houston, TX, pp. 1825–1833.
Chen, Q., Wood, M., Zhao, J., 2019. Case study of the Tianjin accident: application of barrier and systems analysis to understand challenges to industry loss prevention in emerging economies. Process Saf. Environ. Protect. 131, 178–188.
Cheng, W., Hu, X., Xie, J., Zhao, Y., 2017. An intelligent gel designed to control the spontaneous combustion of coal: fire prevention and extinguishing properties. Fuel 210, 826–835.
Chinchilla-Rodríguez, Z., Miguel, S., Perianes-Rodríguez, A., Sugimoto, C.R., 2018. Dependencies and autonomy in research performance: examining nanoscience and nanotechnology in emerging countries. Scientometrics 115, 1485–1504.
Ciccarelli, G., Dorofeev, S., 2008. Flame acceleration and transition to detonation in ducts. Prog. Energy Combust. Sci. 34, 499–550.
Cooper, M.G., Fairweather, M., Tite, J.P., 1986. On the mechanisms of pressure generation in vented explosions. Combust. Flame 65, 1–14.
Cozzani, V., Gubinelli, G., Salzano, E., 2006. Escalation thresholds in the assessment of domino accidental events. J. Hazard. Mater. 129, 1–21.
Ding, Y., Chowdhury, G.G., Foo, S., 2000. Journal as markers of intellectual space: journal co-citation analysis of information retrieval area, 1987–1997. Scientometrics 47, 55–73.
Duan, W., Chen, G., Ye, Q., Chen, Q., 2011. The situation of hazardous chemical accidents in China between 2000 and 2006. J. Hazard. Mater. 186, 1489–1494.
Eckhoff, R.K., 2003. Dust Explosions in the Process Industries, third ed. Gulf Professional Publishing, Amsterdam, The Netherlands.
Ferrara, G., Di Benedetto, A., Salzano, E., Russo, G., 2006. CFD analysis of gas explosions vented through relief pipes. J. Hazard. Mater. 137, 654–665.
Gao, X., Abdul Raman, A.A., Hizaddin, H.F., Bello, M.M., 2020. Systematic review on the implementation methodologies of inherent safety in chemical process. J. Loss Prev. Process. Ind. 65, 104092.
Garfield, E., 1979. Is citation analysis a legitimate evaluation tool? Scientometrics 1, 359–375.
Gazni, A., Sugimoto, C.R., Didegah, F., 2012. Mapping world scientific collaboration: authors, institutions, and countries. J. Assoc. Inf. Syst. 63, 323–335.
Gibson, S.B., 1976. Risk criteria in hazard analysis. Chem. Eng. Prog. 72 (2), 59–62.
Gil, M., Wróbel, K., Montewka, J., Goerlandt, F., 2020. A bibliometric analysis and systematic review of shipboard Decision Support Systems for accident prevention. Saf. Sci. (in press).
Gobbo, J.A., Busso, C.M., Gobbo, S.C.O., Carreão, H., 2018. Making the links among environmental protection, process safety, and industry 4.0. Process Saf. Environ. Protect. 117, 372–382.
Goerlandt, F., Reniers, G., 2016. On the assessment of uncertainty in risk diagrams. Saf. Sci. 84, 67–77.
Grant, M.J., Booth, A., 2009. A typology of reviews: an analysis of 14 review types and associated methodologies. Health Inf. Libr. J. 26, 91–108.
Huang, L., Ban, J., Sun, K., Han, Y., Yuan, Z., Bi, J., 2013. The influence of public perception on risk acceptance of the chemical industry and the assistance for risk communication. Saf. Sci. 51, 232–240.
Jin, R., Zou, P.X.W., Piroozfar, P., Wood, H., Yang, Y., Yan, L., Han, Y., 2019. A science mapping approach based review of construction safety research. Saf. Sci. 113, 285–297.
Khakzad, N., Khan, F., Amyotte, P., 2013. Dynamic safety analysis of process systems by mapping bow-tie into Bayesian network. Process Saf. Environ. Protect. 91, 46–53.
Khan, F., Rathnayaka, S., Ahmed, S., 2015. Methods and models in process safety and risk management: past, present and future. Process Saf. Environ. Protect. 98, 116–147.
Kletz, T., 2012. The history of process safety. J. Loss Prev. Process. Ind. 25, 763–765.
Lawley, H.G., 1974. Operability studies and hazard analysis. Chem. Eng. Prog. 70, 45–56.
Leydesdorff, L., Wagner, C.S., 2008. International collaboration in science and the formation of a core group. J Informetr. 2, 317–325.
Li, J., Goerlandt, F., Reniers, G., 2020a. Mapping process safety: a retrospective scientometric analysis of three process safety related journals (1999-2018). J. Loss Prev. Process Ind. (in press).
Li, J., Goerlandt, F., Van Nunen, K., Reniers, G., 2020b. Safety and security research: identifying similarities and differences using scientometric analysis methods. J. Integrat Secur. Sci. (forthcoming).
Li, J., Goerlandt, F., Reniers, G., Zhang, B., 2020c. Sam Mannan and his scientific publications: a life in process safety research. J. Loss Prev. Process Ind. 66, 104140.
Li, J., Goerlandt, F., Reniers, G., 2021. An overview of scientometric mapping for the safety science community: methods, tools, and processes. Safety Sci. 134, 105093.
Li, J., Hale, A., 2015. Identification of, and knowledge communication among core safety science journals. Saf. Sci. 74, 70–78.
Li, J., Hale, A., 2016. Output distributions and topic maps of safety related journals. Saf. Sci. 82, 236–244.
Li, J., Reniers, G., Cozzani, V., Khan, F., 2017. A bibliometric analysis of peer-reviewed publications on domino effects in the process industry. J. Loss Prev. Process. Ind. 49, 103–110.
Li, X., Chen, G., Zhu, H., 2016. Quantitative risk analysis on leakage failure of submarine oil and gas pipelines using Bayesian network. Process Saf. Environ. Protect. 103, 163–173.
Luo, M., Shin, S.-H., 2019. Half-century research developments in maritime accidents: future directions. Accid. Anal. Prev. 123, 448–460.
Lynch, K., 2015. Control by numbers: new managerialism and ranking in higher education. Crit. Stud. Educ. 56, 190–207.
Maisonobe, M., Jégou, L., Yakimovich, N., Cabanac, G., 2019. NETSCITY: a geospatial application to analyse and map world scale production and collaboration data between cities. In: International Conference on Scientometrics and Informetrics (ISSI 2019), Rome, Italy.
Mannan, M.S., 2012. Trevor Kletz's impact on process safety and a plea for good science-An academic and research perspective. Process Saf. Environ. Protect. 90, 343–348.
McCain, K.W., 1991. Mapping economics through the journal literature: an experiment in journal cocitation analysis. J. Am. Soc. Inf. Sci. 42, 290–296.
Merigó, J.M., Miranda, J., Modak, N.M., Boustras, G., de la Sotta, C., 2019. Forty years of Safety Science: a bibliometric overview. Saf. Sci. 115, 66–88.
Meyer, T., Reniers, G., 2016. Engineering Risk Management. De Gruyter Graduate, Berlin.
Milazzo, M.F., Aven, T., 2012. An extended risk assessment approach for chemical plants applied to a study related to pipe ruptures. Reliab. Eng. Syst. Saf. 99, 183–192.
Milch, V., Laumann, K., 2016. Interorganizational complexity and organizational accident risk: a literature review. Saf. Sci. 82, 9–17.
Mkpat, E., Reniers, G., Cozzani, V., 2018. Process safety education: a literature review. J. Loss Prev. Process. Ind. 54, 18–27.
Moral-Muñoz, J.A., Herrera-Viedma, E., Santisteban-Espejo, A., Cobo, M.J., 2020. Software tools for conducting bibliometric analysis in science: an up-to-date review. El Prof. Inf. (EPI) 29.
Nguyen, Q.B., Mebarki, A., Saada, R.A., Mercier, F., Reimeringer, M., 2009. Integrated probabilistic framework for domino effect and risk analysis. Adv. Eng. Software 40, 892–901.
Nie, B., He, X., Zhang, R., Chen, W., Zhang, J., 2011. The roles of foam ceramics in suppression of gas explosion overpressure and quenching of flame propagation. J. Hazard. Mater. 192, 741–747.
O'Connor, M., Pasman, H.J., Rogers, W.J., 2019. Sam Mannan's safety triad, a framework for risk assessment. Process Saf. Environ. Protect. 129, 202–209.
Park, S., Xu, S., Rogers, W., Pasman, H., El-Halwagi, M.M., 2020. Incorporating inherent safety during the conceptual process design stage: a literature review. J. Loss Prev. Process. Ind. 63, 104040.
Pasman, H.J., Rogers, W.J., Mannan, M.S., 2012. How to consolidate Trevor's experience and knowledge? Impossibilities, reflections on possibilities, and call to action. J. Loss Prev. Process. Ind. 25, 870–875.
Paté-Cornell, E., 2012. On "Black Swans" and "Perfect Storms": risk analysis and management when statistics are not enough. Risk Anal.: Int. J. 32, 1823–1833.
Ponomarev, I.V., Williams, D.E., Lawton, B.K., Cross, D.H., Seger, Y., Schnell, J., Haak, L. L., 2012. Breakthrough Paper Indicator: Early Detection and Measurement of Ground-Breaking Research.
Pritchard, A., 1969. Statistical bibliography or bibliometrics. J. Doc. 25, 348–349.
Reniers, G.L.L., Van Erp, H.R.N., 2016. Operational Safety Economics: a Practical Approach Focused on the Chemical and Process Industries. John Wiley & Sons, p. 318.
Sanders, R.E., 2018. Tributes received in honor of M. Sam mannan. Process Saf. Prog. 37, 448–451.
She, W., 1998. Hu Huanyong: father of China's population geography. China Popul. Today 15, 20.
Small, H., 1973. Co-citation in the scientific literature: a new measure of the relationship between two documents. J. Am. Soc. Inf. Sci. 24, 265–269.
Small, H., 1999. Visualizing science by citation mapping. J. Am. Soc. Inf. Sci. 50, 799–813.
Sonnenwald, D.H., 2007. Scientific collaboration. Annu. Rev. Inf. Sci. Technol. 41, 643–681.
Swuste, P., Theunissen, J., Schmitz, P., Reniers, G., Blokland, P., 2016. Process safety indicators, a review of literature. J. Loss Prev. Process. Ind. 40, 162–173.
Tao, J., Qiu, D., Yang, F., Duan, Z., 2020. A bibliometric analysis of human reliability research. J. Clean. Prod. 260, 121041.
Taraba, B., Michalec, Z., 2011. Effect of longwall face advance rate on spontaneous heating process in the gob area – CFD modelling. Fuel 90, 2790–2797.
Torretta, V., Rada, E.C., Schiavon, M., Viotti, P., 2017. Decision support systems for assessing risks involved in transporting hazardous materials: a review. Saf. Sci. 92, 1–9.
Townsend, D.I., Tou, J.C., 1980. Thermal hazard evaluation by an accelerating rate calorimeter. Thermochim. Acta 37, 1–30.
van Eck, N.J., Waltman, L., 2007. VOS: a new method for visualizing similarities between objects. In: Decker, R., Lenz, H.J. (Eds.), Advances in Data Analysis. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 299–306.
van Eck, N.J., Waltman, L., 2010. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 84, 523–538.
van Eck, N.J., Waltman, L., Dekker, R., van den Berg, J., 2010a. A comparison of two techniques for bibliometric mapping: multidimensional scaling and VOS. J. Am. Soc. Inf. Sci. Technol. 61, 2405–2416.
Van Eck, N.J., Waltman, L., Noyons, E.C.M., Buter, R.K., 2010b. Automatic term identification for bibliometric mapping. Scientometrics 82, 581–596.
van Nunen, K., Li, J., Reniers, G., Ponnet, K., 2018. Bibliometric analysis of safety culture research. Saf. Sci. 108, 248–258.
Vaughen, B.K., 2012. A tribute to Trevor Kletz: what we are doing and why we are doing it. J. Loss Prev. Process. Ind. 25, 770–774.
Wagner, C.S., Leydesdorff, L., 2005. Network structure, self-organization, and the growth of international collaboration in science. Res. Pol. 34, 1608–1618.
Waltman, L., van Eck, N.J., 2013. A smart local moving algorithm for large-scale modularity-based community detection. Eur. Phys. J. B 86, 471.
Waltman, L., van Eck, N.J., Noyons, E.C.M., 2010. A unified approach to mapping and clustering of bibliometric networks. J. Inf. 4, 629–635.

Wang, B., Wu, C., Kang, L., Reniers, G., Huang, L., 2018a. Work safety in China's Thirteenth Five-Year plan period (2016–2020): current status, new challenges and future tasks. Saf. Sci. 104, 164–178.
Wang, B., Wu, C., Reniers, G., Huang, L., Kang, L., Zhang, L., 2018b. The future of hazardous chemical safety in China: opportunities, problems, challenges and tasks. Sci. Total Environ. 643, 1–11.
White, H.D., Griffith, B.C., 1981. Author cocitation: a literature measure of intellectual structure. J. Am. Soc. Inf. Sci. 32, 163–171.
Yang, S., Feng, X., Liu, L., Zhang, Z., Deng, C., Du, J., Zhao, J., Qian, Y., 2019a. Research advances on process systems integration and process safety in China. Rev. Chem. Eng. 147.
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. J. Clean. Prod. 263, 121433.
Yang, Y., Reniers, G., Chen, G., Goerlandt, F., 2019b. A bibliometric review of laboratory safety in universities. Saf. Sci. 120, 14–24.
Yuan, L., Smith, A.C., 2008. Numerical study on effects of coal properties on spontaneous heating in longwall gob areas. Fuel 87, 3409–3419.
Zhang, H.-D., Zheng, X.-P., 2012. Characteristics of hazardous chemical accidents in China: a statistical investigation. J. Loss Prev. Process. Ind. 25, 686–693.
Zhang, N., Shen, S.L., Zhou, A.N., Chen, J., 2019. A brief report on the March 21, 2019 explosions at a chemical factory in Xiangshui, China. Process Saf. Prog. 38.
Zhao, B., 2014. Qingdao pipeline explosion: introductions and reflections. Nat. Hazards 74, 1299–1305.
Zhao, J., Joas, R., Abel, J., Marques, T., Suikkanen, J., 2013. Process safety challenges for SMEs in China. J. Loss Prev. Process. Ind. 26, 880–886.
Zhao, J., Suikkanen, J., Wood, M., 2014. Lessons learned for process safety management in China. J. Loss Prev. Process. Ind. 29, 170–176.
Zhao, L., Qian, Y., Hu, Q.-M., Jiang, R., Li, M., Wang, X., 2018. An analysis of hazardous chemical accidents in China between 2006 and 2017. Sustainability 10.
Zhou, A., Fan, L., Ma, M., Tao, B., 2017. Chinese process safety management core elements and control measures. Process Saf. Prog. 36, 378–381.