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Sam Mannan and his scientific publications: A life in process safety research

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ABSTRACT

Dr. M. Sam Mannan is one of the true pioneers in the process safety area, spending almost his entire lifetime in process safety and risk research. He was dedicated to 'make safety second nature' and published an impressive body of work. An overview of his research helps understanding the process safety area and provides insight in the legacy of this process safety pioneer. In this paper, 327 publications authored by Dr. Mannan from 1999 to 2019 in Web of Science core collection were downloaded and visually analyzed from four perspectives: his publication outputs, collaboration networks, topic areas, and highly cited papers and cited references. The results show a rapidly increasing trend in his research activity, mostly through journal publications. He published in 53 different outlets, with *Journal of Loss Prevention in the Process Industries* being most frequently selected. Dr. Mannan had a very active and diverse worldwide network, and collaborated with 18 different countries/regions, nearly 90 different institutions and 387 authors. His publications addressed process safety-related topics widely, including safety related to liquefied natural gas, explosions, runaway reactions, inherent safety, flammability and aerosol, and more recently resilience. Dr. Mannan's most cited paper focused on 'fuzzy risk matrix', whereas the most frequently cited reference in his work is 'thermal hazard evaluation by an accelerating rate calorimeter' by Townsend DI in 1980. Based on his most recent research activity, promising future directions for process safety research include resilience linked to risk assessment and management, for instance through the 'safety triad' concept he promoted shortly before passing away.

1. Introduction

Dr. Mahboobul Sam Mannan (1954–2018)[1] is one of the most influential researchers and is widely regarded as one of the pioneers in the process safety research area. He was born in Noakhali (Bangladesh), where he spent his youth. He received his bachelor's degree in Chemical Engineering from Bangladesh University of Engineering and Technology in 1978. After a few years of work, he went to the University of Oklahoma to continue his studies, receiving the master's degree in 1983 and PhD in 1987, both in chemical engineering. He first worked a few years in different industries, including the Bangladesh Development Bank, Power and Desalination Plant Libya and RMT Inc. Afterwards, he worked at the University of Oklahoma, and took a position as vice-president of the RMT Inc from 1994 to 1997. With encouragement from his mentor Trevor Kletz (Mannan, 2015), he left industry and joined the Mary Kay O'Connor Process Safety Center at the Texas A&M University as an associate professor and director in August 1997. This marked an important turning point in his career, from industry to academia, where he became a group leader. He later became full professor of Chemical Engineering at the Texas A&M University and was appointed regents professor, in recognition of his high academic merits. During his 23 years of work together with his colleagues, the Mary Kay O'Connor Process Safety Center has become a world leading scientific center in process safety research (Li and Li, 2020).

Dr. Mannan was a very active and highly productive researcher in process safety area. In his academic, he has supervised 61 PhD students

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[1] Mannan, M. Sam [Resume], https://engineering.tamu.edu/media/608771/1_dr._m._sam_mannan_director_9798623985_mannan_tamu.edu.pdf.

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and 79 MSc students in Texas A&M University (Sanders, 2018). He published over 300 peer-reviewed journal publications, more than 220 proceedings papers and more than 270 technical meeting presentations (Thompson, 2018). These publications have received more than 10,000 citations and at least 44 of his publications have received more than 44 citations, leading to an impressive h-index of 44 according to his Google Scholar profile. These numbers are truly extraordinary: process safety is an applied and multidisciplinary domain within the chemical engineering discipline, in which much lower author and article citation rates are the norm compared to other scientific disciplines (Patience et al., 2017; Thomson-Reuters., 2020). Dr. Mannan's scientific publications represent an impressive and highly influential body of knowledge in the process safety community, reverberating his thoughts and ideas on process safety to a wide community of researchers following in his footsteps.

Therefore, it is valuable to reflect on his achievements in scientific research, industrial impacts, and education. A recent special issue was dedicated to Dr. Mannan in *Process Safety and Environmental Protection*, highlighting these important contributions and significant impacts (Wang et al., 2020). For instance, his immense work on the editions 3 and 4 of the book Lees' Loss Prevention in the Process Industries is worth highlighting, as it is an extraordinarily impactful work within process safety research (Li et al., 2020a,b). In his educational role and from the perspective of industrial impact, Dr. Mannan was highly influential to bring process safety in the chemical engineering core curriculum in the United States, and in the related requirements of the Accreditation Board for Engineering and Technology (Kerin and Mannan, 2011).

To highlight especially Dr. Mannan's academic impact, it is valuable to obtain an overview of his core publications in process safety research. This article presents such an overview, based on a scientometric analysis of this publications. In Section 2, the data and methods applied in this analysis are introduced. In Section 3 to 6, different results are presented. Section 3 presents overall trends and statistics of his publications. In Section 4, an overview is given of his international collaboration networks, addressing countries/regions, organizations, and authors. Section 5 provides insights in the research topics he was engaged in, through an analysis of the keywords of his articles. In Section 6, focus is on the highly influential papers. This includes Dr. Mannan's highly influential articles, which can be regarded as his core scientific legacy. This also focuses on highly cited references in his body of work, providing insight in what work has been influential in his thinking. Finally, Section 7 concludes.

2. Data and methods

2.1. Data

Dr. Mannan has published hundreds of documents in various publication outlets. These are recorded in different databases and with different data formats. In order to obtain all Dr. Mannan's publication in the same format, Web of Science (WoS) was chosen as the data source. Publications in WoS not only have a high quality, but also contain a lot of information about each record, which is necessary for a meaningful bibliometric analysis (Li et al., 2020a,b). Papers were searched and downloaded on 10 December 2019 using the authors retrieval function in the database, i.e. using "Mannan, M. Sam" as the search criterion. A total of 327 papers were obtained and exported in plain text format. The downloaded publication records include information about authors, the geographic information (cities, countries/regions, institutions), publication outlet name (i.e. journal or conference), publication year, document type, cited references, and number of citations to the document, as shown in Fig. 1.

2.2. Methods

Fig. 2 shows a flowchart of the process of the publication analysis of Dr. Mannan's work. After downloading the data from Web of Science, bibliometric methods have been applied for mining and visualizing the data. Bibliometrics analysis is a group of methods to analyze the scientific publications in a quantitative way. For example, to measure the research activities based on the publications output, an author's scientific impact can be measured by citations or h-index, while a journal's impact can be evaluated based its impact factor. To analyze co-author networks, keyword networks, and co-citations and bibliographic coupling of articles, network visualization methods allow a visual analysis to obtain insights in these aspects of the selected body of

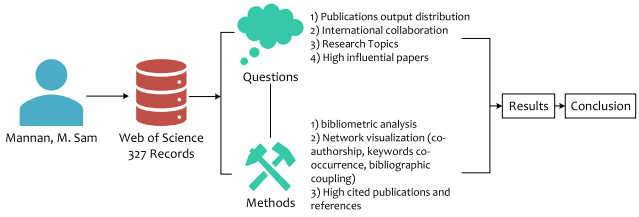

Fig. 2. Flowchart of Dr. Mannan's publication analysis process:data collection, research questions, and methods.

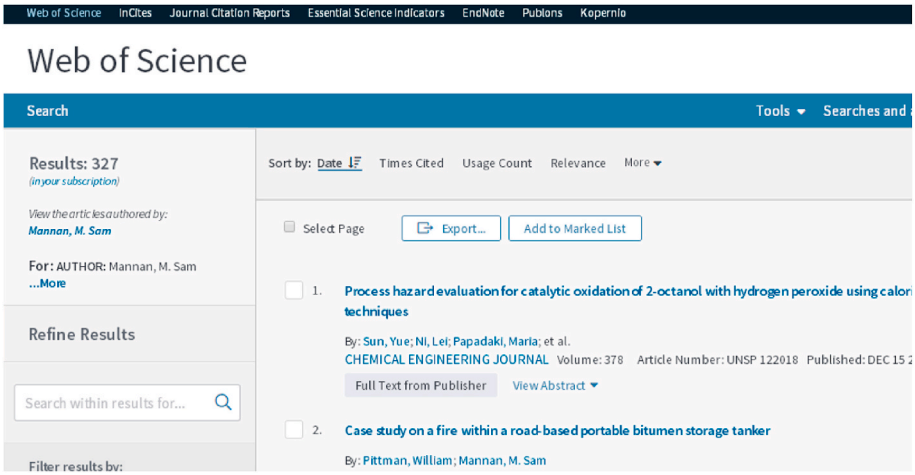

Fig. 1. Records from web of science (retrieved on 10 December 2019).

publications. As indicated in Fig. 2, Dr. Mannan's body of work is investigated with a focus on the distribution of publication outputs, international collaborations, research topics, and highly influential papers. Bibliometric analysis, network visualizations, and statistical analysis of highly cited publications and references is applied to obtain the results, to provide insights in the questions.

Several bibliometric tools have been developed for bibliometric mapping analysis, which have been applied to various safety-related domains of research (Li et al., 2020a,b). In this study, three bibliometric analysis tools are used to obtain different types of results and visualizations. The bibliographic analysis tool (Li and Li, 2020) is applied to extract descriptive insights in Dr. Mannan's papers, including document types, annual trends, journals output distribution, and highly cited papers. The VOSviewer software is used to construct bibliometric networks, including collaboration networks, keywords co-occurrence networks, and bibliographic coupling networks of Dr. Mannan's highly cited papers. VOSviewer is developed by (van Eck and Waltman, 2010), and has become one of the most widely used tools in the area of bibliometric mapping. It implements the visualization of similarities mapping technique (van Eck and Waltman, 2007), creating network visualizations where the distanced between the nodes show how closely related these are. Within the safety science research domain alone, more than 20 articles have been published where VOSviewer has been applied (Li et al., 2020a,b).

3. Publications output distribution

The distribution of publication outputs is a key indicator to provide insights in the research activities of a given set of documents. The document types, the annual publications trend, and the specific journals in which Dr. Mannan has published are analyzed. Descriptive analysis is employed as the method in this section.

Fig. 3(a) shows the document types of Dr. Mannan's publications. It is seen that his publications are distributed across eight documents types. Most of his publications are original research articles, totaling 261 publications which account for 80% of the complete dataset. This category is followed by 'proceedings paper' (34, 10%), 'editorial material' (14, 4%), 'meeting abstract' (7,2%) and 'review' (7, 2%). The high number of original research articles shows Dr. Mannan's strong academic leadership, creativity, and impact, whereas his commitment to writing reviews shows his commitment to summarize and provide overviews of specific knowledge domains. Proceedings papers and editorials are commonly regarded as less academically valuable, but these also show Dr. Mannan's commitment to share his knowledge and ideas in conferences and through personal views in editorial communications.

Annual trends of Dr. Mannan's publications are shown in Fig. 3(b). The data sample data covers 21 years, from 1999 to 2019. It is seen that Dr. Mannan has published 327 papers indexed in Web of Science, with an average output of 15 publications per year. This obviously implies that he has published more than one paper per month, and that he can be regarded as a highly productive researcher. While the complete output shows a relatively high volatility, the cumulative number of publications shows an approximately linear trend. Four significant peaks can be observed in the publication curve: 2003 with 19 publications, 2006 with 16 publications, 2010 with 27 publications, and 2016 with 31 publications. The peaks of 2010 and 2016 mark the culmination of highly productive periods, where the number of records show a linearly growing trend over three to four years.

Dr. Mannan's publications are distributed over 53 different sources, as shown in Fig. 4(a). His work is mainly published in process safety related journals, including *Journal of Loss Prevention in the Process Industries* (118), *Journal of Hazardous Materials* (42), *Industrial & Engineering Chemistry Research* (32), *Process Safety and Environmental Protection* (25) *and Process Safety Progress* (13). The output distribution of the publication sources is very unbalanced: the top 5 journals account for 70% of his articles, while the remaining sources share 30% of the

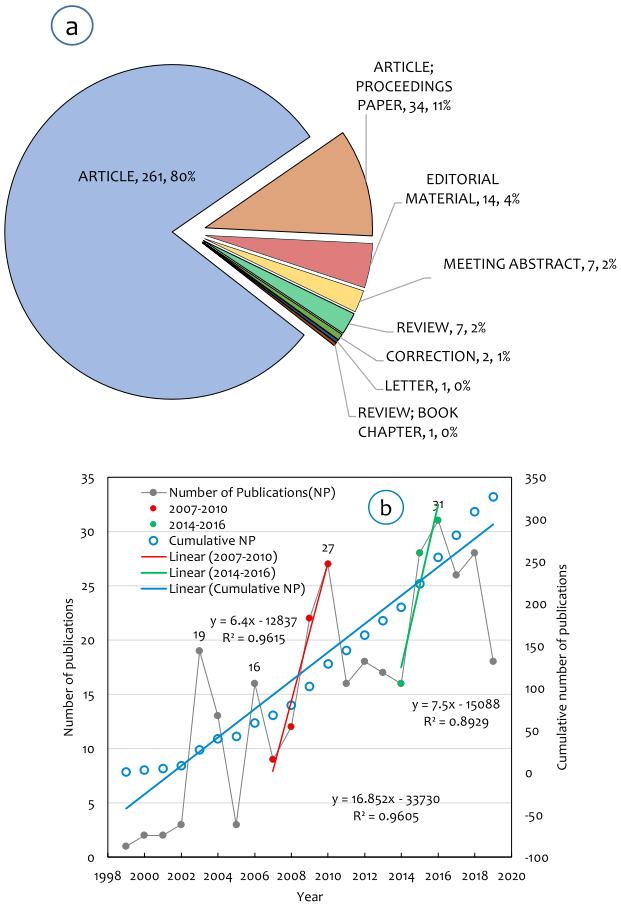

Fig. 3. Output distributions of Dr. Mannan's publications:(a) document types, (b) and annual publication trends.

publications. This shows that Dr. Mannan was very focused to contribute to process safety-oriented journals and their associated research communities.

The distribution of the top 5 journals in each year is shown in Fig. 4 (b). Dr. Mannan has published 16 articles in *Journal of Loss Prevention in the Process Industries* in 2010 and 2016, and more than 10 papers each year from 2015 to 2018. His active period in *the Journal of Hazardous Materials* was during 2003, 2006 and 2009, in which more than 5 papers were published. Furthermore, of his 32 papers published in *Industrial & Engineering Chemistry Research*, six of these were published there in 2011, marking his most productive year for that journal.

4. International collaboration

An analysis of international collaboration is made to understand Dr. Mannan's social academic connections in the process safety research community. Collaboration network visualization is used as a method to identify these collaborations. Geographic collaboration focuses on countries/regions and cities, as well as institutions with which Dr. Mannan has collaborated. Author collaboration networks show the collaboration strengths between individual scholars in Dr. Mannan's publication record.

4.1. Geographic collaboration

Among his publications, 83 were the result of an international collaboration, with 244 resulting from domestic collaboration. Fig. 5 shows Dr. Mannan's the international collaboration with a focus on countries/regions and cities. Fig. 6 illustrates the network of inter-

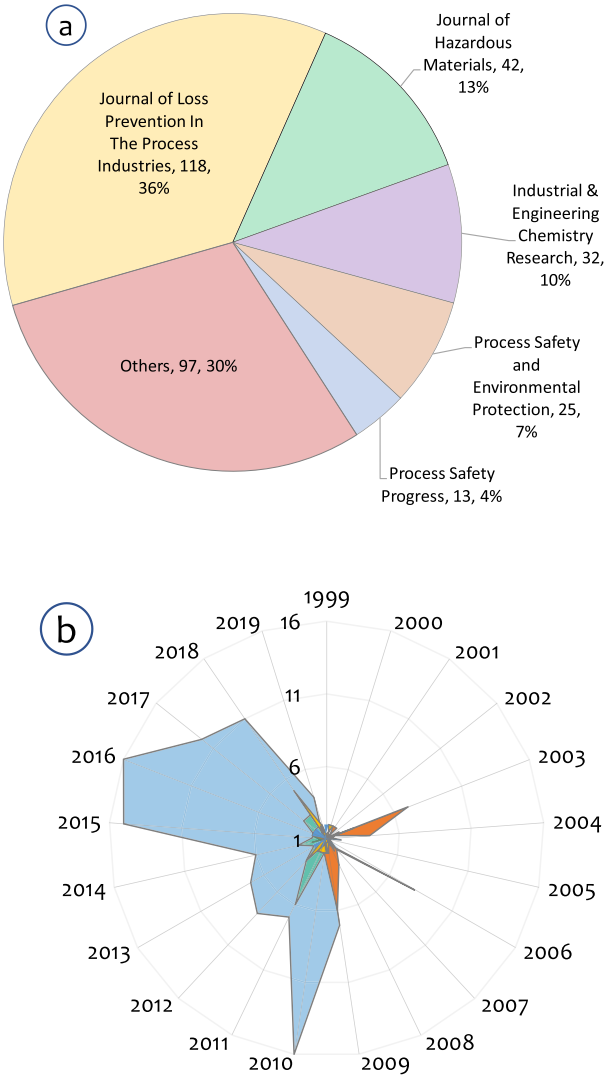

Fig. 4. Sources of Dr. Mannan's publications:(a) distribution of complete dataset, (b) temporal evolution of records in top 5 journals.

organizational collaborations. Detailed outputs of each country/region and institution are listed in Table 1.

Dr. Mannan has collaborated with authors from 18 countries/regions, see Fig. 5(a). Among these countries/regions, he has 18 co-authored publications with Mexico, followed by China (17), Greece (15), Qatar (13), and Poland (9). In recent years, he has increased his connectivity with China, as seen from the average publication year: the 17 co-authored articles with Chinese scholars were published with an average year of publication of 2017. In terms of the city-focused collaboration network, shown in Fig. 5(b), he is connected with several cities from China, including Beijing, Nanjing, Tianjin, and Guangzhou. In terms of the institutional collaborations, shown in Fig. 6, close scientific linkages can be observed with Inst Tecnol Celaya (16), Oklahoma State Univ (9), Tech Univ Lodz (8), Nanjing Tech Univ (7), and Univ Patras (7).

4.2. Authors collaboration

There are in total 387 co-authors in Dr. Mannan's publications, 209 of whom have only one co-authored article, and 70 authors having 2 co-authored publications with him. Among these publications, he was the first author in 28 (8.6%) of the papers, and he acted as corresponding author in 193 (59%) of them. Researchers with at least have 5 co-authored publications with Dr. Mannan were extracted from the dataset, and the corresponding records have been used to create the authors collaboration network. Finally, 61 authors (including Dr. Mannan) were obtained and were mapped in the collaboration network, shown in Fig. 7.

In the network, Rogers William has 64 co-publications with Dr. Mannan, followed by Cheng Zheng-dong (20), Liu Yi (19), Ng Dedy (19), Mentzer Ray (18), Zhang Bin (17), Papadaki Maria (15) and Vazquez-Roman Richart (15). Almost all of these were his colleagues at the Mary Kay O'Connor Process Safety Center at Texas A & M University. Furthermore, the authors collaboration network is clustered into different research communities, as seen from the color codes in Fig. 7. Inside each research community, the authors have a strengthened collaboration with each other than with authors outside these communities. The authors' average publication year (APY) is calculated to show the temporal dynamics of the collaborations, as shown in Fig. 8 and Table 2. Dr. Mannan's author collaboration network shows that his collaborations before 2010 were primarily with Rogers William (APY around 2006) and Ng Dedy (APY around 2010), as indicated in blue in Fig. 8. His more recent collaborations are shown in yellow, orange, and red colors in the figure, with significant more recent collaborators being Cheng Zhengdon, Liu Yi, and Zhang Bin. Given Dr. Manan's very extensive and active collaboration network, it is clear that without the tremendous efforts of his co-authors, his scientific impacts would have been impossible to achieve. It is thus appropriate to consider their merits as well.

5. Research topics

An analysis of research topics in focus in Dr. Mannan's publications give an indication of his research focus areas and academic interests during in career in process safety research. A keywords frequency and co-occurring terms analysis (Callon et al., 1983) are applied to analyze the research focus topics, the temporal evolution, and impact of Dr. Mannan's research work. Keywords are denoted as co-occurring if two keywords appeared together in the same publication. Aggregating such co-occurring keywords can be used to identify narrative patterns in a collection of documents, providing insights in the topics with which the documents are concerned (Li et al., 2020a,b). In the current analysis, keywords which appear at least 2 times are selected to create the co-occurring keywords map. In total, 176 keywords were extracted from the publications.

The keywords co-occurrence network of Dr. Mannan's publications is represented in Fig. 9. The term 'process safety' was removed from the network, because its meaning is too wide to give detailed insights in Dr. Mannan's process safety research, and because all his work relates to it. The sizes of the nodes and the associated labels indicate the occurrence frequency of keywords: larger nodes and labels are associated with more frequently occurring keywords. The keywords are furthermore clustered into different groups, indicated by different colors, based on the connection strength of the keywords. This clustering is done based on a clustering algorithm included in the VOSviewer software, see (van Eck and Waltman, 2010).

In Dr. Mannan's research publications, liquefied natural gas (19), runaway reaction (15), risk assessment (14), hydroxylamine (12), inherent safety (12), computational fluid dynamics (11), resilience (10), and thermal decomposition (10) are frequently used keywords with at least occurred 10 occurrences. A more elaborate list of frequently used keywords is given in Table 3.

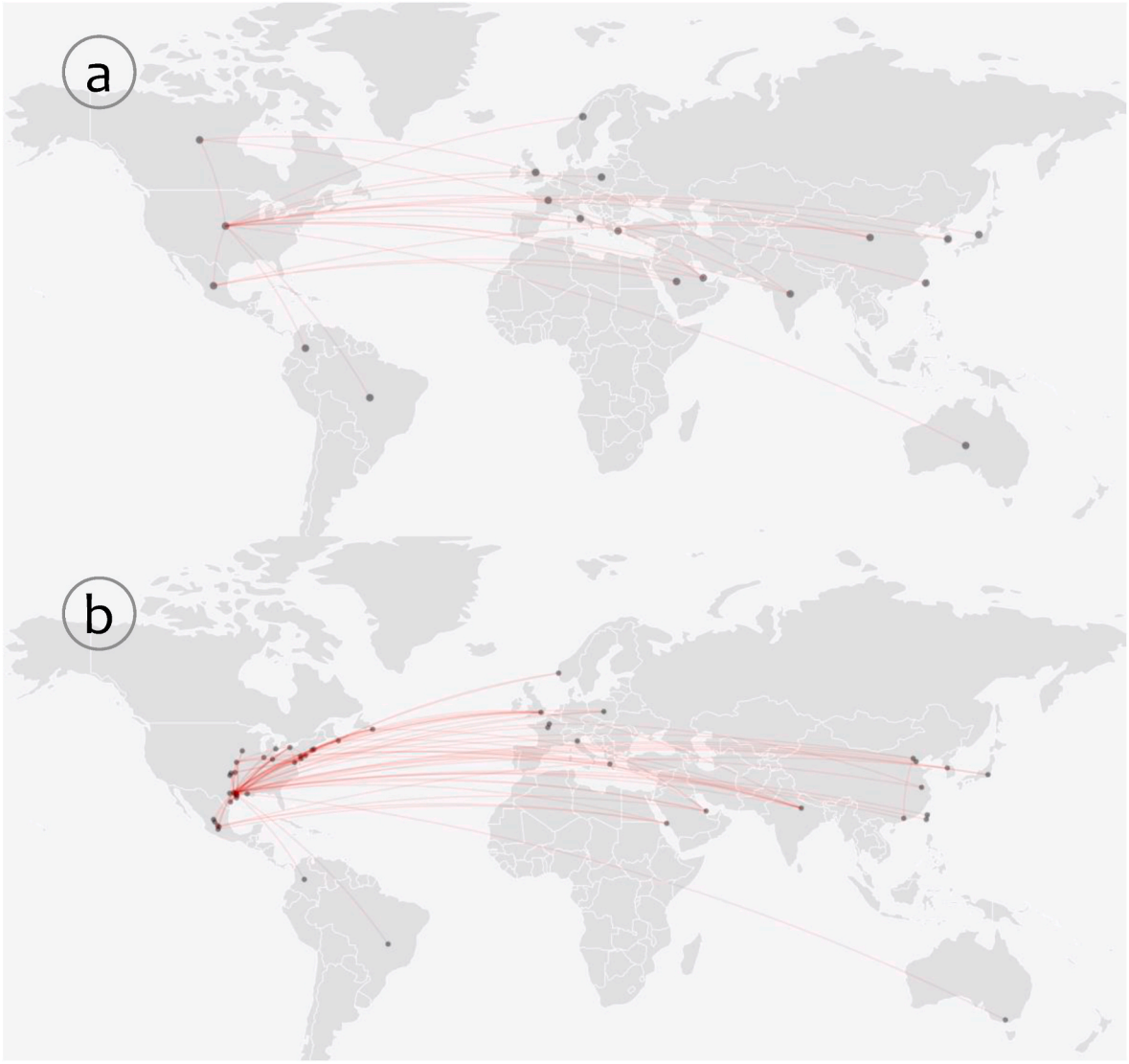

Fig. 5. Dr. Mannan's collaboration network: (a) countries/region, (b) cities.

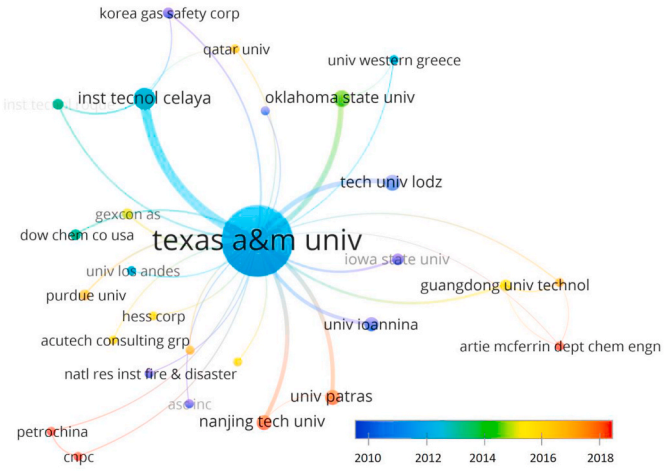

Fig. 6. Dr. Mannan's institutional collaboration network and average publication year of associated co-authored articles.

Table 1
Countries/regions and institutions having more than 5 co-publications with Dr. Mannan.

No.	Country	NP	APY	Institution (Country)	NP	APY
1	Mexico	18	2013.17	Inst Tecnol Celaya (Mexico)	16	2012.75
2	China	17	2017.00	Oklahoma State Univ (USA)	9	2014.44
3	Greece	15	2014.00	Tech Univ Lodz (Poland)	8	2010.75
4	Qatar	13	2014.46	Nanjing Tech Univ (China)	7	2017.71
5	Poland	9	2011.11	Univ Patras (Greece)	7	2017.57

Notes: NP= Number of publications, APY = Average publication year.

As can be seen from Fig. 9, his research topics are primarily focused on technology and chemical engineering. The keyword clusters show the breadth of Dr. Mannan's research interests and expertise, where eight topic clusters can be identified. Cluster #1 concerns risk assessment, and focuses on quantitative risk assessment, layer of protection analysis, fuzzy sets, Monte Carlo simulation, Bayesian inference, fault trees, and bowtie. Cluster #2 focuses on runaway reactions and thermal aspects, including keywords such as hydroxylamine, thermal decomposition, and adiabatic calorimetry. Cluster #3 addresses liquefied natural gas, with

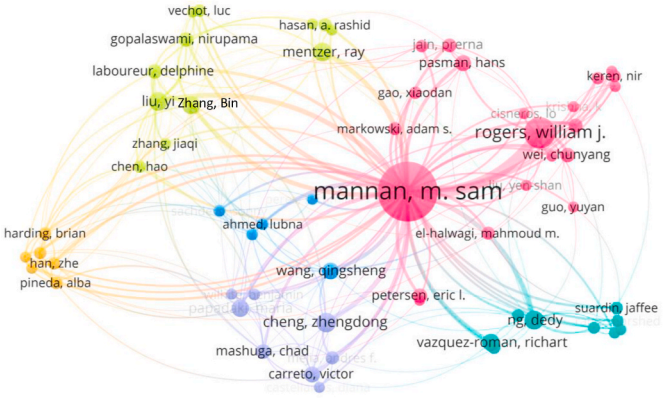

Fig. 7. Dr. Mannan's authors collaboration network; researchers with at least 5 co-authored articles.

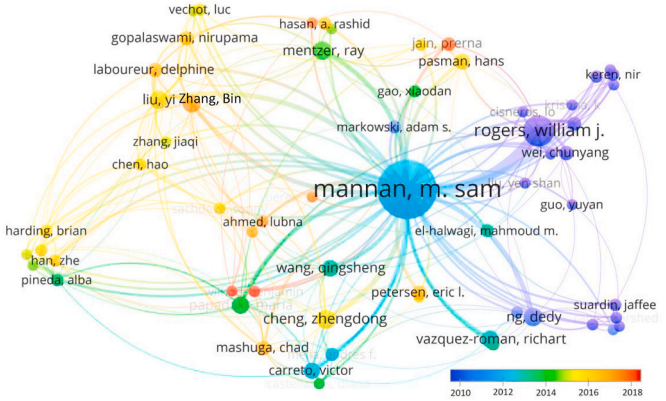

Fig. 8. Average publication year of each author in the collaboration network.

Table 2
Authors with at least 10 co-authored publications with Dr. Mannan.

No.	Author	Institution	NCA	NP	APY
1	Rogers, William J	Texas A & M University	62	64	2006.56
2	Cheng, Zhengdong	Texas A & M University	61	20	2015.50
3	Liu, Yi	Texas A & M University	25	19	2015.58
4	Ng, Dedy	Texas A&M Univ	30	19	2010.42
5	Mentzer, Ray	Texas A&M Univ	31	18	2014.33
6	Zhang, Bin	Nanjing Tech Univ (China)	33	17	2016.82
7	Papadaki, Maria	Univ Ioannina (Greece)	30	15	2014.00
8	Vazquez-Roman, Richart	Tecnol Nacl Mexico (Mexico)	19	15	2012.93
9	Wang, Qingsheng	Texas A&M Univ	30	14	2013.21
10	Carreto, Victor	Texas A&M Univ	33	12	2012.58
11	Pasman, Hans	Texas A&M Univ	17	12	2015.75
12	Gopalaswami, Nirupama	Texas A&M Univ	9	10	2016.00
13	Laboureur, Delphine	Texas A&M Univ	17	10	2016.40
14	Mashuga, Chad	Texas A&M Univ	28	10	2016.40
15	Petersen, Eric L	Texas A&M Univ	15	10	2016.30
16	Wei, Chunyang	Texas A&M Univ	10	10	2006.70

Notes: NCA=Number of co-authors in the network, NP= Number of publications, APY = Average publication year.

keywords such as Computational Fluid Dynamics, vapor cloud and mitigation system, and MINLP (mixed integer nonlinear programming) Cluster #4 focuses on resilience and risk/safety management, with keywords such as systems approach, loss prevention, risk management, and hazard identification. Cluster #5 concerns explosions, with keywords such as dust explosion, deflagration, thermal stability, lower

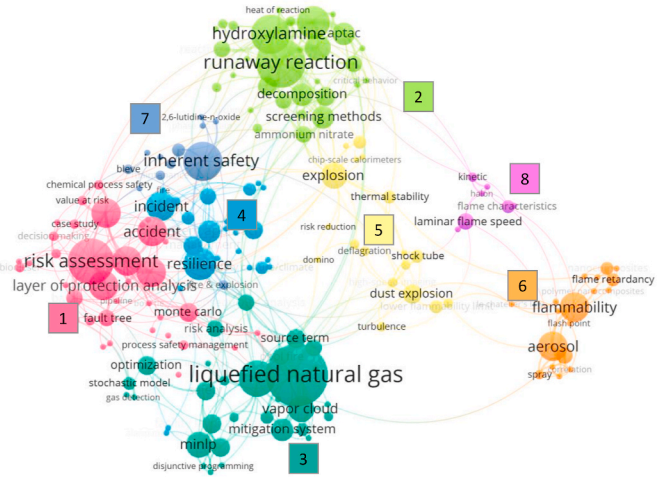

Fig. 9. Keywords network and research topic clusters of Mannan's publications; keywords appearing at least 2 times in the documents.

Table 3
Keywords which appeared at least 5 times in Dr. Mannan's publications.

No.	Keyword	Occurrences	APY	AC	ANC
1	liquefied natural gas/LNG	19	2013.63	10.89	0.73
2	runaway reaction	15	2010.73	8.60	0.76
3	risk assessment	14	2010.86	36.36	2.30
4	hydroxylamine	12	2006.08	13.42	0.90
5	inherent safety	12	2012.25	16.42	1.47
6	computational fluid dynamic	11	2014.45	9.36	0.54
7	resilience	10	2017.10	14.60	2.27
8	thermal decomposition	10	2008.10	13.20	0.94
9	accident	9	2011.89	20.56	1.27
10	aerosol	9	2010.33	7.00	1.02
11	flammability	9	2013.56	11.44	0.97
12	fuzzy	9	2009.78	49.78	2.75
13	incident	9	2013.22	5.11	0.45
14	layer of protection analysis	9	2011.11	22.33	1.28
15	quantitative risk assessment	9	2010.33	12.67	0.97
16	uncertainty	9	2011.33	27.67	1.93
17	adiabatic calorimetry	8	2008.25	10.13	0.72
18	explosion	8	2013.38	11.88	1.40
19	MINLP	8	2013.13	16.63	1.17
20	vapor cloud	8	2014.50	7.50	0.66
21	APTAC	7	2005.00	15.00	0.99
22	decomposition	7	2009.86	5.71	0.47
23	mitigation system	7	2014.43	4.71	0.32
24	screening methods	7	2009.86	9.00	0.94
25	system approach	7	2016.43	15.71	1.83
26	dust explosion	6	2016.50	4.67	0.56
27	facility layout/siting	6	2011.50	15.00	1.09
28	hydrogen peroxide	6	2013.83	4.67	0.32
29	loss prevention	6	2014.17	9.50	1.04
30	monte Carlo	6	2015.17	6.50	0.65
31	optimization	6	2013.17	19.17	1.85
32	reactive chemical	6	2009.50	9.67	0.73
33	risk management	6	2017.00	9.00	2.02
34	safety	6	2013.33	20.50	1.60
35	source term	6	2013.83	11.67	0.59
36	toxic release	6	2011.67	19.17	1.14

Notes: APY = Average publication year, AC = Average citations, ANC = Average normalized citations.

flammability limit, and shock tube. Cluster #6 focuses on flammability, with keywords such as aerosols, polymer nanocomposites, flashpoint, and flame retardancy. The smaller clusters #7 and #8 focus on inherent safety, and flame characteristics and fire suppression.

The average publication year of each keyword in Fig. 10 gives an indication of the temporal evolution of the research focus areas over Dr. Mannan's research career. Topics in Cluster #2 (runaway reactions and

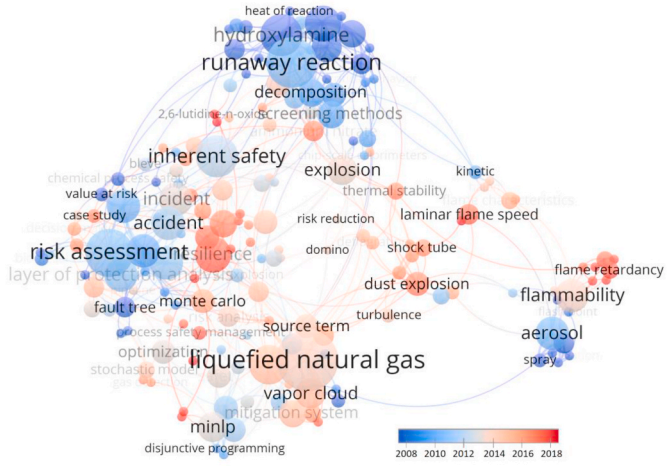

Fig. 10. Average publication year in which the keywordsassociated with Dr. Mannan's publications appear.

thermal aspects) and a few topics in Cluster #1 (risk assessment) and #6 (flammability) appeared in his earlier years of research activity. In more recent years, his research interest shifted towards Cluster #3 (liquefied natural gas), and to topics ranging from resilience and safety/risk management to explosions and flammability.

The average normalized citation (van Eck and Waltman, 2020) of the keywords associated with Dr. Mannan's research output is shown in Fig. 11. This analysis provides insights in which of his research topics have had a comparatively higher research impact. The figure shows that highly influential topics relate to risk assessment, with especially topics focusing on 'fuzzy', 'analytical hierarchy process (AHP)', 'Bayesian', 'fault tree' and 'bow-tie' attracting significant academic attention. Furthermore, topics related to resilience, risk management, and inherent safety also have a high impact. More specialized technical and engineering analyses, such as the topics in Cluster #2 (runaway reactions) and Cluster #3 (liquefied natural gas), although constituting important areas of Dr. Mannan's research focus, have a comparatively lower scientific impact.

It is also noteworthy that Dr. Mannan, briefly before passing away, promoted the idea of the 'safety triad', a novel framework linking resilience to risk assessment, stressing the need to focus on human and organizational factors, and accounting for unexpected events (black swans). The keywords-based analyses presented above does not explicitly show this safety triad idea, as there has currently been relatively little research published in line with that thinking within process safety. However, given recent interest in this topic, it can be expected to be an important final contribution by Dr. Mannan, see e.g. (O'Connor et al., 2019) (Parker et al., 2019).

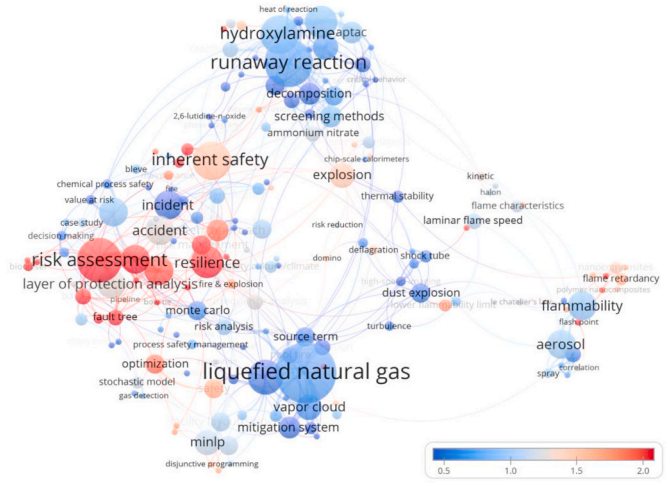

Fig. 11. Average normalized citations of the keywords associated with Dr. Mannan's publications.

6. Highly influential papers

6.1. Dr. Mannan's highly cited paper

The number of citations is one of the critical metrics in bibliometric analyses, and has been widely used to give an indication of the impact of publications and individuals (Li et al., 2020,Li et al., 2020). In this section, the citations distribution, h-index and highly cited publications are analyzed and discussed.

The distribution of citations to Dr. Mannan's 327 publications is shown in Fig. 12(a). It is evident that many publications have received less than or equal to 10 citations, accounting for 64.2%. In contrast, 18% of his publications have received more than 20 citations. In order to take both the number of research outputs of authors and the citations to their work into account, Hirsch has developed the h-index as an indication of the impact of an individual's scientific research output (Hirsch, 2005). He defined the h-index as follows: "*A scientist has index* h *if* h *of his or her* N *papers have at least* h *citations each and the other* (N - h) *papers have less than or equal to* h *citations each.*" Dr. Mannan's h-index is 30, meaning that 30 of his publications have received at least 30 citations in Web of Science at the time of data extraction. This is a very high number, showing the broad and important impact of Dr. Mannan's research in the process safety research community.

Fig. 12(b) shows the box plot distribution of the citations to Dr. Mannan's publications. It shows that the average number of citations of Dr. Mannan's publications is 11.9, with a mean of 6 and lower 25% and upper 75% quantile value of 2 and 16. The boxplot analysis is used to identify 23 outlier points, which can be regarded as Dr. Mannan's highly cited papers, i.e. articles which have had a particularly important academic impact on the process safety research community. These are listed in Table 4.

Furthermore, these 23 publications are clustered into different groups based on their bibliographic coupling, i.e. accounting for the number of identical references in their references lists. Bibliographic coupling provides an indication of how closely related research activities are, with the assumption that similar reference lists lead to partially similar narrative patterns in the associated articles (Li et al., 2020a,b). As shown in Fig. 13, the articles are clustered in different groups, with a color code used to identify the clusters, using the clustering method of the VOSviewer software (van Eck and Waltman, 2010). Nodes with the same color are included in the same cluster, with topics showing more similarity than with other nodes. These papers can mainly be linked to 'flash point' (Patel et al., 2009; Vidal et al., 2004, 2006), 'soft matter

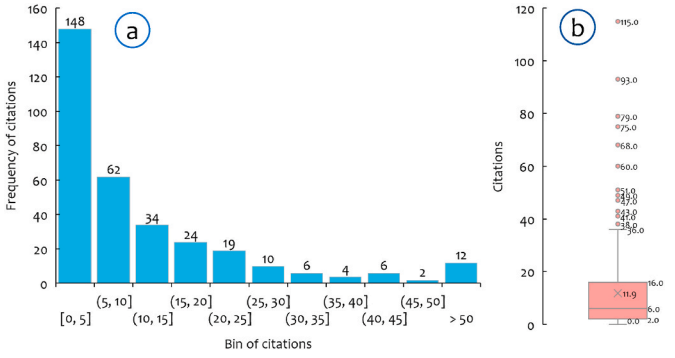

Fig. 12. Citations distribution of Dr. Mannan's publications:(a) Histogram, (b) Boxplot.

Table 4
High cited papers from Dr. Mannan's publications.

No.	First Author	AR	FAOC	Title	Source	PY	TC
1	Markowski, AS	2	Tech Univ Lodz, Poland	Fuzzy risk matrix	Journal of Hazardous Materials	2008	115
2	Vidal, M	4*	Texas A&M Univ, USA	A review of estimation methods for flash points and flammability limits	*Process Safety Progress*	2004	93
3	Markowski, AS	2	Tech Univ Lodz, Poland	Fuzzy logic for process safety analysis	*Journal of Loss Prevention in The Process Industries*	2009	93
4	Pokoo-Aikins, G	4	Texas A&M Univ, USA	A multi-criteria approach to screening alternatives for converting sewage sludge to biodiesel	*Journal of Loss Prevention in The Process Industries*	2010	79
5	Markowski, AS	2	Tech Univ Lodz, Poland	Fuzzy logic for piping risk assessment (pfLOPA)	*Journal of Loss Prevention in The Process Industries*	2009	76
6	Dinh, LTT	4*	Texas A&M Univ, USA	Resilience engineering of industrial processes: Principles and contributing factors	*Journal of Loss Prevention in The Process Industries*	2012	75
7	El-Halwagi, AM	5	Texas A&M Univ, USA	Multiobjective optimization of biorefineries with economic and safety objectives	*Aiche Journal*	2013	68
8	Mejia, AF	8	Texas A&M Univ, USA	Pickering emulsions stabilized by amphiphilic nano-sheets	*Soft Matter*	2012	68
9	Patel, SJ	3*	Texas A&M Univ, USA	QSPR Flash Point Prediction of Solvents Using Topological Indices for Application in Computer Aided Molecular Design	*Industrial & Engineering Chemistry Research*	2009	61
10	Vidal, M	4*	Texas A&M Univ, USA	Evaluation of lower flammability limits of fuel-air-diluent mixtures using calculated adiabatic flame temperatures	*Journal of Hazardous Materials*	2006	60
11	Cormier, BR	5*	Texas A&M Univ, USA	Application of computational fluid dynamics for LNG vapor dispersion modeling: A study of key parameters	*Journal of Loss Prevention in The Process Industries*	2009	51
12	Henning, JB	5	Texas A&M Univ, USA	The influence of individual differences on organizational safety attitudes	*Safety Science*	2009	51
13	Gentile, M	3*	Texas A&M Univ, USA	Development of an inherent safety index based on fuzzy logic	*Aiche Journal*	2003	49
14	Dinh, LTT	3*	Texas A&M Univ, USA	Sustainability Evaluation of Biodiesel Production Using Multicriteria Decision-Making	*Environmental Progress & Sustainable Energy*	2009	47
15	Gentile, M	3*	Texas A&M Univ, USA	Development of a fuzzy logic-based inherent safety index	*Process Safety and Environmental Protection*	2003	44
16	Saraf, SR	3*	Texas A&M Univ, USA	Prediction of reactive hazards based on molecular structure	*Journal of Hazardous Materials*	2003	43
17	Mejia, AF	5	Texas A&M Univ, USA	Aspect ratio and polydispersity dependence of isotropic-nematic transition in discotic suspensions	*Physical Review E*	2012	43
18	Barua, S	4	Texas A&M Univ, USA	Bayesian network based dynamic operational risk assessment	*Journal of Loss Prevention in The Process Industries*	2016	42
19	Vidal, M	3*	Texas A&M Univ, USA	Prediction of minimum flash point behaviour for binary mixtures	*Process Safety and Environmental Protection*	2006	41
20	Qi, RF	4*	Texas A&M Univ, USA	Numerical simulations of LNG vapor dispersion in Brayton Fire Training Field tests with ANSYS CFX	*Journal of Hazardous Materials*	2010	41
21	Suardin, J	2*	Texas A&M Univ, USA	The integration of Dow's fire and explosion index (F&EI) into process design and optimization to achieve inherently safer design	*Journal of Loss Prevention in The Process Industries*	2007	39
22	Guevara, JS	5	Univ Los Andes, Colombia	Stabilization of Pickering foams by high-aspect-ratio nano-sheets	*Soft Matter*	2013	39
23	Castellanos, D	6*	Texas A&M Univ, USA	The effect of particle size polydispersity on the explosibility characteristics of aluminum dust	*Powder Technology*	2014	38

Notes: AR = Authors rank of Dr. Mannan, * Corresponding author of the paper, FAOC=First authors organization/country, PY = publication year, TC = total citations.

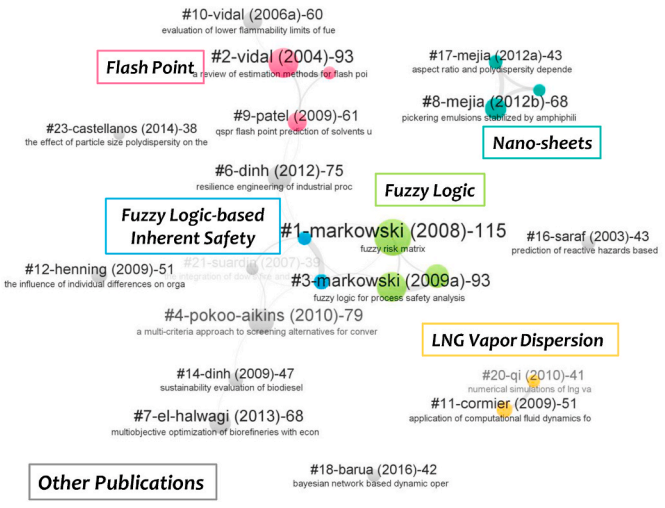

Fig. 13. Clusters of Dr. Mannan's 23 highly cited publications, based on their bibliographic coupling.

related nano-sheets etc.' (Guevara et al., 2013; Mejia et al., 2012a, 2012b), 'fuzzy logic in risk assessment' (Markowski and Mannan, 2008, 2009; Markowski et al., 2009), 'fuzzy logic-based inherent safety' (Gentile et al., 2003a, b) and 'LNG vapor dispersion' (Cormier et al., 2009; Qi et al., 2010). These topics contain at least 2 papers in the clusters. The other ten grey colored nodes indicate stand-alone papers in the network and represent different topics which do not have a bibliographic coupling with Dr. Mannan's highly cited publications. For example, resilience engineering of industrial processes (Dinh et al., 2012), organizational safety attitudes (Henning et al., 2009), and dynamic operational risk assessment (Barua et al., 2016) are such articles.

6.2. Highly cited references of Dr. Mannan's papers

A total of 10,326 cited references were extracted from Dr. Mannan's 327 publications. The year of publication of these references spans a period of 634 years, ranging from 1386 to 2019. The distribution of the year of publication of the references in Dr. Mannan's work is shown in Fig. 14. Among these, there are 10 references dating from before 1900. Each of these has received only one citation in Dr. Mannan's publications, except Morozzo (1795), which was cited twice. Detailed information of the references from before 1900 which he cited are listed in

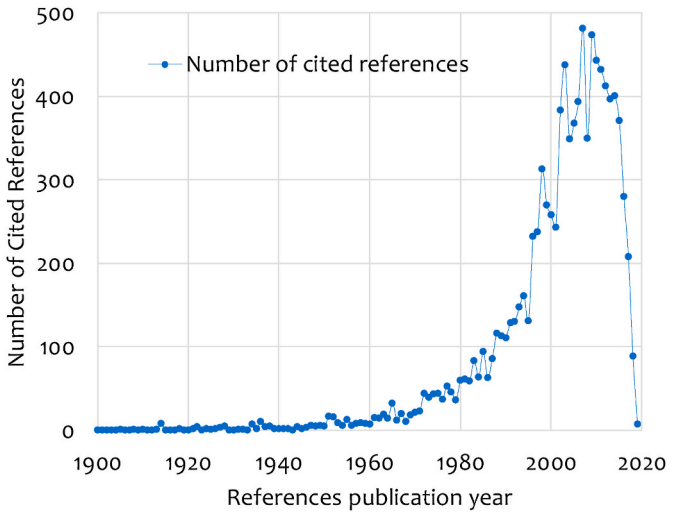

Fig. 14. Evolution of the year of publication of the references in Dr. Mannan's publications.

Table 5. In his paper, '*Learning lessons from incidents: A paradigm shift is overdue' (*Mannan and Waldram, 2014*)*, he has cited Chaucer's work from 1386 as follows: *"Barton and Rogers remind us that as early as the* 14th *century, industrial accidents were described (*Barton and Rogers, 1997*), with comments such as "Don't be alarmed, help to sweep up the floor, just as we always do, and try once more!"*(Chaucer, 1386)*."* The second older cited reference was authored by Morozzo in 1795, entitled *"Account of a violent explosion which happened in a flour-warehouse at Turin, December the* 14th*, 1785, to which are added some observations on spontaneous inflammations"*. This publications was cited twice in Dr. Mannan's publications, in (Jain et al., 2017; Mannan and Waldram, 2014). Such older publications were commonly cited as a historical background related to dust explosion research themes. More detailed information of other cited references before 1900 can be seen in Table 5.

The distribution of the publication year of the references in Dr. Mannan's publications show that most references refer to more recent literature, with only a relatively small proportion of the cited publications published before the 1970s. This is a normal occurrence in academic research, where research outputs are usually cited more frequently near its year of publication than long afterwards (Marx et al., 2014). The highly cited references (taken as having more than 10 citations) from Dr. Mannan's research output are listed in Table 6. These frequently cited references can be regarded as being highly influential to Dr. Mannan's thinking and constitute a research base of his own research. The most frequently cited paper by Dr. Mannan is '*Thermal hazard evaluation by an accelerating rate calorimeter*', which was cited 16 times in Mannan's publications, followed by Becke (1993) and Mannan et al. (2005). Among these papers, 4 out of 8 are listed Dr. Mannan as the corresponding author, and there are two highly cited books in Dr. Mannan's papers. One of these is '*Chemical Process Safety: Fundamentals with Applications*', which was published by Crowl DA in 2002. Crowl has received 12 citations from Dr. Mannan's publications. This book also has a high impact in the wider process safety research community, see (Li and Li, 2020). The other book was authored by Mannan himself, titled '*Lees' Loss Prevention in the Process Industries*'. As a re-edited version of Lees' standard reference work on loss prevention, it is also a very influential book in the wider process safety community (ibid). It is noteworthy that the frequently cited references in Dr. Mannan's publications are mostly related to engineering and technology topics. However, as seen in Section 6.1, his own highly cited publications are mostly related to management related aspects.

Table 5
Cited references dating from before 1900 in Dr. Mannan's publications.

NO.	Cited references	Citing papers	Citing sentences
1	(Chaucer, 1386)	Mannan and Waldram (2014)	Barton and Rogers (1997) remind us that as early as the 14th century, industrial accidents were described, with comments such as "Don't be alarmed, help to sweep up the floor, Just as we always do, and try once more!", Chaucer (1386).
2	(Morozzo, 1795)	(Jain et al., 2017; Mannan and Waldram, 2014)	(1) An early accident investigation involved a flour dust explosion in Giacomelli's bakery in Turin (Morozzo, 1795*). (2) One of the first recorded accident investigations followed an explosion at about 6.00 p.m. on 14th December 1785 in Giacomelli's flour warehouse in Turin, Morozzo (1795).
3	Brodie (1859)	Lakhe et al. (2019)	Since GO's isolation in the 1850s, the energetic nature of GO has been well documented [12].
4	Lewes (1877)	Jain et al. (2018)	Emergence: this implies that the tasks or actions and their results at the system or collective level arise or develop from the individual actions and interactions between the individual components (Black and Koopman, 2009; Lewes, 1877).
5	Divers (1883)	Cisneros et al. (2003)	There are several publications that describe possible reaction mechanisms when hydroxylamine comes in contact with metals such as tin (5).
6	Hexamer (1883)	Castellanos et al. (2013)	Vent openings should not discharge into workrooms, so when process units are placed inside buildings it is common practice to convey explosions to safe areas by means of vent ducts (2–6).
7	(Kharbanda and Stallworthy, 1988)	Mannan et al. (2007)	Further reading recommends by Mannan.
8	Thomsen (1892)	Saraf et al. (2003)	The reported experimental value for the heat of formation of gaseous HA is −12.0 (2.4 kcal/mol,4 which was derived by an indirect calculation from the experimentally determined heat of formation of solid HA and the heat of sublimation (5–7).
9	Noyes and Whitney (1897)	Harding et al. (2016)	The standards follow the dissolution rate predicted by the Noyes-Whitney equation, shown in Equation (2) (Noyes and Whitney, 1897)

Note: * in Dr. Mannan's Publication, the publication year of appeared as 1785 and 1795. Upon checking the original publication by Morozzo, the publication year is revised to 1795.

7. Conclusions

Dr. M. Sam Mannan is one of the pioneers in process safety research, spending most of his career in process safety and risk research and practice. He was dedicated to improving process safety through research

Table 6
Frequently cited references in Dr. Mannan's publication.

No.	First author, publication year	CA	Title	Source	Citations	% of 327
1	Townsend and Tou (1980)	_	Thermal hazard evaluation by an accelerating rate calorimeter	*Thermochim Acta*	16	4.9%
2	Becke (1993)	_	Density-functional thermochemistry. III. The role of exact exchange	*J Chem Phys*	15	4.6%
3	Mannan et al. (2005)	* 1	The legacy of Bhopal: The impact over the last 20 years and future direction	*J Loss Prevent Proc*	14	4.3%
4	Reisch (1999)	_	Capital spending up modestly in 2000	*Chem Eng News*	12	4.0%
5	Cisneros et al. (2001)	*3	Adiabatic calorimetric decomposition studies of 50 wt% hydroxylamine/water	*J Hazard Mater*	12	3.7%
6	(Crowl and Louvar, 2002)	_	Chemical Process Safety: Fundamentals with Applications [BOOK]	*Chem Process Safety*	12	3.7%
7	Cisneros et al. (2002)	*3	Effect of air in the thermal decomposition of 50 mass% hydroxylamine/water	*J Hazard Mater*	11	3.4%
8	Mannan (2005)	*1	Lees' Loss Prevention in the Process Industries [BOOK]	*Lees Loss Prevention*	11	3.4%

Notes: CA=Corresponding author, * = Dr. Mannan listed as co-author in the paper, with the number indicating his author rank, PY = publication year, % of 327 = percentage of citations from 327 papers, for example (Townsend and Tou, 1980), have been cited 16 times in 327 papers, account for 4.9%.

and practice and set out to 'make safety second nature' for the process industries. In his lifetime, he has published hundreds of papers in various scientific domains within process safety.

The bibliometrics overview of his research outputs serves not only as a tribute in Honor of Dr. M. Sam Mannan. It furthermore sheds light on some key themes in the process safety research field, through mapping the various clusters of research topics in which he was engaged. Especially for young researchers in the process safety area, Dr. Mannan's success can be inspirational to help them chart a successful career in process safety research and practice, and to help the industries and inspectorates to further improve safety practices and outcomes.

As evident from the presented analysis, Dr. Mannan was a highly productive researcher. There are 327 articles authored by Dr. Mannan spanning a period of 21 years from 1999 to 2019 in the Web of Science database. Hence, he has published more than one paper per month, which is an impressive achievement. His papers are published in 53 different sources, with by far most of his publications being 'original research articles'. His top 5 publication outlets are *Journal of Loss Prevention in the Process Industries*, *Journal of Hazardous Materials*, *Industrial & Engineering Chemistry Research*, *Process Safety and Environmental Protection* and *Process Safety Progress*, together accounting for 70% of his 327 papers. Dr. Mannan had a highly diverse and very international collaboration network, with many authors from different countries/regions and institutions. He has collaborated with 18 different countries/regions, with Mexico, China, and Greece being the top 3 countries with research collaborations. A total of 90 institutions have collaboration links with Dr. Mannan, who was based at Texas A&M Univ. Of these, the Inst Tecnol Celaya (16), Oklahoma State Univ (9), and Tech Univ Lodz (8) are the top three most strongly linked institutions. There are 387 authors who have collaboration links with Dr. Mannan, with Rogers, William J (64), Cheng, Zhengdong (20), Liu, Yi (19) and Ng, Dedy (19), Mentzer, Ray (18), and Zhang, Bin (17) being the closest co-authors with Dr. Mannan.

The topics of his publications are mainly focused on process safety-related research, including process safety in liquefied natural gas, explosions, runaway reactions, inherent safety, flammability, risk assessment and safety/risk management, and more recently resilience. Among these topics, risk assessment related topics such as 'fuzzy sets', 'Analytic Hierarchy Process', and 'Bayesian inference' have received a high number of citations and a higher impact in the research community compared to other topics. Despite his work on resilience being a more recently emerging topic, it also has a high impact. Based on the analysis of the keywords in the keywords network, it clear that most of Dr. Mannan's work focused on technology and engineering related topics. However, his work on management-related topics have received comparatively more citations within the scientific community. His most cited paper is 'Fuzzy risk matrix', which is a technical topic with a management objective. The most frequently cited reference in his papers is 'Thermal hazard evaluation by an accelerating rate calorimeter' by Townsend DI in 1980, which can be regarded as being one of the most influential works on Dr. Mannan's research activities.

Declaration of competing interest

The authors herewith confirm that there is no conflict of interest with regard to this manuscript.

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