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Comprehensive assessment of recent major chemical accidents in China and path to sustainable solutions

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Abstract

China's chemical manufacturing sector has experienced remarkable growth in recent years, making it a global leader in chemical production. However, this rapid expansion has led to an increase in chemical accidents, particularly major chemical accidents (MCAs), resulting in significant casualties and property loss. This study focuses on MCAs that occurred in China between 2017 and 2022, using mathematical statistics. It examines various aspects of accidents, including the annual number of accidents and casualties, distribution across months, types of accidents, accident stages, direct causes of accidents, and geographical distribution of accidents. Furthermore, this study investigated the potential of using novel digital tools to enhance the safety of chemical production. By analysing the data and identifying trends, this study aims to contribute to the prevention of large-scale chemical disasters. Furthermore, it explores the implementation of smart management of chemical plants, utilising the Internet of Things (IoT) for example, to ensure the sustainable advancement of the chemical industry.

Keywords Chemical accidents, Sustainable development, Artificial intelligence, Production safety, Risk assessment

1 Introduction

Chemicals are indispensable in industrial, agricultural, and other applications. Benefiting from China's rapid economic growth, the production and consumption of chemicals have seen tremendous growth. Since 2011, China has been the dominant player in the global chemical sector in terms of revenue, accounting for 50% of the growth of the international chemical market over the last two decades [25, 52]. However, the rapid expansion of the Chinese chemical industry has raised several safety concerns [14]. For example, two disastrous hazardous-chemical accidents occurred in China in 2019. On March 21, 2019 a blast at Tianjiayi Chemical Company located in Jiangsu Province resulted in 78 fatalities and seriously injured 76 people, which caused direct economic losses of 1.986 billion RMB [64]. An explosion that occurred at the Yima Gasification Plant in Henan Province on July 19, 2019 resulted in 15 deaths and 16 severe injuries, with a direct economic loss of 81.7 million RMB [54].

These severe chemical incidents have not only resulted in the tragic loss of life and significant economic repercussions but have also led to severe environmental impacts, including water and soil pollution, air contamination, biodiversity loss, and potential risks to human health. The released chemicals may persist and cause lasting harm to ecosystems and communities [1, 2, 7, 29, 49]. As reported, the '3·21' explosion at Tianjiayi Chemical Company led to substantial water pollution within a 4-km radius, notably affecting nearby rivers. Initial atmospheric contamination involved elevated levels of sulphur dioxide and nitrogen oxides. The soil impact, concentrated within 300 m, was primarily attributed to

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semi-volatile organic compounds [3]. Additionally, findings from an environmental dynamics model reveal that harmful substances, including formaldehyde, released during a chemical accident persist for approximately 150 d in the surrounding atmosphere and 632 d in the soil [44].

Compared to other types of industrial accidents or natural disasters, the intensity of major hazardous-chemical accidents is more severe because chemical plants usually house hundreds or thousands of adjacent hazardous installations [66]. Damage to one unit in a chemical plant can therefore trigger a series of accidents causing damage on a wider scale, often referred to as a domino effect [13]. Therefore a chemical accident can cause huge property damage, casualties, serious environmental pollution, and other problems [9]. Moreover, the average number of personnel employed at chemical firms in China is much higher than in Europe and North America, and large-scale chemical plant accidents in China typically result in more fatalities [8]. Therefore, there is an urgent need for China to understand the characteristics of past chemical plant accidents and their causes and improve safety management (SM) to reduce the number of such accidents in the future [48].

Consequently, a considerable number of studies have investigated chemical accidents in China, with a predominant focus on employing mathematical and statistical methods for analysis and assessment. Duan et al. [14] studied the occurrence of dangerous chemical accidents in China between 2000 and 2006. Zhang and Zheng [62] examined data from 2006 to 2010 and reported 1,632 hazardous-chemical accidents in China. Zhao et al. [63] focused on the characteristics of hazardous-chemical accidents in China between 2006 and 2017. Wang et al. [52] collected accident data from chemical plants in recent years and discussed future directions for hazardous-chemical safety in China. He et al. [23] analysed hazardous-chemical accidents that occurred in China over the previous four decades. These studies primarily analysed accident cases in terms of accident development trends, accident types, causes of occurrence, and seasonality. Moreover, previous studies developed environmental impact assessment methods, such as expert judgement, the Analytical Hierarchy Process (AHP), and the ecosystem quality index (EQI), to offer practical recommendations, including risk investigation, legislation, regulation, and scientific and technological research, for enhancing chemical industry management [6, 50].

However, these previous studies explored chemical accidents in China before 2017, with a notable gap in the analysis of more recent data. In addition, most previous studies have concentrated solely on examining chemical accident types, causes, and seasonal patterns. Furthermore, in several of these studies, the analyses included all chemical accidents that occurred in China within a specific timeframe. This restriction hinders the acquisition of comprehensive and precise data, potentially diminishing the scientific merit of such investigations. Major chemical accidents (MCAs) were frequently reported by the Chinese government due to their substantial property damage and fatalities, necessitating effective prevention measures. However, the features of the MCAs that occurred recently between 2017 and 2022 have not been analysed in order to derive strategies for the future development of chemical plant management. Therefore, a comprehensive analysis report and perspective on all the MCAs during the rapid development of chemical production in China are necessary.

In this study, MCAs in China spanning the years 2017 to 2022 were comprehensively analysed. The analysis includes an examination of the annual incidence of accidents and casualties, monthly distribution, accident types, stages, direct causes, and geographical patterns of MCAs. Subsequently, the potential causes and characteristics of MCAs are discussed, supplemented with insights from relevant literature, with the aim of offering valuable countermeasures for the prevention of these serious accidents. In addition, novel methods and prospects for enhancing the safety of chemical production through industrial digitalisation and emerging technologies are discussed. The findings of this study provide valuable insights and recommendations to enhance safety measures in the chemical industry, not only in China but also in other developing countries. Furthermore, an investigation of the potential for digital transformation in the chemical sector may present innovative ideas and strategies to improve chemical industry safety standards, ultimately fostering sustainable development for chemical enterprises.

2 Materials and methods

2.1 Data collection

The accident data analysed in this study were predominantly derived from the Ministry of Emergency Management of the People's Republic of China (MEMPRC) and the China Chemical Safety Association (CCSA). These two sources are the most authoritative and commonly used official channels for statistics on chemical plant accidents, as they report all production safety accidents that occur in China. MEMPRC regularly publishes quarterly and annual summaries of disasters nationwide. Thus, the annual count and basic data on major chemical factory accidents in China can be obtained from MEMPRC. Furthermore, detailed investigations for each incident are available from both the MEMPRC and the CCSA, which provide comprehensive reports, including the occurrence, processes, and potential causes of every incident. Moreover, data from the SM platform were used to verify the reports and analyses of chemical plant accidents. Additionally, the geographical dispersion of large-scale chemical plants in China was obtained from the National Bureau of Statistics of China (NBSC) to investigate the regional distribution patterns of MCAs. The MCA data from the MEMPRC, CCSA, SM, and NBSC are credible and reliable for public consumption.

2.2 Methods

Production safety accidents are classified into four types according to China's regulations: general, major, extraordinary, and tremendous accidents [21]. Table 1 lists the typical types of production safety accidents based on casualties or direct economic losses [18]. In recent years, there has been a lack of studies that have comprehensively collected and examined information regarding MCAs, i.e., chemical accidents leading to three or more deaths or ten million RMB of direct economic losses (Table 1). Therefore, this study focuses on collecting and analysing data on 72 MCAs that occurred between 2017 and 2022 in China from various perspectives, including information on their annual trends, monthly distributions, accident types, stages of occurrence, direct causes, and regional distributions. This study integrates and compares its findings with those of previous research, investigates the underlying causes of the identified patterns, and proposes relevant countermeasures and recommendations. The advantages and disadvantages of the utilised methods compared with those of other studies are presented in Table 2.

Table 1 Categories of production safety accidents

Type	Number of fatalities	Number of serious injuries	Direct economic losses (million yuan)
General accident	0–2	0–9	0–10
Major accident	3–9	10–49	10–49
Extraordinary accident	10–29	50–99	50–99
Tremendous accident	> 30	> 100	> 100

This study addresses a significant gap in the prior research on chemical accidents in China by focusing on MCAs that took place between 2017 and 2022. Compared with previous studies before 2017, this study takes a pioneering approach by comprehensively categorising and analysing recent MCA data instead of emphasising accident types and causes. It explores potential causes and characteristics and provides valuable countermeasures for prevention. In addition, this study discusses the prospective advancement of chemical plants by highlighting the adoption of innovative technologies and digitalisation to enhance safety. These analyses and investigations can improve safety standards and the sustainable development of chemical enterprises. Figure 1 shows the flowchart for MCA analysis.

As shown in Fig. 2, a visualisation co-occurrence network map of important terms extracted from relevant scientific literature obtained from the Web of Science was constructed using VOSviewer software. The co-occurrence map effectively reveals prominent topics, crucial concepts, and major themes within this research domain. It distinguishes three distinct clusters of keywords, represented by the colours red, blue, and green. (i) Cluster 1: The red segment of the graph encompasses keywords related to the level, year, country, and casualties of chemical accidents. Moreover, it includes aspects of chemical plant management, governance, and production safety. (ii) Cluster 2: The green section comprises keywords associated with case studies, accident analyses, accident consequences, risk analyses, and other related factors. (iii) Cluster 3: The blue portion corresponds to keywords linked to different types of chemical accidents,

Table 2 Advantages and disadvantages of utilised methods

Advantages	Limitations
1. Captures a broad overview of all chemical plant accidents over a long period, providing a historical context 2. Enables identification of long-term trends and patterns 3. Facilitates a comprehensive understanding of overall risk factors and contributing factors 4. Allows for in-depth examination of specific aspects, such as seasonal variations in accident frequency 5. Provides more targeted insights into specific risk factors and patterns 6. The data used in this research is of high quality and accuracy 7. Using data from recent years ensures timely, relevant insights into current trends, enabling informed decision-making and aligning with contemporary regulatory standards 8. Providing appropriate countermeasures and recommendations for improving chemical production safety	1. Ignores individual-specific details in each accident 2. Overlooks systemic issues and interconnected factors influencing accident patterns 3. The findings may not be directly applicable to specific scenarios

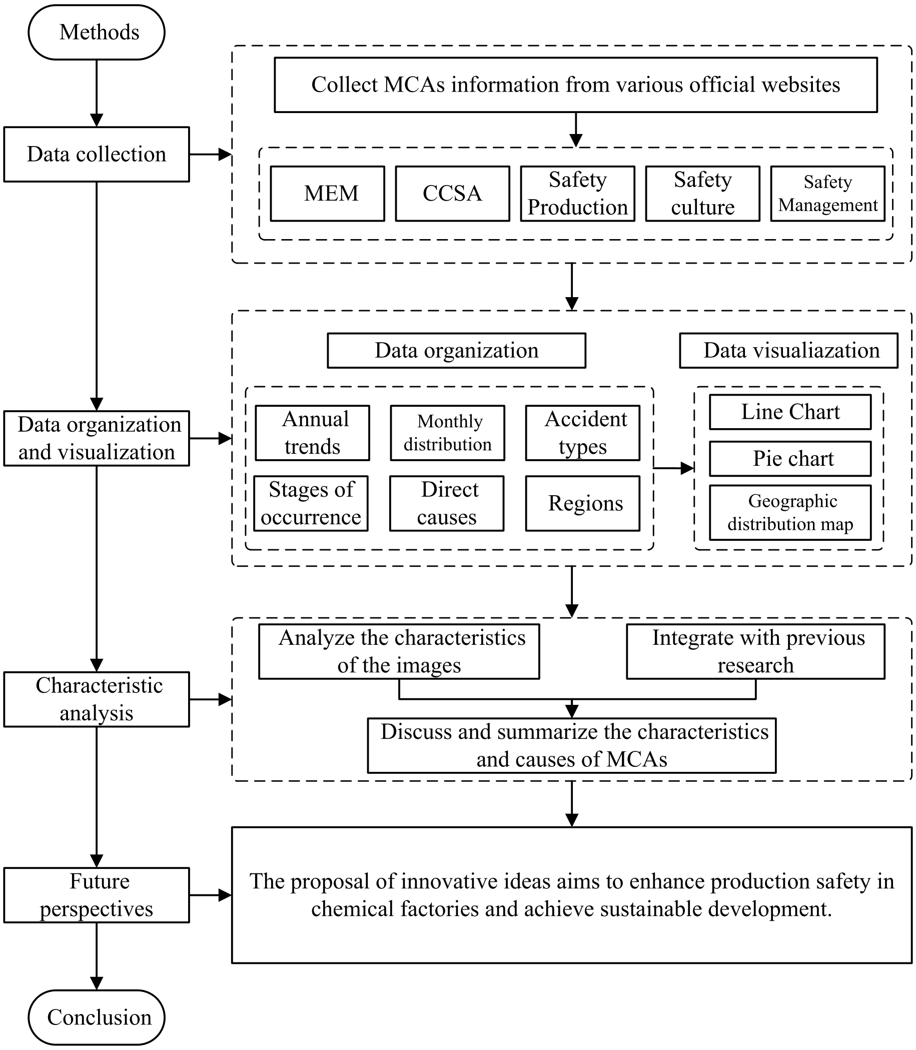

Fig. 1 Research methodology flowchart

such as explosions, fires, and leaks. The keyword clusters depicted in the network graph offer valuable insights into various facets of chemical plant accidents, ranging from management practices and safety measures to case studies and accident analyses. However, an evaluation of the keywords used in these studies reveals that case analyses of major chemical plant accidents are scarce. In addition, there is a dearth of terms associated with upcoming technological advances such as artificial intelligence and machine learning. This study aims to fill this gap and contribute to this underexplored area.

3 Data characteristic analysis

3.1 Trend of number of MCAs and fatalities

Figure 3 presents a graphical representation of the number of MCAs and associated fatalities recorded between 2017 and 2022. The number of accidents has steadily declined. The highest number of MCAs occurred in 2017 (17) and decreased to its lowest in 2021 (9), indicating a decrease of 47.06%. The trend in the number of fatalities can be divided into three phases. The initial phase, from 2017 to 2019, was characterised by an increase. The number of fatalities was 77 in 2017, which thereafter had a significant surge, reaching its peak of 138 in 2019. From 2017 to 2019, the number of accidents decreased while the number of fatalities increased. This is primarily because of the occurrence of several serious accidents. In 2018, two extraordinary accidents occurred: on July 12, an explosion and fire at an enterprise located in Yangchun Industrial Park in Sichuan Province killed 19 people [15], and on November 28, an explosion and fire at the Shenghua Chemical Company in Hebei Province killed 23 people [43]. In 2019, a massive chemical explosion accident occurred in Xiangshui, Jiangsu, on March

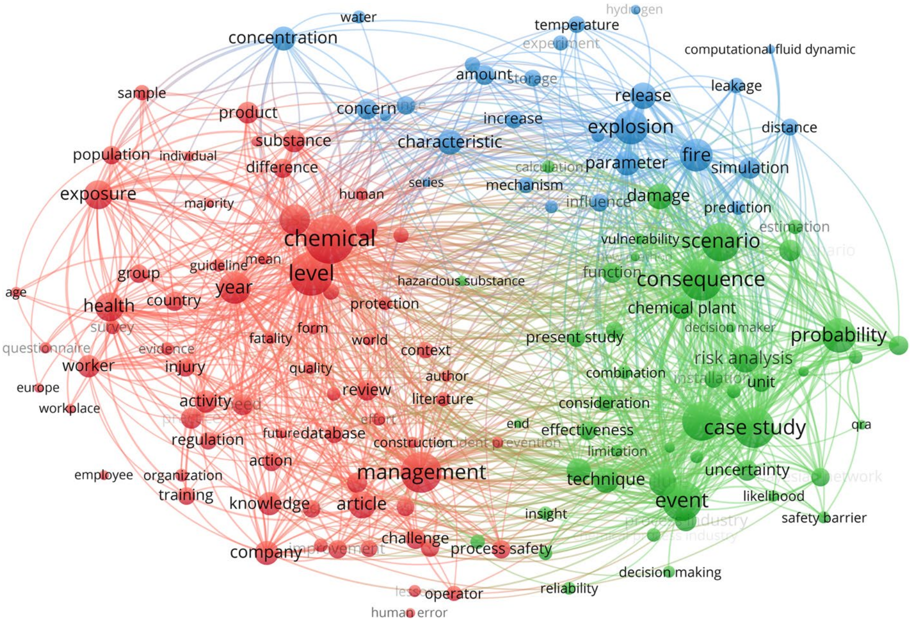

Fig. 2 Network visualisation map with keywords of chemical accidents

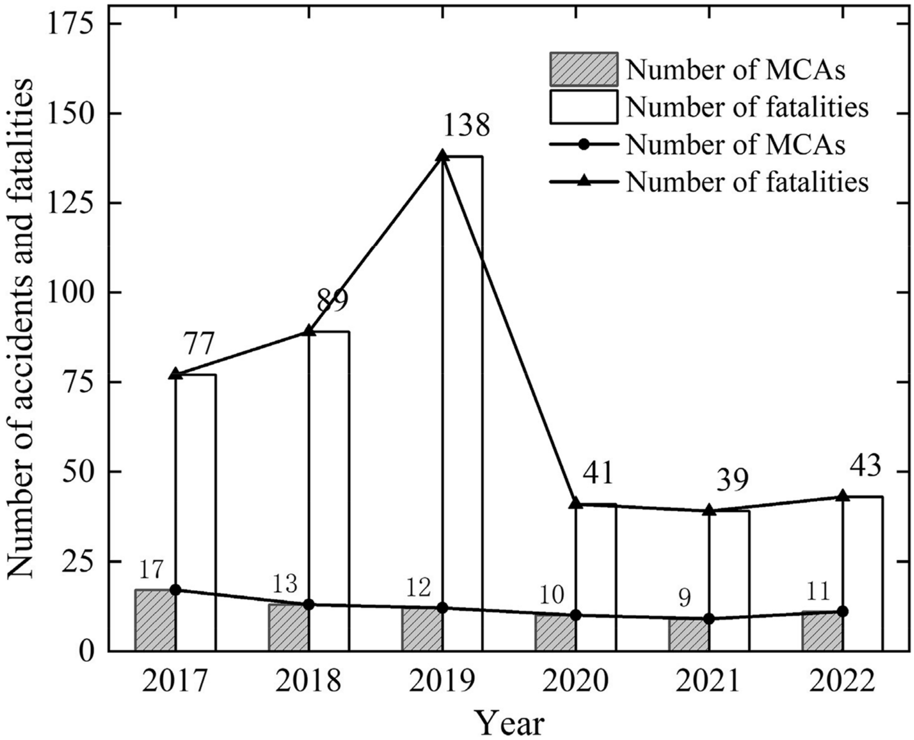

Fig. 3 Number of MCAs and associated fatalities caused per year in China from 2017 to 2022

21, which was the most serious chemical plant accident in recent years, causing 78 fatalities [3], accounting for 56.52% of the total MCA fatalities in 2019. The second phase, spanning 2019–2020, exhibited a significant decline. The number of fatalities decreased from 138 in 2019 to 41 in 2020. The third phase, including the period from 2020 to 2022, exhibited some fluctuations. During this period, the number of fatalities remained relatively stable at approximately 40, with approximately ten cases of MCA per year. This can be attributed to the absence of extremely severe accidents in the period from 2020 to 2022. The most serious incident during this period was the 6.12 Toxic Chemicals Leakage disaster in Guiyang, which resulted in nine fatalities [11]. Other MCAs witnessed during this period did not result in a substantial number of deaths. Between the years 2017 and 2022, the annual incidence of MCAs in China remained approximately 20. However, the resulting number of deaths was alarmingly high. MCAs in China typically result in more casualties than in developed countries. This is because the number of personnel working in chemical firms in China is typically much greater than in Europe or North America [8].

3.2 Monthly distribution of MCAs

The monthly distribution of MCAs is presented in Fig. 4. The results showed a certain seasonal distribution. It is worth highlighting that MCAs frequently occurred from January to February, with a total of seven cases per month recorded between 2017 and 2022. This pattern persisted from March to June, with over six cases recorded per month. A peak of ten cases was recorded in April. Notably, in 2019, four MCAs occurred in April, whereas five MCAs occurred in June 2017. A total of ten accidents were recorded in November and seven in December from 2017 to 2022. Based on the data presented, MCAs occur most frequently at the beginning of the year, followed by March to June, and November and December. However, during the summer season (July to September), the frequency of MCAs decreased to fewer than five cases per month. Notably, only one case of MCA was reported in August.

The seasonal distribution of chemical accidents could be attributed to several factors. As noted by Zhao et al. [63], weather is a significant external factor that significantly influences the frequency of chemical accidents. In China, spring and summer are characterised by increased rainfall and high temperatures. Consequently, accident rates tend to increase during the warm and humid months of March–April and June–August. Wang et al. [53] highlighted the substantial impact of high-temperature weather on hazardous-chemical safety. Elevated temperatures can lead to the volatilisation of hazardous chemicals, increasing the risk of combustion or explosion accidents. Additionally, increased employee fatigue and high-temperature working conditions during the spring and summer can contribute to decreased attentiveness, thereby increasing the likelihood of accidents.

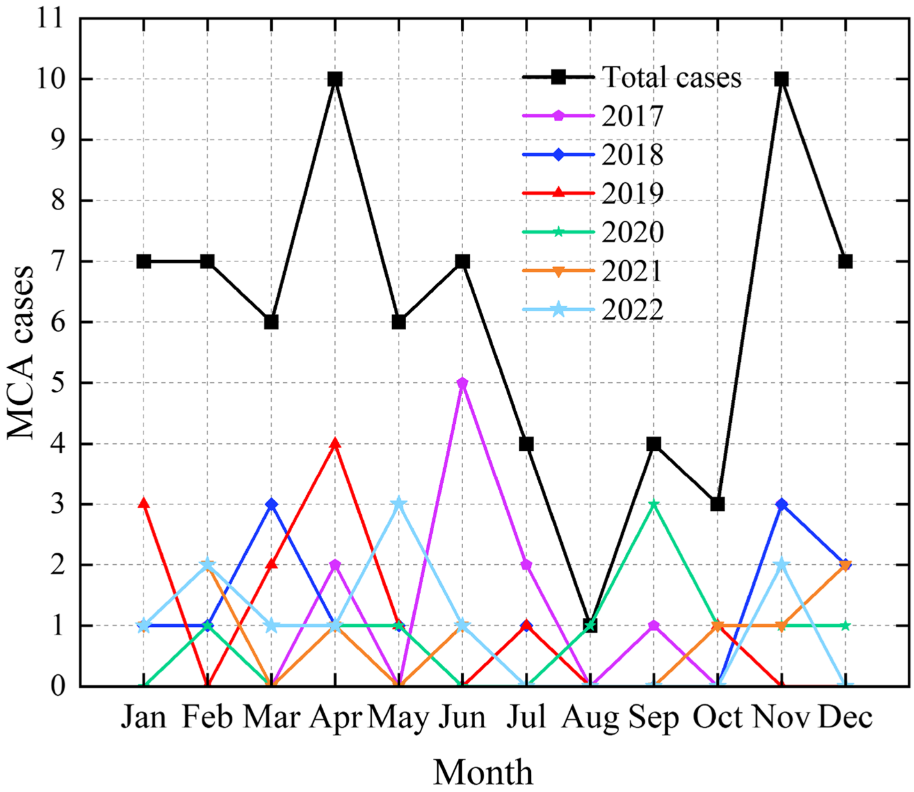

Fig. 4 Monthly statistics of MCA cases from 2017 to 2022

In contrast, this study identified a lower occurrence of MCAs during the summer in recent years. Several factors might have contributed to this trend. During the summer, chemical enterprises implement stringent maintenance and safety measures to counteract the adverse effects of high temperatures and humidity on equipment and chemicals and reduce the risk of accidents. Moreover, the summer season often corresponds to a period of low production and workload, along with employee vacations, leading to a less hectic workplace environment that reduces accident risks. Furthermore, some chemical enterprises adjust their schedules in response to extremely high temperatures, such as by decreasing production during the hottest hours of the day, to reduce risks to equipment and personnel. This proactive measure further enhances accident prevention efforts.

Conversely, a notable increase in accidents was seen during March and April, which typically coincide with the Chinese Lunar New Year. During this period, employees often work overtime to keep pace with production demands and workload, leading to an increased risk of accidents. Similarly, a significant number of accidents occurred between November and February, partly because of factors such as staff shortages during the Chinese Lunar New Year and the vulnerability of facilities to freezing and cracking during the winter season, which can result in material leaks and related accidents. In response to seasonal variations in accident rates, it is imperative for chemical enterprises to adopt comprehensive safety protocols during specific periods to reduce accidents and prioritise employee well-being. Despite the lower incidence of accidents during the summer, chemical factories must maintain constant vigilance and uphold rigorous preventive measures to ensure workplace safety. Safety in the chemical industry requires continuous attention and improvement.

3.3 Accident types

All MCAs from 2017 to 2022 are classified (Fig. 5) according to the National Standard of the People's Republic of China GB/T 6441–1986, which classifies the casualty accidents of enterprise staff and workers [40]. Note that several types of accidents may occur simultaneously. For example, explosion accidents are usually accompanied by fire and collapse. As shown in Fig. 5, explosion incidents (53.9%) accounted for more than half of all MCAs, followed by poisoning and suffocation accidents (22.5%). Fire accidents ranked third in terms of occurrence rate, accounting for 13.5% of the total incidents. The remaining types of accidents include object strikes, thermal injuries, collapses, and other injuries, accounting for less than 4% of accidents. In summary, these findings indicate that explosions present a substantial hazard, leading to serious safety accidents and fatalities in the chemical industry. The risk factor ranked second is poisoning and suffocation, followed by fire-related accidents, which is the third most prominent concern.

The frequency of explosion accidents occurring in chemical factories is relatively high and can result in serious accidents and casualties. This is closely related to the characteristics of explosion accidents. Once an explosion occurs, it often releases large amounts of energy, leading

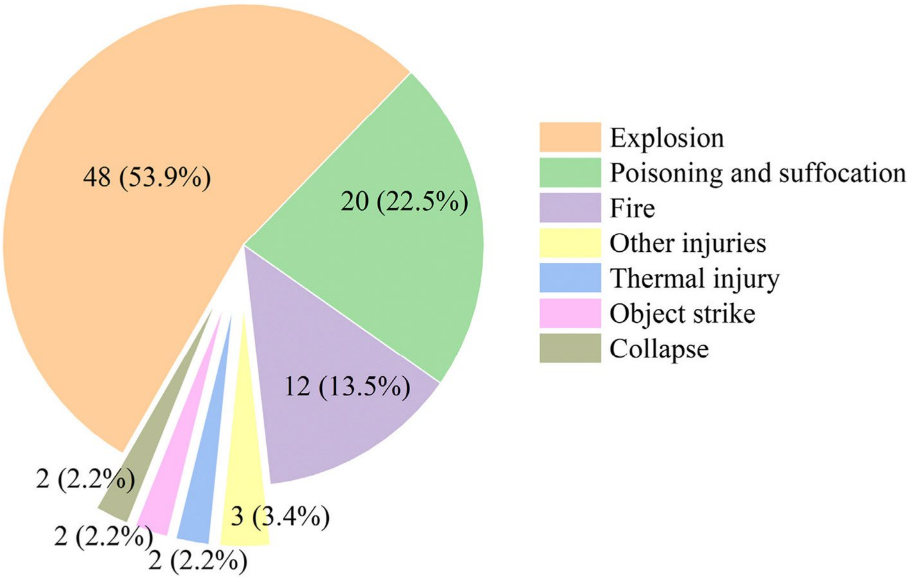

Fig. 5 Categorising MCAs in China in terms of type of mishap from 2017 to 2022

to unforeseen consequences and making preventive measures difficult to implement. In addition, fires and explosions usually lead to MCAs owing to the domino effect [13]. For instance, when an explosion occurs inside a chemical factory, the resulting heat impacts the adjacent facilities, resulting in fires and other threats. The flame then generates a large amount of heat and impacts nearby containers, which can easily trigger a series of explosions.

Accidents involving poisoning and suffocation in chemical facilities often lead to severe accidents. This is because chemical plants frequently use highly poisonous compounds, such as ammonia and hydrogen sulphide, in their production processes. When these chemicals leak, they spread swiftly over a vast region, resulting in additional injury. Many chemicals release substantial amounts of toxic gases upon leakage. These gases can displace oxygen from the surrounding environment, resulting in suffocation, unconsciousness, or immobilisation. This can increase the likelihood that people will be unable to evacuate or receive prompt emergency assistance. Considering the leading causes of explosions, poisoning, suffocation, and fire accidents, it is crucial for chemical companies to prioritise preventive measures and implement appropriate strategies to avoid these three types of incidents and ensure the safety and well-being of their operations and personnel.

3.4 Number of accidents that occur during different stages

According to the different stages of occurrence, MCAs can be classified as production, maintenance operations, loading and unloading, trial production, start-up/shut-down, storage, cleaning, hot-work operations, confined-space operations, and other stage MCAs (Fig. 6). MCAs occurring during production (18 cases and 26.4%), which account for almost one-third of all MCA cases, have the highest incidence. The primary reason for this is that chemical manufacturing involves hazardous processes such as chlorination, oxidation, diazotisation, fluorination, sulfation, and nitrification. In addition, the operating unit is rife with dangerous and accident-prone process conditions, including high temperatures, high pressure, high velocity, and cryogenic temperatures [62]. Furthermore, MCAs occurring during hot-work operations have the second-highest incidence, with 14 MCAs occurring during this stage, constituting 19.4% of all cases. Following closely are MCAs that occur during maintenance operations, accounting for 13.9% ($n = 10$) of total MCAs. In addition, MCAs that occur during confined-space operations account for 11.1% of total cases, followed by those occurring during loading and unloading and other stages, each accounting for five cases. The final category is MCAs that take place during cleaning, trial production, storage, start-up/shut-down, and loading and unloading, each contributing less than five cases.

Generally, accidents are more likely to occur when the source of the hazard is easily accessible. For example, during the aforementioned production processes, individuals are exposed to significant levels of danger. In addition, in hot-work operations, which involve sources of ignition and often flammable and explosive substances, fires and explosions can occur easily. In confined-space operations, employees must operate machines in narrow or enclosed spaces, which may include storage tanks, pipelines, reactors, underground passages, containment pits, and similar structures. This restricts the employees from moving and ventilating freely. As such, they may encounter various potential hazards, such as limited air

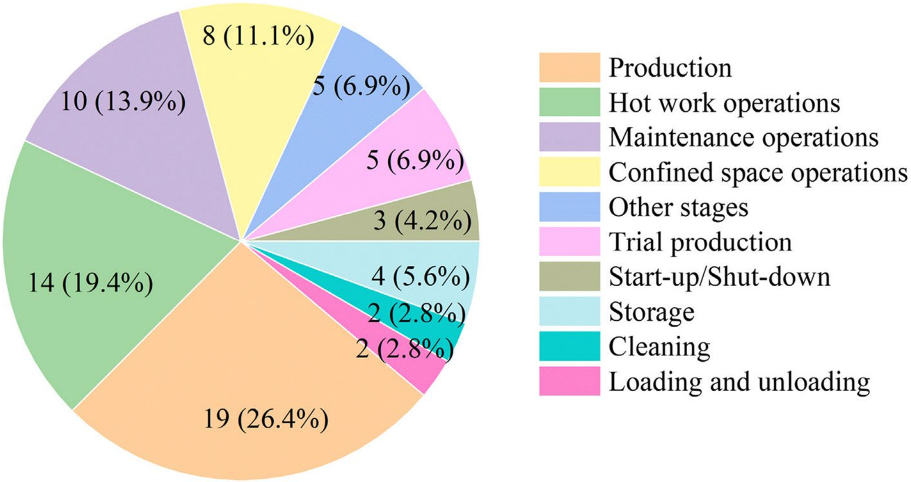

Fig. 6 MCA cases during different stages

supply, accumulation of toxic gases or vapours, and hazardous substance leaks, resulting in poisoning and suffocation. Therefore, special safety measures and procedures must be implemented to ensure the safety of workers during the high-risk stages. For example, during hot-work operations, controlling ignition sources, ensuring the availability of firefighting equipment, and requiring workers to wear appropriate protective gear are essential precautionary measures. Similarly, during confined-space operations, special measures should be taken, such as effective ventilation, continuous air-quality monitoring, and emergency rescue planning. These safety measures are paramount for mitigating risks and safeguarding the well-being of workers.

3.5 Direct causes of MCAs in China from 2017 to 2022

Based on the direct causes of MCAs, the MCAs can be classified as those occurring due to unsafe operating environments and those occurring due to improper personnel operations; the detailed classification results are shown in Table 3. The first category, which is MCAs occurring due to unsafe operating environments, accounts for approximately 40% of the total. Among these, 14 cases (19.4%) of MCAs were caused by the absence of detective alarms or safety assurance devices. Defective equipment or facilities resulted in ten cases, accounting for 13.9% of the cases. These two types accounted for approximately 35% of the total. Several safety concerns regarding the equipment and infrastructure of Chinese chemical plants exist, particularly the absence of safety guarantees and warning devices.

Notably, this study highlights that the primary factor for MCAs in China is improper personnel operations, constituting 60% of the cases. These included violations of process operating regulations, blind operation without risk analysis, and improper maintenance, which resulted in 17, 11, and 7 MCAs, respectively. Blind rescue caused six accidents. According to Moura et al. [39], several industrial accidents are linked to human factors, leading to catastrophic consequences. The lack of a strong safety culture and inadequate safety awareness among personnel in most chemical industries in China, where many operators have low qualifications, add further risk [8]. For example, according to a report proposed by the Emergency Management Department [15], on July 12, 2018, an explosion in Jiang'an, Sichuan Province, killed 19 people and injured 12 others. In this particular case, the assistant workshop director had received only primary school education and was unable to recognise the essential symbols related to the chemical components. In addition of the 19 people who died in the accident, 16 were migrant workers from the countryside. They lacked basic knowledge of chemical production safety and did not understand the safety risks associated with the production processes they were involved in. Such personnel are prone to adopting a haphazard approach during operational links and oversimplifying critical safety procedures, both of which significantly increase the likelihood of incidents occurring.

Furthermore, when delving deeper into the analysis of some MCA cases, it was found that many severe poisoning and suffocation accidents were attributable to the blind rescue of workers. For example, an accident occurred on November 18, 2022, at Zhejiang Tianma Industrial, where four people entered a chemical tank for rescue without wearing proper safety protective gear, thereby leading to fatalities due to poisoning [12]. This incident demonstrates that several employees of Chinese chemical enterprises lack professional qualifications. To mitigate risks in the Chinese chemical industry, it is vital to address infrastructure- and human-related factors. Thus, a holistic approach including education, training, safety culture, infrastructure improvement, and stringent safety regulations is required to ensure safe working environments.

3.6 Distribution of MCAs

In China, the chemical and petroleum sectors have long been pillars of the economy, with the petroleum and

Table 3 Direct causes of MCAs in China (2017–2022)

Direct Causes		**Accidents (Cases)**	**Percent (%)**
Unsafe operating environment	Absence of defective alarms or safety assurance devices	14	19.4
	Defective equipment or facilities	10	13.9
	Poor environment	5	6.9
Improper personnel operation	Violation of process operating rules	17	23.6
	Blind operation without risk analysis	11	15.2
	Improper maintenance	7	9.7
	Blind rescue	6	8.3
Other reasons	/	2	2.7

chemical industries holding significant importance in nearly every province, leading to the establishment of numerous chemical facilities [62]. To evaluate variations in the development of the chemical industry across provinces, we examine the distribution of the top 500 chemical enterprises (TCEs) in mainland China by sourcing data from the China Statistical Yearbook published by the NBSC [42]. For this analysis, the distribution of TCEs in each province in 2019 was used as a reference, considering that the ranking and distribution of these chemical companies underwent slight changes from 2017 to 2022. Table 4 provides an overview of the MCAs and TCEs across all provinces in mainland China. The number of TCEs within a province can serve as an indicator of the level of development of the chemical industry. In contrast to previous studies, this study not only visualised the regional distribution of MCAs but also analysed the chemical industry's development status in various provinces in China. The distribution map depicting the MCAs and TCEs across all provinces is illustrated in Fig. 7 (for specific statistics, see Table 4 and the accompanying bar chart in Fig. 8).

The majority of Chinese chemical companies are located in the coastal provinces of eastern China. The northeastern provinces include Shandong, Hebei, Beijing, and Tianjin, followed by Zhejiang, Jiangsu, and Shanghai in the east, and Guangdong in the southeast. These regions possess a substantial number of TCEs. The Yellow Province hosts several chemical companies, primarily in central and northern China. There are few chemical companies in the interior provinces of western and southern China. TCEs were typically concentrated in economically advanced provinces. Regarding the regional distribution of MCAs, Fig. 7 shows that most MCAs

Table 4 Statistics of MCAs and TCEs in mainland China (2017–2022)

Province	Number of MCAs per year						No. of MCAs	No. of TCEs
	2017	2018	2019	2020	2021	2022		
Shandong (SD)	2	3	1	0	0	0	6	104
Hubei (HuB)	2	0	0	2	1	0	5	18
Henan (HeN)	1	0	1	1	1	1	5	19
Shanxi (SX)	0	0	1	1	1	2	5	18
Zhejiang (ZJ)	2	0	0	0	1	2	5	34
Neimenggu (NMG)	1	0	1	1	1	1	5	20
Sichuan (SC)	1	1	2	0	0	0	4	20
Jiangsu (JS)	1	1	2	0	0	0	4	53
Anhui (AH)	1	0	1	0	0	2	4	17
Jilin (JL)	1	0	1	0	1	0	3	0
Jiangxi (JX)	1	1	0	1	0	0	3	1
Xinjiang (XJ)	2	1	0	0	0	0	3	6
Liaoning (LN)	1	0	1	1	0	0	3	20
Hebei (HeB)	0	3	0	0	0	0	3	41
Shaanxi (SAX)	0	0	0	1	0	2	3	11
Gansu (GS)	0	0	0	1	1	1	3	3
Heilongjiang (HLJ)	0	0	0	1	1	0	2	8
Qinghai (QH)	1	0	0	0	0	0	1	1
Fujian (FJ)	0	1	0	0	0	0	1	4
Guangxi (GX)	0	0	1	0	0	0	1	1
Guizhou (GZ)	0	0	0	0	1	0	1	8
Tianjin (TJ)	0	1	0	0	0	0	1	8
Shanghai (SH)	0	1	0	0	0	0	1	17
Ningxia (NX)	0	0	0	0	0	0	0	6
Yunnan (YN)	0	0	0	0	0	0	0	8
Chongqing (CQ)	0	0	0	0	0	0	0	7
Hunan (HuN)	0	0	0	0	0	0	0	6
Guangdong (GD)	0	0	0	0	0	0	0	31
Beijing (BJ)	0	0	0	0	0	0	0	8
Total	17	13	12	10	9	11	72	500

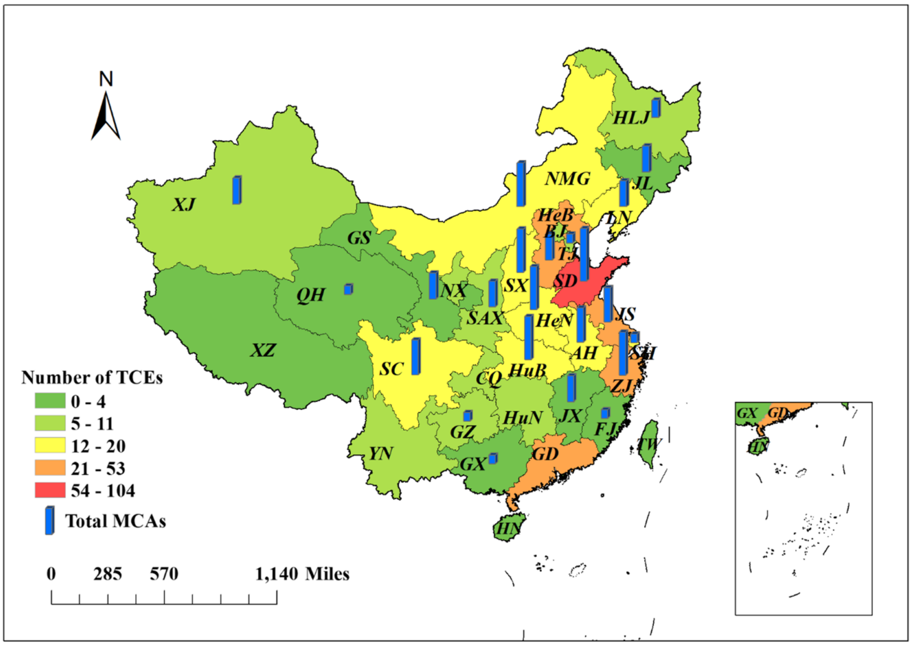

Fig. 7 Distribution map of MCAs and TCEs

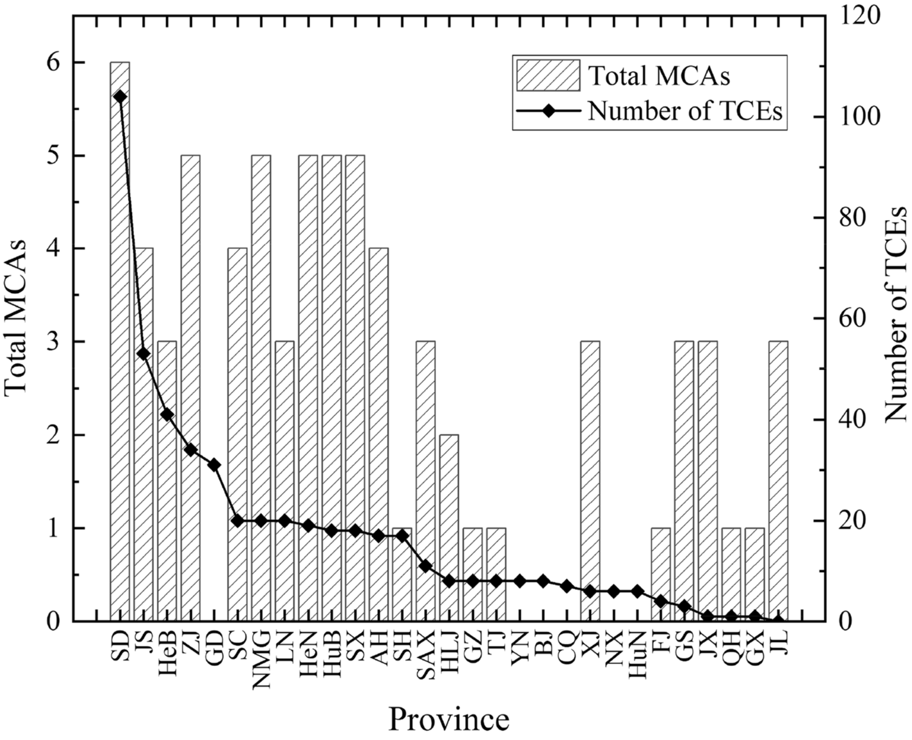

Fig. 8 Number of TCEs versus number of MCAs

occurred in the yellow and orange provinces, that is, the provinces with more TCEs. According to Table 4, Shandong Province has the highest TCEs (104) and MCAs (6) of all areas. It had experienced MCAs for three consecutive years. Jiangsu, which ranked second in the number of TCEs (53), also experienced four MCAs for three consecutive years. Similarly, Zhejiang had 34 TCEs and encountered 5 MCAs during this timeframe.

The regional disparities in the growth of the chemical sector affect the number of accidents, with chemical accidents occurring more frequently in economically developed provinces, such as the coastal provinces of eastern China (e.g., Shandong, Zhejiang, and Jiangsu). This can be attributed to the establishment of numerous chemical companies in these provinces, resulting in an increase in the occurrence of accidents. Several studies have documented this regional difference. [14, 23, 53, 62]. According to Table 4 and Fig. 8, Jilin does not have a leading chemical industry but witnessed three MCAs between 2017 and 2022. Jiangxi, Gansu, and Xinjiang, which had only one, three, and six TCEs, respectively, have also each witnessed three MCAs over the same period. Notably, Guangdong, which has the highest number of TCEs (31) in southern China, has not experienced any major accidents during this timeframe. Similarly, some provinces with a considerable number of TCEs, such as Yunnan, Beijing, Chongqing, Ningxia, and Hunan, recorded zero MCA cases, indicating a commendable level of chemical production management.

From another perspective, the pattern of decreasing accidents from east to west, as shown in Fig. 7, has resemblance to the spatial temperature distribution during the hot season. Consequently, it can be deduced that, apart from variations in economic prosperity, the effect of high temperatures on the number of accidents must not be underestimated. Geographical variations, which are also influenced by temperature, have a substantial impact on the frequency of hazardous-chemical accidents in China [53]. In conclusion, provinces with higher concentrations of chemical industries and less-developed regions deserve heightened attention. In less-developed areas such as Jilin, Jiangxi, and Xinjiang, stricter and regular monitoring of SM in chemical enterprises is imperative. The implementation of best practices from provinces with a commendable track record in SM, such as Guangdong Province, should also be extended to other regions [8].

3.7 Summary of characteristics of the investigated MCAs

This study of MCAs in China from 2017 to 2022 yields valuable insights into their characteristics and prevailing trends. The key findings are as follows:

1. From 2017 to 2022, the number of MCAs in China decreased. The fatality trend may be categorised into three periods: an increase from 2017 to 2019 with some severe accidents, followed by a significant drop in 2020, and a relatively stable period from 2020 to 2022. The MCAs in China resulted in a higher number of casualties than those in developed countries, primarily because of the larger workforce in Chinese chemical firms.
2. Another feature of MCAs in China from 2017 to 2022 is the seasonal pattern. MCAs are most common at the beginning and end of the year. In contrast, the MCAs decreased during the summer from March to June. This reduction in MCAs may be attributed to rigorous safety measures, decreased production, and adjusted schedules in Chinese chemical industries aimed at improving accident prevention during the summer.
3. This study demonstrates that explosions present the most significant hazard in MCAs, resulting in serious accidents and fatalities in the chemical industry. Poisoning and suffocation follow as subsequent hazards. Explosions are particularly dangerous because of the sudden release of energy, which initiates chain reactions including fires and further explosions. Accidents involving toxic chemical leaks are also a major concern because of their rapid spread, leading to injuries and oxygen displacement.
4. MCAs can occur at various stages, with the most frequent incidents occurring during production operations (26.4%), primarily owing to hazardous-chemical processes and high-risk conditions. Another stage with frequently occurring MCAs is hot-work operations, responsible for 19.4% of MCAs. This stage often involves the use of ignition sources and flammable materials. Maintenance operations contribute to 13.9% of MCAs, whereas confined-space operations account for 11.1% of accidents, owing to limited mobility and potential hazards in enclosed spaces. Such accidents tend to occur under specific circumstances involving hazardous operations. Therefore, countermeasures must be implemented to enhance safety in high-risk operational environments.
5. The causes of MCAs in China can be classified into two main categories: unsafe operating environments and improper personnel operations. Approximately 40% of cases were attributable to an unsafe operating environment. Improper personnel operations were responsible for 60% of the incidents among MCA cases. Underqualified operators who lack a strong safety culture and awareness may contribute to this risk.
6. The geographical distribution pattern of MCAs in China decreased from east to west, mirroring the temperature distribution during the hot season. This suggests that the effect of high temperatures on accident rates should not be underestimated. Economically advanced coastal provinces such as Shandong, Jiangsu, and Zhejiang, with a high concentration

of chemical companies, have experienced a greater number of accidents. However, less-developed regions, including Jilin, Gansu, Xinjiang, and Jiangxi, also report high accident rates. To enhance safety, it is vital to implement stricter monitoring of SM in provinces with numerous chemical companies and areas with lower safety levels. Adopting best practices from provinces with better safety records is essential.

4 Perspectives for sustainability of chemical industry

Severe chemical accidents are prevalent globally, and several countries are taking proactive steps to improve their safety standards and adopt measures to prevent them. The incorporation and utilisation of advanced and emerging technologies is imperative for enhancing operational safety and promoting sustainable development in the chemical industry [34]. Advanced information technologies, including Big Data, Cloud Computing, the Internet of Things (IoT), and Artificial Intelligence (AI), have been introduced into the management of production industries. Consequently, the advent of Industry 4.0 [5, 65] has brought about transformative innovations in the manufacturing sector, enabling traditional factories to evolve into smart factories by adopting smart devices, advanced monitoring systems, and digital information technologies. Embracing Industry 4.0 technologies has significant implications for optimising sustainable industrial management [19, 33]. Despite the wide use of digital environments in various industries, the chemical sector has been relatively slow in embracing these technologies [59]. Moreover, a comparison between China and Europe underscores the deficiency in digital capabilities in China's chemical industry. This is evident in the absence of chemical plant information management platforms, accident analysis systems, and novel technical instruments designed to improve chemical safety [8].

Given the pressing need for transformation and upgrading in the chemical manufacturing sector [26], emerging technologies such as IoT and AI are expected to play a pivotal role in modern factory management [31]. Digitalisation has the potential to significantly enhance the efficiency, quality, and safety of chemical production, which are crucial factors for achieving sustainability. The subsequent paragraphs focus primarily on innovative methods and practices derived from recent research to enhance production safety in the chemical industry, as safety is a vital element for achieving long-term sustainability. Figure 9 illustrates the corresponding flowchart outlining innovative approaches.

4.1 Risk assessment and management

Risk assessment is a crucial technique for SM and development [32]. A comprehensive risk assessment of chemical production involves the examination of a wide array of considerations [10]. Hazard and operability surveys, fault tree analysis (FTA), failure mode and effects analysis (FMEA), and safety checklist procedures are often used for assessment [35]. Unfortunately, each of these methods has limitations and does not accurately fulfil the safety evaluation function [37, 60]. It is now feasible to conduct risk assessments and safety evaluations of chemical production through process simulations and intelligent technology to prevent losses and establish a safe production environment [48, 67].

4.1.1 Artificial neural networks

Accidents occurring in chemical production facilities are characterised by randomness, ambiguity, and uncertainty, lacking adherence to specific rules or procedures [24]. These traits bear resemblance to the features of artificial neural networks, which establish the potential and remarkable malleability of artificial neural networks for use in chemical production safety assessments [48]. Yang [60] established a safety assessment system for chemical enterprises by considering the features of the artificial neural network. The model consists of two levels and five neural networks. It covers physical, human operation, SM, and operational environmental factors. It overcomes the limitations of traditional evaluation methods, produces more scientific evaluation results, and minimises the risk of chemical production maps.

4.1.2 Bayesian networks

Graphical modelling techniques such as Bayesian networks are rapidly gaining traction for assessing risk in chemical process systems. Guo et al. [22] presented a Bayesian network model based on copula functions for industrial production processes. The model helps to overcome the challenges of nonlinear relationships, successfully mitigating the limitations of other risk analysis methods. The model has been validated in practical case studies and can be effective in preventing accidents [4]. Similarly, Pan et al. [45] developed a risk analysis model utilising Bayesian networks that incorporated a comprehensive weight parameter that blended subjective and objective weights. To overcome challenges in obtaining accurate conditional probability parameters in traditional Bayesian networks, they employed a hybrid approach combining fuzzy set theory with a noisy-OR gate model. The effectiveness of the proposed methodology was

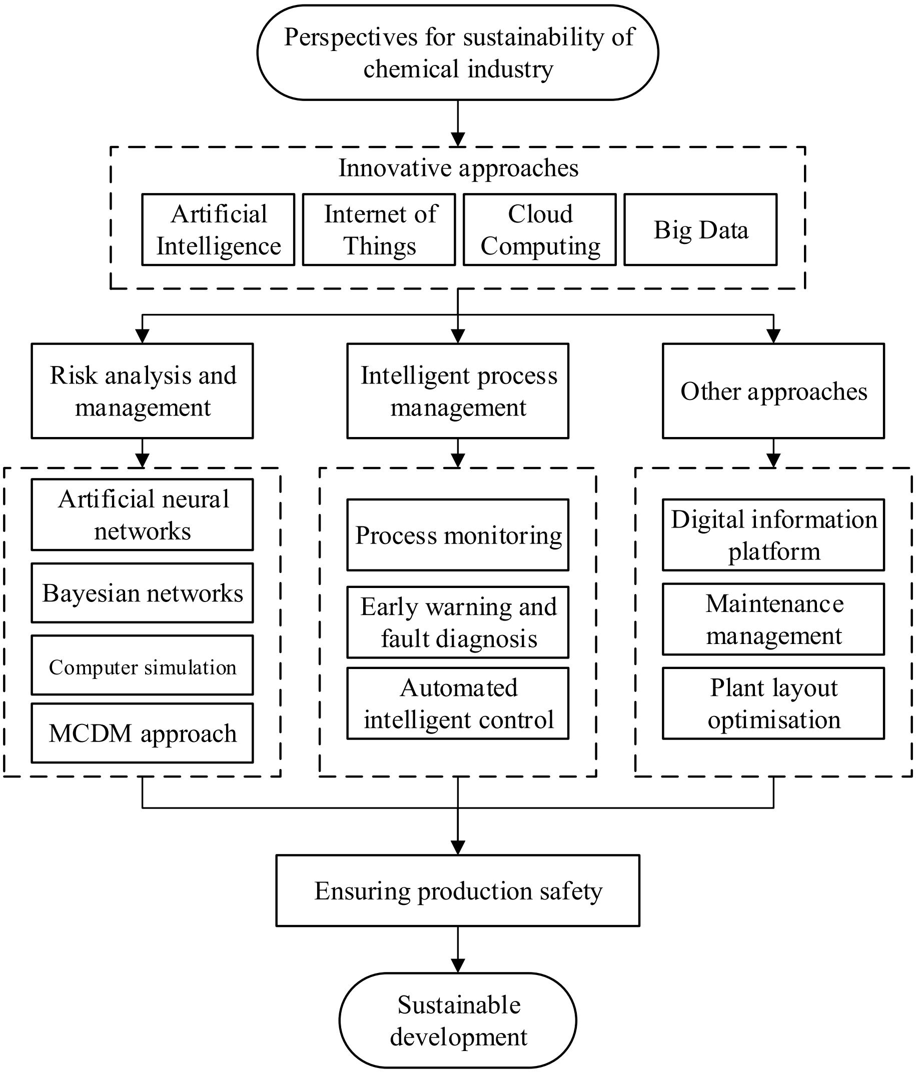

Fig. 9 Methods for the sustainable evolution of the chemical industry

demonstrated through a case study conducted at a petrochemical enterprise.

4.1.3 Computer simulation

Graf and Schmidt-Traub [20] proposed a unique method for identifying process hazards based on computer simulations and statistical analyses. Initially, qualitative equipment models were developed, implemented, and stored in a model library using state-diagram language. Appropriate equipment models were then extracted from the model library and integrated to produce a qualitative plant model expressed as a state diagram. Special safety issues can be solved through reachability checks of the plant states in the model [57]. The method has been applied to an example plant, and the results demonstrate the potential efficacy of this novel approach.

4.1.4 Multicriteria decision-making (MCDM) approach

Multicriteria decision-making (MCDM) is widely used in various research domains to address complex problems with high effectiveness in risk analyses [51]. For example, Lyu and Yin [36] introduced an MCDM approach to assess multiple hazard risks in Hong Kong, including flooding and landslides, indicating promising accuracy in identifying high-risk areas. However, the application of MCDM techniques to risk assessment in chemical factory production is limited. Marhavilas et al. [38] introduced a risk assessment approach combining the AHP with safety-level coloured maps (SLCM) to assess safety and health risks in a petrochemical workplace. This method effectively identified high-risk areas, enabling the optimisation of safety measures and resource allocation. The integration of MCDM and AI techniques in the management of chemical factory production has the potential to significantly reduce production risks and enhance employee safety.

4.2 Intelligent process management

The highly nonlinear behaviour of chemical processes poses many challenges to the chemical industry [24, 60]. However, with the emergence of novel technologies, new opportunities have become available to address these challenges. For example, studies have shown that AI can improve the reliability and accuracy of abnormal situation detection, enhance process monitoring and fault diagnosis, and increase overall chemical production safety [61]. Therefore, better chemical plant process management can be achieved using advanced sensing technologies, intelligent instruments and equipment, data-analysis algorithms, and other methods to comprehensively monitor and control chemical production processes [48, 61]. The goal is to increase the automation level, production efficiency, and safety of the chemical production process; reduce production costs; and ensure the safety of the production environment and personnel.

4.2.1 Process monitoring

Modern chemical plants are complex and integrated systems in which operators find it challenging to access all relevant information and make prompt decisions to control anomalous events. Therefore, a real-time process-monitoring system is required. Natarajan and Srinivasan [41] presented a multi-agent-based process-monitoring system called ENCORE, which was demonstrated to be advantageous through case studies in chemical production. ENCORE is characterised by its ability to seamlessly collaborate with modern automation systems, external applications, and software to deliver diagnostic results in the required formats. In addition, it employs coordinated decision-making and multiple process-monitoring methods that are adaptable to various sections, equipment, and instruments, facilitating the exchange of diagnostic results. Moreover, ENCORE demonstrates scalability and is effortlessly integrated with technologies such as Java, MATLAB, new monitoring technologies, and other AI technologies. These features render ENCORE an ideal choice for process monitoring in chemical plants.

4.2.2 Early warning and fault diagnosis

New technologies such as machine learning, deep learning, and expert systems are increasingly being utilised for real-time data analysis in chemical production processes. By monitoring various parameters, such as temperature, pressure, liquid level, and gas concentration, these technologies can detect anomalies and provide early warning signals for abnormal data, thereby improving the accuracy of identifying equipment defects and enhancing process monitoring and fault diagnostics. Research has shown that the use of AI in chemical production enhances safety [16, 61]. For example, Wang [58] proposed a deep learning and AI-based industrial safety production supervision system that integrates industrial plant output data with fundamental theories of safety supervision and early warning. This system offers management measures to increase enterprise safety, enabling the effective control of production safety hazards through early warnings and intelligent operations.

To improve the safety of hazardous-chemical factories, Fang et al. [17] presented an intelligent security system based on AI, the IoT, and other information technologies. This system leverages cameras and factory and workshop sensors to monitor and warn against unsafe behaviours, unsafe conditions of plant equipment and facilities, and adverse environmental factors. By comprehensively assessing the safety status of chemical plants, this technology provides an accurate basis for assessing the safety production status and implementing targeted improvement strategies, thereby enhancing the efficacy of everyday safety monitoring and management and reducing the probability of accidents involving hazardous chemicals.

4.2.3 Automated intelligent control

Intelligent control involves the automated regulation of chemical production processes in real time through the analysis and processing of monitored data. It is crucial to maintain safety and prevent resource and financial losses. Sahebjamnia et al. [47] presented a fuzzy Q-learning multi-agent quality control system (FQL-MAQCS) for controlling continuous chemical production lines. The proposed system leverages a multi-agent system for controlling unexpected situations, comprising a quality checker, process data scrutineer, central decider, part decider, knowledge, and a regulation management agent. Additionally, the system incorporates a self-education mechanism that gradually develops knowledge based on the learning results, which are stored in the knowledge base. Furthermore, a fuzzy Q-learning approach and rule-formation mechanism were used to construct the system. Case studies were conducted to evaluate the usefulness of the newly implemented quality control system and, the results validated the usefulness of the proposed FQL-MAQCS.

Ji et al. [30] suggested that multi-device collaborative control is a fundamental requirement for intelligent chemical manufacturing in the chemical industry. This represents a crucial feature that sets it apart from traditional process control and aligns with technological advancements and emerging industry trends. Therefore, they recommended an astute chemical system founded on a cyber-physical system with key technologies, including Big Data and online modelling, which can be employed to evaluate equipment operation status, recognise irregularities, and examine multidevice collaboration. Experimental results show that this system is robust and can amplify the optimal control level of the entire production system.

4.3 Other innovative approaches

4.3.1 Digital information platform

Despite the alarming frequency of chemical accidents in China, a consistent and adequate system for collecting and preserving information related to such accidents is conspicuously absent. A national management system is in high demand to coordinate consistent chemical risk and accident information using mobile devices [8, 23, 52]. Several studies have concluded that a digital information system is necessary for the effective regulation of dangerous chemical use. If a uniform regulatory system is in place and all data concerning hazardous chemicals are input and exchanged, the production, usage, and expulsion of hazardous chemicals can be managed through regulation. Consequently, each province can gain a comprehensive understanding of its situation, thereby preventing chemical accidents more effectively [63]. Moreover, an accident collection platform is required. By gathering vast quantities of chemical safety accident data, companies can learn from these events and better prevent accidents. For instance, Jing and Han [31] developed an AI-based method for mining the causes of production accidents to take full advantage of accident data. By initially ascertaining the accident information, identifying safety issues, this model can leverage the valuable information from past accident records and offer efficient recommendations for accident prevention.

It would be advantageous to have a digital management platform for chemical parks. The prevailing circumstance in contemporary chemical parks is that most chemical plants have preventive and protective measures that disregard the fact that other plants process or store hazardous materials in their vicinity, which poses a major accident risk. Therefore, Reniers et al. [46] created and implemented a cluster SM system within a chemical park that permits full cooperation and interchange of all essential information between chemical plants, thereby minimising chemical risks in their area. This effort has led to the establishment of detailed criteria for the SM of chemical parks.

4.3.2 Managing imperfect maintenance actions

The durability of components in chemical plants has a significant impact on both the safety and efficiency of production and is subject to the influence of maintenance strategies [18]. Owing to the complexity of technology, labour, and resources, failure to maintain defective components properly may result in serious accidents and personal injuries [55, 56]. Traditional control techniques have limitations in fully investigating the complex process configuration of chemical plants, necessitating new strategies such as intelligent maintenance management systems to assess and track the mechanical level of chemical plants and improve the durability of their components.

Ismail [27] proposed a novel approach for automating the safe maintenance of components and facilities in chemical plants. This involves integrating programme-integrated control methods into a system of unified automation models to enhance the diagnostic capabilities of plant facilities and facilitate subsequent risk management. This system enables chemical plant operators to handle test data for risk assessment and analysis, select suitable operating conditions and monitoring requirements, and enhance safety measures. Managers can also identify potential risks leading to project failure, thereby reducing losses and achieving optimal production and operational goals in a safer working environment while mitigating environmental hazards and chemical accidents.

4.3.3 Plant layout optimisation

The design of the process layouts for chemical plants is complex. Jung [28] introduced an approach for optimising plant layouts that could enhance chemical process safety by combining process safety and quantitative risk analysis into the models used to tackle plant layout issues. Moreover, computer-aided plant design, optimisation, and consequence analysis were combined with consequence analysis using 3D simulation programmes (e.g., toxic gas diffusion and its mitigation, as well as fire and explosion risks). This plant layout optimisation approach may assist designers in devising layouts with minimal hazards and in determining whether the proposed plant is cost-efficient and secure.

4.4 Applications and limitations of sustainable management strategies

Previously mentioned strategies, such as a multi-agent system for process supervision [41], have demonstrated practical applications. This system was tested in an oil and gas production process, revealing that it could optimise the entire production process to maximise efficiency and ensure safety. However, its effectiveness in larger plants remains unclear. In addition, potential sensor malfunctions may lead to system errors, requiring correct judgement from operators. Guo et al. [22] proposed a copula-based Bayesian network risk assessment model applied to the process flow of a petrochemical plant to effectively predict accident probabilities. However, further testing is necessary to ensure its broader applicability. It is noted that the application of these innovative technologies mostly involves proposing a framework or applying them to small-scale chemical processes. The validation of the generalisability of practical implementation and improvement of overall chemical plant management at large is yet to be performed. Furthermore, the aforementioned methods are relatively singular, and no case studies have comprehensively integrated these approaches. Additionally, these methods are considered supportive mechanisms for operators, emphasising the importance of highly skilled operators in the field.

5 Conclusions

This study analysed the trends and characteristics of MCAs in China from 2017 to 2022 by considering the annual accident numbers, fatalities, monthly distribution, accident types, stages, direct causes, and geographical distribution. This study also provided insight into the integration of novel technologies to enhance the safety in chemical production processes. The following conclusions were drawn:

1. MCAs often occur in stages where hazards are easily accessible. The production stage accounted for nearly one-third of all cases, followed by hot work, maintenance, and confined-space operations. Safety measures must be implemented to ensure production safety during high-risk stages. For hot-work operations, special measures include controlling ignition sources, providing firefighting equipment, and wearing protective gear. Ventilation, air-quality monitoring, and emergency rescue plans are necessary for confined-space operations.
2. Almost 60% of MCAs in China are attributed to improper personnel operations, which generally result from employees' limited safety awareness and qualifications. The effective mitigation of risks in the Chinese chemical industry requires a holistic approach to address infrastructure concerns and human-related factors. This approach encompasses education, training, safety culture enhancement, infrastructure enhancements, and the enforcement of stringent safety regulations to foster a safer working environment.
3. MCAs occur more frequently in economically developed regions, owing to a higher concentration of chemical industries. Simultaneously, some less-developed areas had comparatively lower safety standards. Provinces with a substantial number of chemical industries and provinces with lower safety levels should prioritise adopting countermeasures to avoid MCAs. Implementing successful SM practices from provinces (e.g., Guangdong and Yunnan) with strong safety records should be introduced to other areas.
4. The adoption of emerging technologies is vital to enhance the safety of chemical production and ensure sustainable growth. These techniques include real-time process monitoring, warning and fault diagnosis systems, and automated intelligent control systems. These technologies use advanced sensors, intelligent tools, and data-analysis algorithms to monitor, alert, and manage chemical production. Other innovative strategies, such as digital platforms and optimised factory layouts, can also improve the safety and efficiency of chemical production.

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Authors' contributions
Hao-Yuan Liang: Investigation, Software, Data curation, Writing-Original draft preparation; Tao Yan: Conceptualization, Investigation, Data curation, Software, Methodology, Writing-Reviewing and Editing; Wei-Wei Zhao: Investigation, Software, Data curation, Writing-Reviewing and Editing.

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Availability of data and materials
Data will be available on reasonable request.

Declarations

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

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