Exploring the Key Direct Causes of Hazardous Chemical Explosion Accidents Using Association Rules

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Abstract

Hazardous chemical accidents pose a serious threat to human life and economic activities. To explore the causes of hazardous chemical explosions in China, this study utilized official data to analyze 242 hazardous chemical accidents in China from 1982 to 2024 based on five aspects: accident locations, times, types, types of hazardous chemicals involved, and direct causes. Through association rule mining (AR), key reasons for hazardous chemical explosion accidents (HCEAs) were identified. The results indicate that human errors are the primary cause of HCEAs, and effective safety management by companies plays a crucial role in reducing human errors and mitigating accident risks. This study can serve as a reference for both domestic and international chemical plants in preventing hazardous chemical accidents and strengthening preventive measures.

Key words: Hazardous Chemical Explosion Accidents (HCEAs); Association rule; Safety management

I. Introduction

Hazardous chemicals generally refer to highly toxic chemicals and other substances that are harmful to human health, facilities, and the environment due to their toxicity, corrosiveness, flammability, explosiveness, and other hazardous properties (State Council of the People's Republic of China, 2011). They are prone to accidents, resulting in significant casualties and property damage, while also exerting adverse effects on the air, water, and soil (Wang et al., 2018; Yang et al., 2020; Chen and Reniers, 2020).

The chemical industry is a cornerstone industry in China and a traditional advantage industry, with China being the world's largest producer of chemicals. These factors significantly escalate the pressure on China's prevention of hazardous chemical accidents. According to statistics, from 2016 to 2023, China experienced a total of 1188 hazardous chemical accidents, resulting in 1549 fatalities. Among these incidents, Hazardous Chemical Explosions (HCEAs) are the predominant type and often lead to the highest casualties (Wang et al., 2021). For instance, in July 2015, an explosion at a chemical warehouse in Tianjin resulted in 165 fatalities and 789 injuries (Zhao, 2016). In March 2019, an explosion at a chemical plant in Jiangsu Province caused 78 deaths and 76 injuries (Wang and Zhu, 2020).

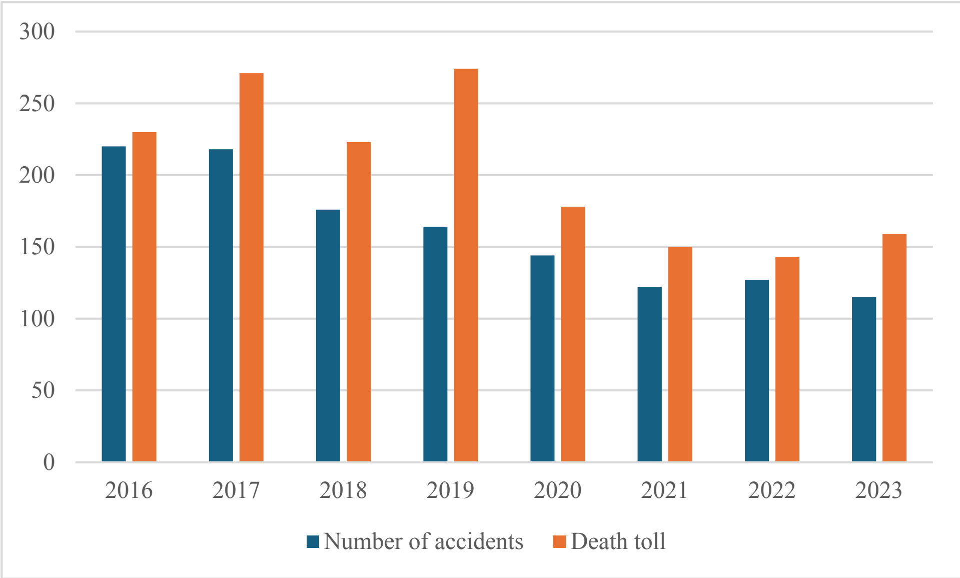

Figure 1 Number of hazardous chemical accidents and death toll in China from 2016 to 2023

Many researchers have conducted statistical surveys on hazardous chemical accidents in China. For instance, Duan et al. (2011) analyzed hazardous chemical accidents in China from 2000 to 2006. Zhang and Zheng (2012) studied the statistical characteristics of 1,632 hazardous chemical accidents in China between 2006 and 2010. They analyzed data on 976 significant hazardous chemical accidents recorded in China from 1970 to 2009 and identified necessary improvements for developing comprehensive risk management. Furthermore, Wang et al. (2018a) conducted a comprehensive statistical analysis of hazardous chemical accidents in China to assess the future of chemical safety in the country. Several scholars (e.g., Lecue and Darbra, 2019; Gunasekera and de Alwis, 2008) have also investigated and analyzed hazardous chemical accidents in other countries.

Hazardous chemical accidents are typically caused by a combination of factors (Nivolianitou et al., 2006). Research on hazardous chemical accidents largely attributes the occurrence of such accidents to Unsafe behaviors of individuals, Unsafe states of materials, Unsafe environments, and Defects in organizational management. Understanding the patterns of historical hazardous chemical accidents and their key direct causes is crucial for effective prevention and scientific response to such accidents. For example, Jiang et al. (2020) and Li et al. (2019) analyzed the impact of unsafe behaviors on hazardous chemical storage accidents. Liu et al. (2021) developed a network model for chemical accidents and found that human unsafe behaviors and unsafe environmental conditions accounted for the highest proportion (87.5%). Zhang et al. (2020) suggested that over 80% of accidents are triggered by unsafe human behaviors. Niu et al. (2019) utilized data mining techniques to analyze data from 1,578 chemical incidents and found that human errors and management deficiencies were the primary causes of accidents.

In terms of analytical methods, Mousa (2021) employed fuzzy Analytic Hierarchy Process to evaluate the fuzzy risks of pipeline fires, explosions, and toxic gas releases, and determined fuzzy risk levels based on five national standards. Shi et al (2014) utilized fault tree analysis to investigate fires and explosions in hazardous chemical tanks and oil depots. Additionally, the academic community has extensively applied Bayesian Network Fault Trees (BN-FT) to accident chain analysis in various domains including oil tanker transportation, waste heat exclusion systems, underwater pipeline leaks, and smoke emissions, among others. However, the construction and use of the aforementioned models or methods heavily rely on the experience of authors or experts, leading to significant subjectivity that can impact the reliability of risk analysis results.

Studies indicate that incorporating objective data can reduce the subjectivity of risk analysis, hence Association Rules (AR) hold promising applications in accident data mining. Li et al. (2017) used AR technology to explore the relationships between influencing factors and not wearing helmets. Wang et al. enhanced the effectiveness of workplace hazard identification using AR. Chen et al. (2020) investigated the role of human factors in ship navigation accidents through AR technology. Cabello et al. (2021) identified the main influencing factors of construction phase accidents using AR. Therefore, AR is considered a tool for integrating objective data in this work. This study aims to conduct causal analysis of HCEAs based on describing and summarizing the characteristics of hazardous chemical accidents in China from 1982 to 2024, and propose specific strategies and recommendations for preventing HCEAs.

The remaining structure of this study is as follows: Section 2 introduces the sources of HCEAs data and their accident factors, outlining the analytical process of the article. Section 3 describes the characteristics of hazardous chemical accidents. Section 4 presents the specific application process of AR and the analysis results of key direct factors of HCEAs. Section 5 provides targeted strategies and recommendations for preventing HCEAs. Section 6 summarizes the research content and limitations of this study, and suggests future research plans.

II. Materials and Methods

1. Data sources

The data sources of this study mainly consist of two entities: the Ministry of Emergency Management of the People's Republic of China and the China Chemical Safety Association (CCSA). The Ministry of Emergency Management of the People's Republic of China was established in 2018 and is the most common source of statistical data for various accidents, including hazardous chemical accidents, in China. The CCSA, founded in 2006, is a social organization in China dedicated to chemical safety exchanges. Scholars can access detailed reports on hazardous chemical accidents from these two official websites.

A total of 242 cases of hazardous chemical accidents were collected from the aforementioned official websites for this study, spanning from 1982 to 2024. The study conducted statistical analysis on the geographical locations, types, direct causes, types of hazardous chemicals involved, the number of fatalities, and the number of injuries reported in the investigation reports. Furthermore, the study categorized the direct causes of accidents to gain a clearer understanding of the impacts of different causal factors.

2. Methods

The analysis of hazardous chemical accidents in this study is primarily composed of two parts: the description of accident characteristics and the exploration of key direct causes. In the first part of the analysis, this study conducted statistical analysis on the basic information of hazardous chemical accidents in China, describing accident characteristics in terms of geographical locations, temporal variations, types of accidents, severity, and other aspects. In the second part of the analysis, the study focused on the key direct causes of explosion accidents in hazardous chemical incidents, extracting 150 HCEAs from a total of 242 accidents, and utilizing AR to determine the correlation between various factors and HCEAs.

III. Characteristics of hazardous chemical accidents

1. Provincial location distribution

The chemical industry is a traditional pillar industry in China. In 2023, the operating revenue of China's petroleum and chemical industry reached 15.95 trillion yuan, with a total profit of 873.36 billion yuan. Chemical enterprises and factories in China are mainly concentrated in regions such as Hebei, Shandong, Jiangsu, Liaoning, and Tianjin, which also increases the likelihood of hazardous chemical accidents in these areas. Figure 2 illustrates the locations and frequencies of these 242 accidents, with darker colors indicating higher frequencies of accidents. Figure 3 shows the number of deaths and injuries caused by hazardous chemical accidents in various regions. In these regions where the development of the chemical industry is emphasized, the number of casualties far exceeds that of other provinces. This may be due to the higher frequency of hazardous chemical accidents in these regions or a major incident causing significant casualties.

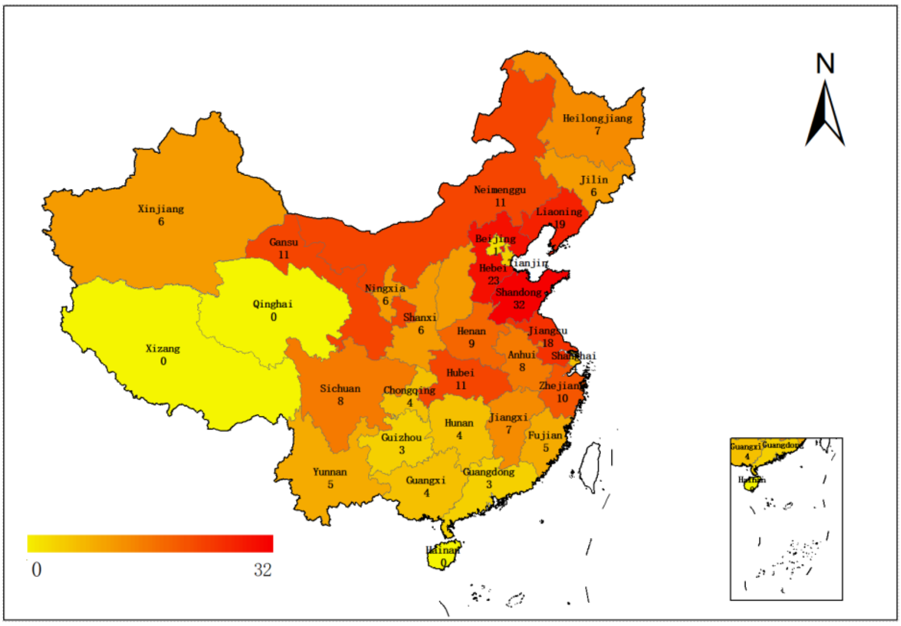

Figure 2 Provincial distribution of hazardous chemical accidents in China (mainland only). Note: Beijing, Tianjin, Shanghai, and Chongqing are municipalities.

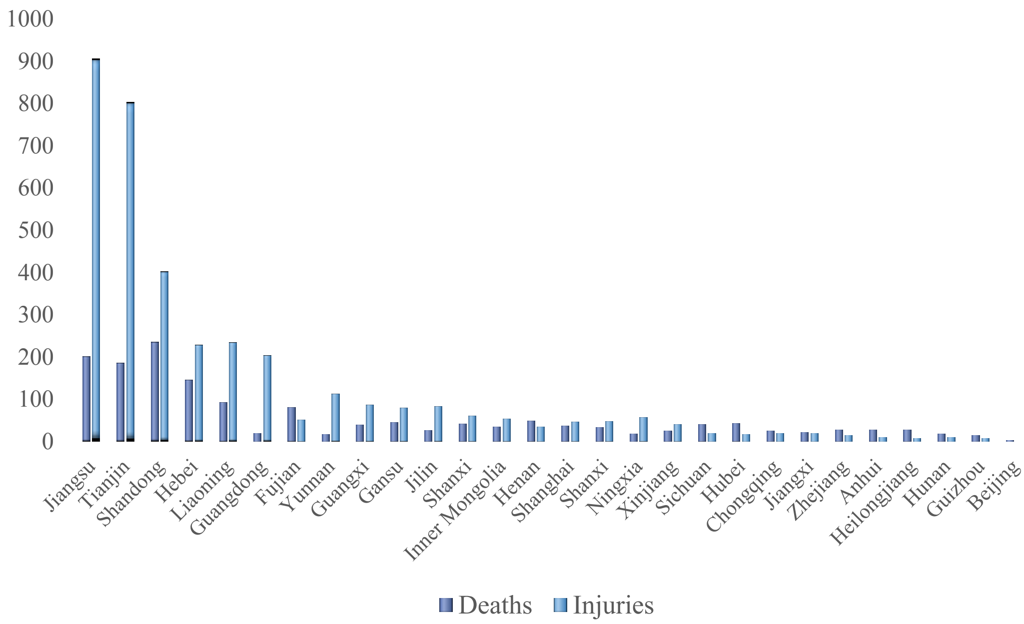

Figure 3 Provincial distribution of deaths and injuries from hazardous chemical accidents (mainland only). Note: Beijing, Tianjin, Shanghai, and Chongqing are municipalities.

2. Time-volatility characteristics

The present study summarizes the occurrence of hazardous chemical accidents on a quarterly and monthly basis.

From Figures 4 and 5, it is evident that the highest number of accidents occurred in the fourth quarter, while the lowest number occurred in the third quarter. Previous research has often posited that the high temperatures in July to September exacerbate the instability of hazardous chemicals, thereby increasing the likelihood of accidents. However, the reality is that more accidents occur during the colder months of October to December. This may be attributed to individuals in low-temperature environments exhibiting slower reactions and actions, leading to an increased propensity for erroneous decision-making. Additionally, equipment operating in cold environments may experience heightened energy consumption and face elevated quality demands.

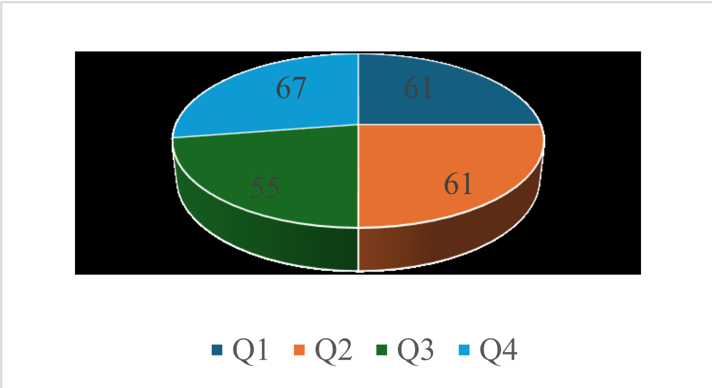

Figure 4 The number of hazardous chemical accidents that occur each quarter.

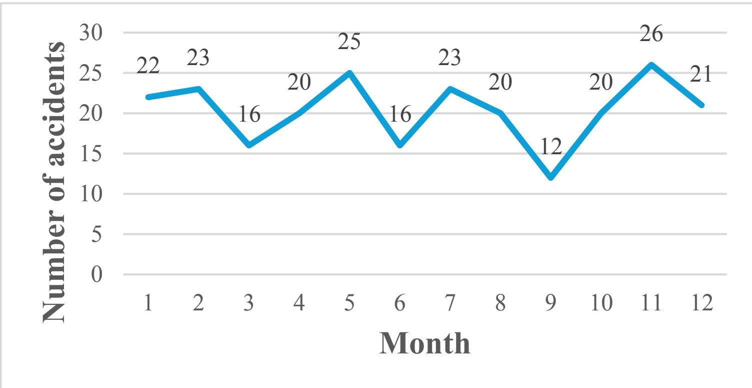

Figure 5 The number of hazardous chemical accidents that occur each month.

3. Accident types

The production processes and operational environments in the hazardous chemical industry are intricate, giving rise to various types of chemical accidents, including explosions, fires, leaks, poisonings, asphyxiations, burns, radiation, and others (Pan and Jiang, 2002; Yu et al., 2009). The 242 accidents collected in this study primarily involve four of these types: explosions, fires, poisonings, asphyxiations, and burns, with some incidents involving multiple types simultaneously. Additionally, there was one scalding accident and one mechanical injury incident. The specific distribution and statistical results of casualties for each type of accident are detailed in Table 1.

The findings indicate that explosions and fires are the primary types of hazardous chemical accidents, aligning with the mechanisms of such accidents. Explosions typically occur first, leading to subsequent fires and other incidents (Hemmatian et al., 2014). Among the individual types of accidents, cases involving explosions were the most prevalent, totaling 150 instances. These incidents also resulted in the highest number of casualties, reaching 3,106 individuals, representing 84.98% of the total casualties. Therefore, preventing explosions and fires should be a focal point in China's efforts to prevent and control hazardous chemical accidents.

Table 1 Statistical investigation of hazardous chemical accident types.

Accident types	Number of accidents	Percentage	Deaths	Percentage	Injuries	Percentage
Explosion	150	61.98%	1260	80.00%	3106	84.98%
Fire	53	21.90%	480	30.48%	1366	37.37%
Poisoning	62	25.62%	223	14.16%	486	13.30%
Asphyxia	20	8.26%	64	4.06%	18	0.49%
Mechanical injury	1	0.41%	5	0.32%	16	0.44%
Empyrosis	1	0.41%	3	0.19%	0	0.00%
Total	242	100%	1575	100%	3655	100%

4. Categories of hazardous chemicals

This study categorized the hazardous chemicals involved in the 242 cases into six categories based on "Classification and Code of Dangerous Goods" (GB 6944-2012) (National Standardization Technical Committee for Hazardous Chemicals, 2012). The categories include explosives, flammable gases, toxic gases, flammable liquids, flammable solids, and corrosive substances. Figure 6 illustrates the casualties associated with different categories of hazardous chemicals in the accidents.

In terms of quantity, the most common hazardous chemicals causing accidents were explosives (116 cases) and toxic gases (72 cases), accounting for 47.93% and 29.75% of the total accidents, respectively. The most severe casualties were caused by flammable solids, followed by explosives and toxic gases. Despite the relatively low number of accidents involving flammable solids (10 cases), the consequences can be extremely severe once an incident occurs. Therefore, enhancing safety management for flammable solids in enterprises is imperative.

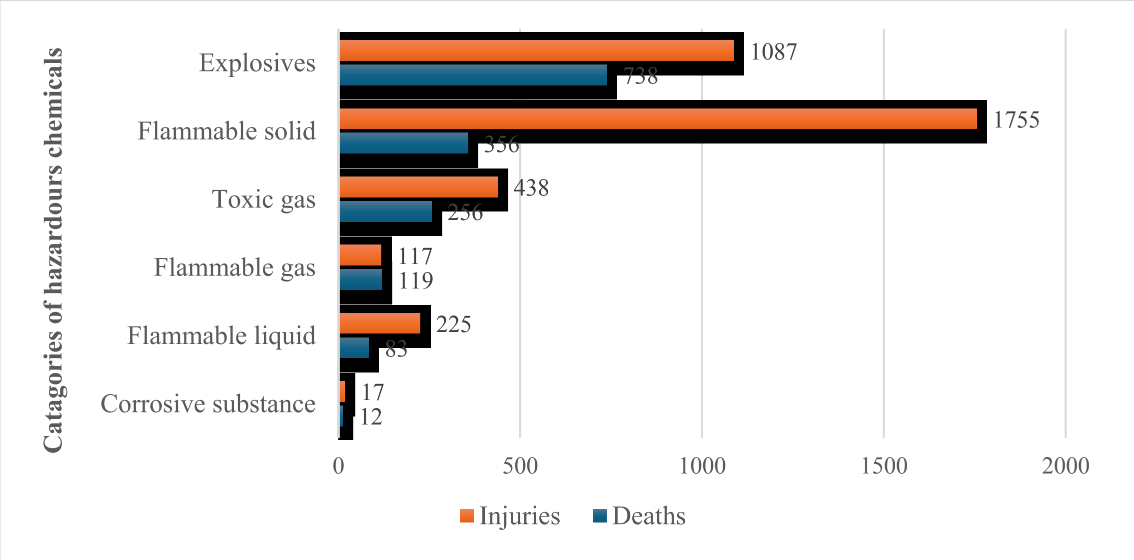

Figure 6 Casualties from various hazardous chemical accidents.

IV. Key Direct Cause Analysis of HCEAs Based on AR

The occurrence of hazardous chemical accidents is often the result of multiple interacting factors, and the objective of this study is to identify the most immediate causes. Based on the analysis of the direct causes of accidents provided by the Ministry of Emergency Management of the People's Republic of China and the official website of CCSA, as well as the widely used accident cause classification methods in previous studies, this study ultimately identified 29 accident causes from the 242 cases. These causes were categorized into Unsafe behaviors of individuals, Unsafe state of materials, Unsafe environment, and Defects of organizational management (refer to Table 2). It is important to note that a single direct cause may fall into multiple categories simultaneously.

Table 2 Causal factors of hazardous chemical accidents

Category	Code	Accident factors
Unsafe behaviors of individual (R)	R1	Unprofessional or inexperienced employees
	R2	Leaving the post without authorization
	R3	Insufficient pre-operation environment check
	R4	Not wearing protective equipment

	R5	Unclear material properties, reaction mechanisms, and operating procedures
	R6	Untimely handling of hidden dangers
	R7	Wrong material input
	R8	Equipment operation error
	R9	Sparking during the use of tools
	R10	Insufficient air purification and replacement
	R11	Improper cooling operation
	R12	Improper hot operation
	R13	Improper temperature control
	R14	Improper disposal of waste or residues
	R15	Violation of regulations
	R16	Illegal production, sale and use of dangerous chemicals
	R17	Blind rescue
Unsafe state of matters (W)	W1	Equipment aging, leakage or malfunction
	W2	Safety valve not installed or malfunctioning
	W3	Inadequate reaction of materials
	W4	Equipment quality is unqualified
Unsafe environment (H)	H1	Mixed explosive gas or substance environment
	H2	Chaotic production environment layout
	G1	Inadequate supervision of the work site
	G2	Insufficient supervision of regulatory implementation
Defects of organizational management (G)	G3	Inadequate equipment maintenance and overhaul
	G4	Inadequate investigation and management of hidden dangers
	G5	Insufficient security measures
	G6	Accident emergency response failure

1. Types of direct cause of HCEAs

From Table 3, it is evident that the highest number of accidents and casualties are attributed to Unsafe behaviors of individuals and Unsafe state of materials. Specifically, 192 accidents were directly linked to Unsafe behaviors of individuals, resulting in 1,095 deaths, accounting for nearly 70% of the total. It is worth noting that inadequate safety management in enterprises can also lead to an increased likelihood of accidents and a higher number of casualties.

Table 3 Causes and casualties of hazardous chemical accidents

Causes	Number of accidents	Percentages	Deaths	Percentages	Injuries	Percentages
Unsafe state of matters	88	36.36%	722	45.84%	1787	48.89%
Unsafe behaviors of individual	192	79.34%	1095	69.52%	2152	58.88%
Unsafe environment	18	7.44%	257	16.32%	1170	32.01%
Defects of organizational management	83	34.30%	658	41.78%	1466	40.11%

2. The AR methods and analysis results

In order to more comprehensively analyze the direct causes of HCEAs and extract the most significant key factors influencing them, this study chose to utilize AR. AR is a data mining method that can discover correlations between different factors in similar events and extract subsets of frequent factors within events. This method operates based on the Apriori algorithm. The Apriori algorithm is a recursive algorithm that generates frequent k-item sets, frequent k + 1-item sets, and so on, through multiple scans of statistical data. The algorithm covers three metrics for measuring AR: support, confidence, and lift. The specific calculation formulas are as follows:

$$S(A \Rightarrow B) = P(A \cap B) = \frac{|A \cup B|}{|D|} \tag{1}$$

In equation (1), A and B are two distinct item sets, |D| represents the transaction set; S(A⇒B) denotes the support of the association from A to B; |A∩B| indicates the number of occurrences where both sets A and B appear together in the transaction set. The support of the association from A to B signifies the probability of A and B occurring together. A high probability of simultaneous occurrence can demonstrate a strong correlation between the two.

$$C(A \Rightarrow B) = P(B|A) = \frac{|A \cup B|}{A} \tag{2}$$

In equation (2), C(A⇒B) represents the confidence of the association from A to B, indicating the probability of B occurring given the occurrence of A. High confidence signifies the presence of a strong causal relationship, implying that the occurrence of A significantly leads to the occurrence of B.

$$L(A \Rightarrow B) = \frac{C(A \Rightarrow B)}{S(B)} = \frac{S(AB)}{S(A) \times S(B)} \tag{3}$$

In equation (3), L(A⇒B) represents the lift of the association between A and B, which is the ratio of the probability of B occurring given the occurrence of A to the probability of B occurring independently. When L = 1, A and B are unrelated. When L < 1, the probability of B occurring given the occurrence of A is lower than the probability of B occurring independently, indicating a negative impact of A on B's occurrence. Conversely, when L > 1, the probability of B occurring given the occurrence of A is higher than the probability of B occurring independently, indicating a positive impact of A on B's occurrence.

The specific calculation process for AR is as follows:

Step 1: Utilize the Apriori algorithm to calculate the support, confidence, and lift of accident factors and HCEAs.

Step 2: Aggregate the AR between accident factors and HCEAs.

Step 3: Based on actual circumstances and objective observations, select effective AR values between accident factors and HCEAs.

Step 4: Determine the direct factors leading to the occurrence of HCEAs.

To obtain ARs, minimum support and confidence levels need to be set. Since this study focuses solely on HCEAs, the confidence between the causes and HCEAs remains at 100%, and the lift remains at 1.007. Therefore, adjusting the minimum support incrementally is sufficient. However, existing research on ARs does not provide a definitive standard for setting the minimum support level. Instead, thresholds are adjusted based on practical needs to determine the appropriate minimum support. In this study, the minimum support is set at 6%, resulting in 23 ARs between accident factors and HCEAs. The top 10 ARs based on support are shown in Table 4.

It is evident that the key direct factors contributing to HCEAs are primarily related to Unsafe behaviors of individuals and Unsafe state of materials, including Equipment aging, leakage, or malfunction, Violation of regulations, Equipment operation error, Improper temperature control, Wrong material input, among others. Among the key direct factors related to Defects of organizational management, Insufficient supervision of the work site and Insufficient supervision of regulatory implementation are more likely to co-occur and lead to HCEAs.

Table 4 ARs for determining direct causes

Association Rules	Support	Confidence	Lift
Equipment aging, leakage or malfunction ⇒ HCEA	37.086	100	1.007
Violation of regulations ⇒ HCEA	26.490	100	1.007
Violation of regulations, Insufficient supervision of regulatory implementation ⇒ HCEA	22.517	100	1.007
Equipment operation error ⇒ HCEA	21.192	100	1.007
Improper temperature control ⇒ HCEA	19.868	100	1.007
Wrong material input ⇒ HCEA	18.543	100	1.007
Inadequate supervision of the work site ⇒ HCEA	15.232	100	1.007
Sparking during the use of tools ⇒ HCEA	14.570	100	1.007
Improper disposal of waste or residues⇒ HCEA	9.934	100	1.007
Inadequate supervision of the worksite, Insufficient supervision of regulatory implementation ⇒ HCEA	9.934	100	1.007

In this study, ARs were further analyzed among the 29 factors. Through trial and error, a suitable quantity of ARs that are easy to analyze was obtained by setting a minimum support of 5% and a minimum confidence of 60%. A total of 32 ARs were generated. After removing some ARs that did not align with actual scenarios, the top ten ARs were arranged based on confidence in descending order, as shown in Table 5.

It can be observed that the lack of equipment quality can lead to equipment aging, leakage, or malfunction, while sparking during tool use and violation of regulations can result in improper hot operations. Of particular note, the findings underscore that defects in organizational management within chemical enterprises are the primary cause of the occurrence of the other three factors, thereby increasing the likelihood of HCEAs. Specifically, insufficient supervision of regulatory compliance and inadequate security measures. Therefore, Chinese chemical enterprises should prioritize enhancing organizational safety management capabilities and fostering a culture of safety, while implementing a system of safe production responsibilities.

Table 5 Results of top ten ARs with confidence

Antecedent	Consequent	Support	Confidence	Lift
Equipment quality is unqualified	Equipment aging, leakage or malfunction	7.285	81.818	2.206
Sparking during the use of tools, Insufficient supervision of regulatory implementation	Violation of regulations	26.490	85.000	2.517
Sparking during the use of tools, Insufficient supervision of regulatory implementation	Violation of regulations	5.960	77.778	2.936
Insufficient security measures	Insufficient supervision of regulatory implementation	8.609	76.923	2.278
Inadequate investigation and management of hidden dangers, Insufficient supervision of regulatory implementation	Violation of regulations	5.298	75.000	2.831
Wrong material input, Insufficient supervision of regulatory implementation	Violation of regulations	5.298	75.000	2.831
Sparking during the use of tools, Violation of regulations	Improper hot operation	5.298	75.000	4.045
Equipment aging, leakage or malfunction, Insufficient supervision of regulatory implementation	Violation of regulations	7.947	75.000	2.831
Improper hot operation, Insufficient supervision of regulatory implementation	Violation of regulations	13.245	70.000	2.643
Accident emergency response failure	Insufficient security measures	5.960	66.667	7.744

V. Discussions

1. Unsafe behaviors of individual is the prominent cause of HCEAs

The fulfillment of personnel duties is not only a requisite for the proper functioning of safety regulations but also a pivotal factor in accident prevention. In China's hazardous chemicals safety regulatory framework, the deficiency in personnel's knowledge, skills, and safety consciousness stands out as the primary cause of mechanism failure. Among the 242 accidents documented in this study, 192 were directly attributed to the unsafe behaviors of individuals, resulting in the demise of 1095 individuals, comprising nearly 70% of the total.

Hence, it is imperative for chemical enterprises to bolster safety education and job-specific training for all employees, while also evaluating their job performance. Prior to assuming their roles, employees should undergo training examinations to acquire knowledge encompassing chemical processes, operating procedures, and hazardous materials management. Furthermore, companies should routinely conduct emergency drills to acquaint employees with protocols and methods for responding to unforeseen circumstances, thereby enhancing their self-rescue capabilities. Establishing a system of rewards and penalties to evaluate employees' training accomplishments and job performance is essential for heightening employees' awareness of the risks associated with chemical accidents.

2. Implementing a system of safe production responsibilities aids in preventing the occurrence of HCEAs

From the analysis results in Section Four, it is evident that violating regulations is the second major cause of HCEAs, with inadequate supervision of the implementation of safety management systems within companies being the core reason for employee non-compliance. Therefore, Chinese chemical enterprises need to prioritize the improvement of safety management systems and the implementation of safe production responsibilities. Companies should clearly define the safe production responsibilities of employees at all levels and ensure their fulfillment, while also instilling a safety-first mentality and integrating safety management into the overall corporate management system.

Furthermore, there are shortcomings in the top-level design of safety supervision for chemical enterprises by the Chinese government. Although the Chinese government has issued regulations such as the "Safe Production Law Enforcement Procedures" and the "Administrative Penalty Discretionary Measures for Safe Production," the current regulations focus more on basic principles and process standardization, with gaps remaining in risk identification, penalties, and other aspects. Therefore, the effectiveness of supervision on the implementation of safe production responsibilities by companies largely depends on the personal awareness and capabilities of safety supervision personnel. In the future, the Chinese government should formulate laws and regulations, provide practical guidance, and oversee the implementation of safe production responsibilities by chemical enterprises to prevent accidents involving hazardous chemicals.

IV. Conclusions

This study analyzed the characteristics of hazardous chemical accidents in China from 1982 to 2024 and drew the following conclusions: (i) The frequency and severity of hazardous chemical accidents in regions such as Hebei, Shandong, Jiangsu, Liaoning, and Tianjin are higher compared to other areas in China, making them key focus areas for risk prevention and control. (ii) Emphasis should be placed on conducting hazard inspections and risk prevention during the winter season for hazardous chemical accidents. (iii) Explosions, fires, and asphyxiation are the main types of hazardous chemical accidents, necessitating targeted strengthening of prevention and control measures for these types of accidents. (iv) Risk assessments and safety management for the storage, production, and transportation of explosives, toxic gases, and flammable solids should be prioritized.

This study also conducted association rule mining on 150 HCEAs, extracting 29 direct causes of HCEAs. Among these, human factors comprised 17 factors, equipment factors comprised 4 factors, management factors comprised 6 factors, and environmental factors comprised 2 factors. Key human factors identified include violations of regulations, equipment operation errors, improper temperature control, wrong material input, sparking during tool use, and improper waste disposal. Key equipment factors include equipment aging, leakage, or malfunction. Insufficient supervision of regulatory compliance within companies can lead to the occurrence of these factors, increasing the likelihood of HCEAs. It is recommended that companies rigorously review the safety of hazardous chemical production processes and operating procedures, and implement safe production responsibilities. Governments should enhance relevant legal frameworks and strengthen supervision of hazardous chemical production.

This study contributes to a more comprehensive and systematic consideration by scholars in the causal analysis of hazardous chemical or other types of accidents, and aids in further research on existing accident causal models in conjunction with the actual situation of safe production work in China. Future studies should further explore association rule mining based on key factors of hazardous chemical accidents, elucidate the chain of hazardous chemical accidents, and provide references for effectively constructing hazardous chemical safety management systems and mechanisms for both enterprises and governments.

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