

Article

Statistical Analysis of the Characteristics and Laws in Larger and Above Gas Explosion Accidents in Chinese Coal Mines from 2010 to 2020

Huimin Guo ^{1,2,*}, Lianhua Cheng ¹ and Shugang Li ¹

¹ College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China; chenglianhua@xust.edu.cn (L.C.); lisg@xust.edu.cn (S.L.)

² College of Mechanical Engineering, Xi'an University of Science and Technology, Xi'an 710054, China

* Correspondence: ghuimin@xust.edu.cn

Abstract: Gas explosions are the most serious type of accident in coal mines in China. This study analyzed 125 gas explosion accidents that occurred between 2010 and 2020. The results showed that the number of gas explosion accidents and deaths in 2010–2020 was stable and decreasing. The number of larger gas explosion accidents in 2010–2020 is the largest, but the death toll from major accidents was much greater. Coal faces, headings, and roadways are the main locations where gas explosions are initiated. The coal mines in which gas explosions occur in coal faces and headings are mainly “township” enterprises and private mines, all of which engage in illegal operations. The main cause of gas accumulations in roadways is ventilation system failure; these failures can be reduced with improved ventilations system management. The number of gas explosion accidents and related deaths in the Sichuan, Guizhou, and Heilongjiang provinces are very high. The annual change in the frequency of gas explosion accidents, the quarterly distribution of gas explosion accidents, and time during a mining shift when gas explosion accidents occur are closely related to national policies and regulations, company annual production goals, and the mental status of miners, respectively.



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Keywords: coal mine; gas explosion; statistical analysis; coupling relationship; countermeasures

1. Introduction

Various types of accidents occur in coal mines, including gas and coal dust explosions, coal and gas outbursts, suffocation accidents, fires, floods, roof falls, and haulage accidents. Gas explosions are undoubtedly the most serious type of accidents [1,2]. Once a gas explosion occurs, it may cause a large number of casualties, huge economic losses, and severe negative societal effects. According to Chinese National Coal Regulatory Administration yearly statistics, the vast majority of major accidents in Chinese coal mines are gas explosions. These gas explosions account for approximately 70% of the total number of major accidents [3] and for about 30% of the total number of deaths in coal mines every year [4]. The risk of a gas explosion is present throughout a coal mine. The coal, the working face, and the coal in the goaf constantly desorb gas (methane) and release it to the mine air. Thus, gas can accumulate in many different places in the mine. In addition, there are many ignition sources, such as open fires, electrical sparks, metal-on-metal sparks, friction sparks, and coal spontaneous combustion. Gas explosion accidents can occur almost anywhere. It is clear that the effective prevention of gas explosion accidents is of great significance for coal mine safety.

In order to prevent the occurrence of coal mine gas explosion, scholars have carried out fruitful research work in areas such as gas drainage technology [5,6]; ventilation system optimization [7]; and gas monitoring and early warning [8], making important contributions to the prevention of gas explosion accidents. The statistical analysis of accidents is an important aspect of safety management. Based on many accident cases, the principles and methods of mathematical statistics are used to explore the causes and laws of accidents, to provide a scientific basis for macro-accident prediction, accident prevention, and emergency decision-making [9]. Strengthening the statistical analysis of coal mine gas disasters and researching accident patterns is highly significant both theoretically and practically [10]. It helps us understand the current prevention and control status, predict accident trends, formulate scientific control objectives and strategies, and drive the safe and sustainable development of the coal industry.

Many scholars at home and abroad have conducted extensive research on the law of gas explosion accidents. Chen et al. (2013) counted the number of gas explosion accidents from 1980 to 2010. Through comparative analysis, the proportion of accidents caused by illegal behaviors in 2001–2010 was 31.13% lower than that in 1980–2000. However, the proportion of accidents caused by poor management increased by 32.38% during this period [11]. Yang et al. (2014) analyzed the gas explosion accidents in 2001–2013 from the aspects of the region, time, and month of gas explosion [12]. Jing et al. (2023) statistically analyzed 65 gas explosion accidents from 2015 to 2021, and concluded that management factors, lack of organizational atmosphere, inadequate supervision, poor state of operators, and operation errors were the five high-frequency causes of gas explosion [13].

This paper reports a statistical analysis of 125 larger and more serious gas explosion accidents in China that occurred from 2010 to 2020 using the China Ministry of Emergency Management classification system. This study is based on relevant information about coal mine gas explosions published by the National Emergency Management, National Safety Supervision, Official Provincial and City Management, and official emergency management websites. The aim is to provide a basis for gas explosion accident prevention in this new safety era.

2. Background

Considering the occurrence mechanism of gas explosion accidents. For a gas explosion to take place, three conditions must be met simultaneously. (1) The gas concentration must be within the explosive limit (generally 5–16% CH₄); (2) the oxygen content in the air must be higher than 12%; (3) a high temperature ignition source (generally > 650 °C) must be present. In underground areas except for the blind lane, the oxygen concentration reaches 20%. Therefore, the prevention of gas explosion accidents must be controlled from two aspects of gas concentration and ignition source. If a condition is not satisfied, the risk of gas explosion accidents can be controlled.

Song and Guo (2010) summed up the physical causes of gas explosion through experience, among which the ignition sources included illegal blasting, metal mineral collision, smoking, and electromechanical equipment aging [14]. The causes of gas accumulation include unreasonable setting of mine ventilation system, shutdown of local fan, shutdown caused by power failure, and other illegal operations. Wang et al. (2014) conducted a statistical analysis of gas explosion accidents in China from 2006 to 2010. The possible causes of gas accumulation and ignition sources in coal mines were obtained. The ignition source includes five factors such as smoking. Gas accumulation includes five factors of low ventilation efficiency [15]. Zhang et al. (2017) analyzed 126 extraordinary serious gas explosion accidents and summarized the core conditions of serious gas explosion accidents are chaotic ventilation gas management, gas inspection not being sufficiently strict, etc. [16].

The four categories of coal mine accidents according to the Coal Mine Production Safety Accidents Report and Investigation Handling Regulation issued by the People's Republic of China Ministry of Emergency Management are shown in Table 1. This classification is also applicable to gas explosion accidents. For example, accidents with 1–2 deaths are general gas explosion accidents, 3–9 deaths are larger gas explosion accidents, 10–29 deaths are major gas accidents, and more than 30 deaths are extraordinarily severe gas accidents. For this paper, the gas accidents from 2010 to 2020 have been grouped according to this classification scheme. According to statistics, 72% of the gas explosion accidents were larger, 24.8% were major, and 3.2% were extraordinarily severe in the 2010–2020 period. The death tolls in those larger, major and extraordinarily severe gas explosion accidents were 466, 477, and 149, respectively, with the average number of fatalities in those three categories being 5.18, 15.39, and 37.25.

Table 1. Classification of coal mine accidents in China.

Accident Grade	General	Larger	Major	Extraordinarily Severe
Deaths	<3	$\geq 3, <10$	$\geq 10, <30$	≥ 30
Serious injuries	<10	$\geq 10, <50$	$\geq 50, <100$	≥ 100
Direct economic losses	$<¥10^7$	$\geq ¥10^7, <¥5 \times 10^7$	$\geq ¥5 \times 10^7, <¥10^8$	$\geq ¥10^8$

3. Methods

The data for the larger and more serious gas explosion accidents in 2010–2020 were retrieved from websites maintained by the China National Coal regulatory bureau and its branches. Through the statistics of coal mine gas explosion accident cases, the original information of the accident is obtained from the analysis of the time, province, death toll, explosion site, cause of gas accumulation, and ignition source, as shown in Appendix A. According to the detailed statistics concerning the accident cases, there were 125 larger or more serious gas explosions and 1092 deaths from those explosions in China from 2010 to 2020.

Accident statistical analysis is an important part of safety management. According to the research purpose, the effective data are extracted from many accident cases. The causes and laws of accidents are explored by chart and mathematical logic, and the characteristics and internal relations of accidents are described, which provides a scientific basis for macroscopic accident prediction and safety decision-making [17]. Industrial accidents patterns can be analyzed by the frequency of accidents in specific periods of time. When many accident cases are considered, this method can analyze many different types of accidents statistically to explore their causes [18–20]. In this paper, this method is used to investigate the statistical patterns and characteristics of larger and more serious gas explosion accidents in Chinese coal mines from 2010 to 2020.

4. Results and Discussion

4.1. Accident Dates and Times

Innovations in industrial technology and the increased safety awareness of management personnel have markedly improved coal mine safety in recent years. To appreciate the new trends in where and when coal mine gas explosion accidents occur, new maps were generated. A map showing the annual distribution of gas explosion accidents from 2010 to 2020 was drawn (Figure 1) and because the production tasks in coal mines are different at different times of the year, gas explosion accidents in the past ten years were analyzed quarterly, as shown in Figure 2. In addition, the working hours in coal mines in China are dominated by the “three-eight system” (the three-eight system means working eight hours,

education for eight hours, and rest for eight hours per day) and the different periods of time during the day influence staff behavior differently for this reason, a working shift-accident diagram (Figure 3) was also prepared.

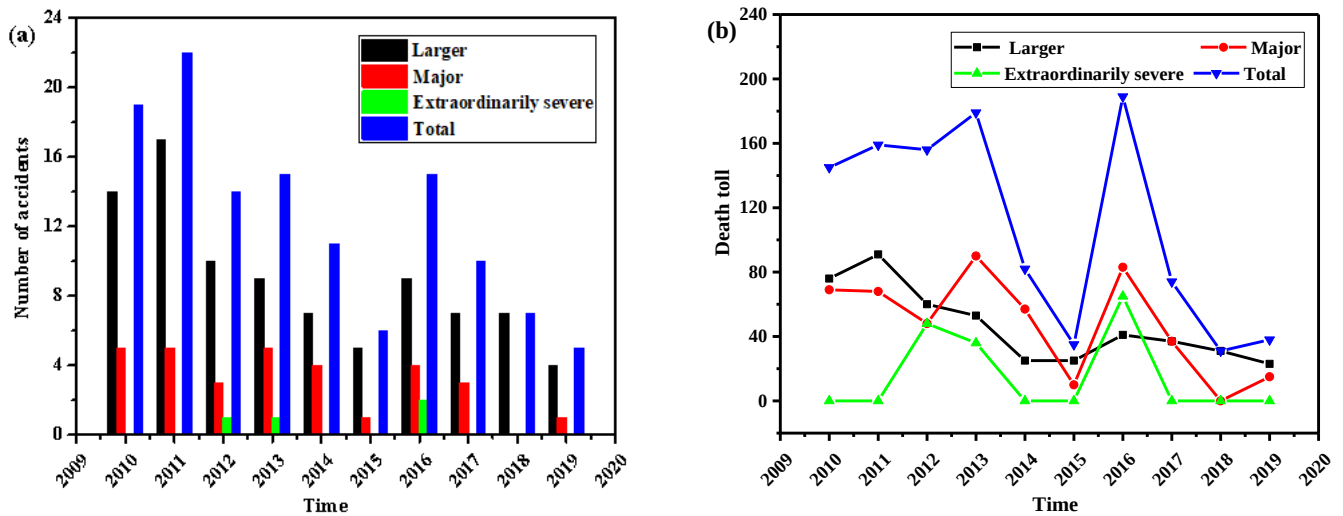


Figure 1. Annual number of coal mine gas explosion accidents and (a) deaths from those accidents (b).

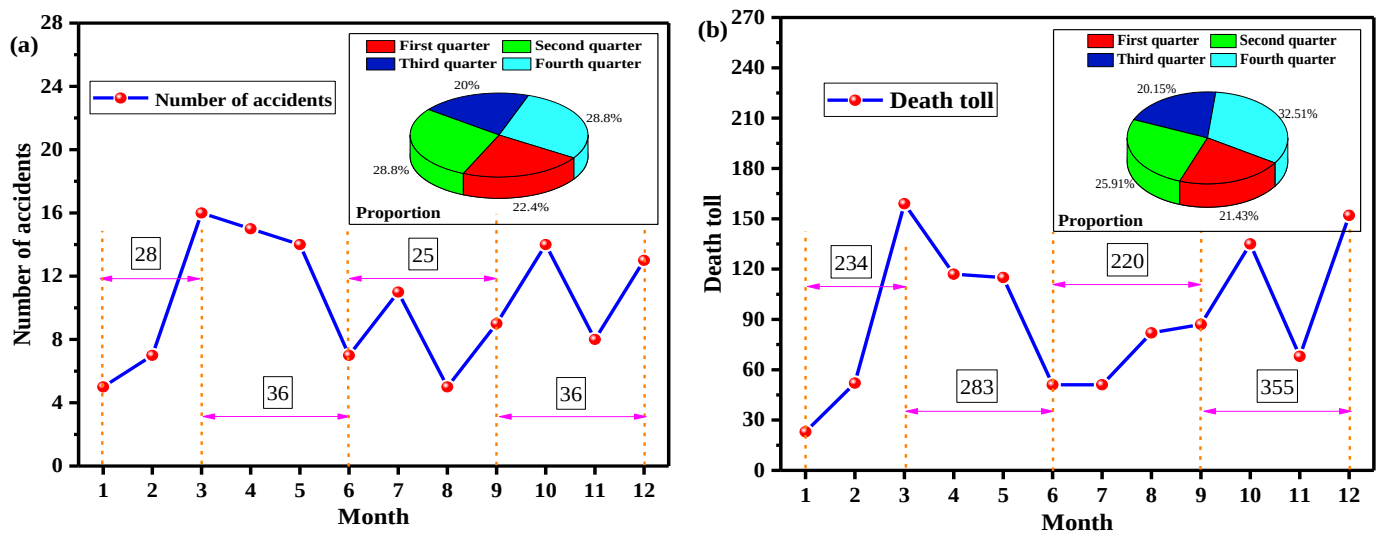


Figure 2. Distribution by month for coal mine gas explosion accidents (a) and deaths from those accidents (b).

4.1.1. Annual Patterns

Zhang et al. (2018) reported on the extraordinarily severe gas explosion accidents in Chinese coal mines that occurred between 1950 and 2014. Since 2006, the number of extraordinarily severe accidents in China has declined every year because coal mine safety has improved [21]. From 2010 to 2020, the number of extraordinarily severe accidents in China's coal mines approached zero, but some accidents still occurred in individual years (2012, 2013, and 2016), as shown in Figure 1a. The number of major accidents was relatively stable between 2010 and 2013 but it decreased, although it fluctuated, starting in 2014. The number of larger gas accidents fluctuated downward between 2010 and 2020, but they still accounted for the largest proportion of gas explosion accidents every year. It can be seen from Figure 1b that the number of deaths in gas explosion accidents shows a trend of decreasing volatility. The years 2013 and 2016 are the peak years for accidents and the number of deaths in those years accounted for the largest proportion of deaths in the last

ten years. Together, Figure 1a,b show that in 2013 and 2016, there were extraordinarily severe gas explosion accidents with the death toll from those accidents accounting for approximately 20.1% (2013) and 34.4% (2016) of the deaths in that decade. The number of major gas explosion accidents is also relatively large, with the death toll accounting for 50.3% in 2013 and 43.9% in 2016. In addition, as can be seen in Figure 1, the trend in the total number of gas explosion accidents is consistent with the trend in the number of larger accidents. In addition, the total number of deaths from gas explosions is consistent with the trend in the number of major accidents. To summarize, from 2010 to 2020 the number of gas explosion accidents has been stable with a slight decline and there have been remarkable achievements in terms of coal mine safety in China. However, circumstances remain dangerous and there is still a certain gap in Chinese coal mine safety compared with coal mine safety in developed countries.

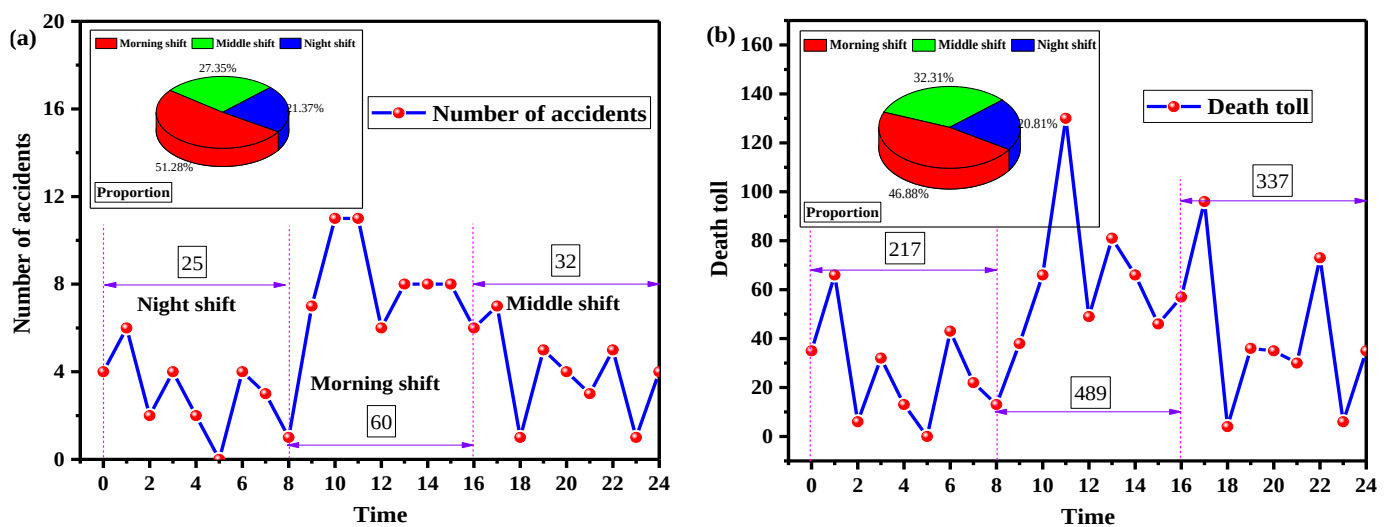


Figure 3. Hourly distribution of coal mine gas explosion accidents during a 24-h day. (a) Number of accidents. (b) Deaths from those accidents.

The data were analyzed to determine the underlying reasons for this trend in coal mine safety. The four main explanations are:

- (1) Coal mine industry policies and regulations have been gradually improved. As coal mine output has increased, coal mine machinery and equipment have been significantly modernized and improved. In addition, the government has accelerated the integration of coal mine resources and the merging and reorganizations of small coal mines. Coal mines producing less than 600,000 t/a that had multiple accidents have been gradually closed [22].
- (2) The number of safety management personnel at coal mining enterprises has increased. State-owned coal mining companies recruit large numbers of employees from colleges and universities every year. These new employees are well educated and have a strong sense of safety. Furthermore, industrial and mining enterprises now regularly organize safety meetings and safety skill training sessions for front-line employees to improve their safety awareness.
- (3) Economic development strategies in coal rich areas have changed. In China, regions rich in coal resources mainly rely on the energy industry to achieve economic growth but in the past, they ignored structural transformation to achieve sustainable development. Zhang et al. (2020) found that the substantial exploitation of coal resources alone is not conducive to industrial transformations. In recent years, provinces with rich coal resources have gradually changed their emphasis. They have increased

the proportion of natural gas, geothermal energy, wind energy, and nuclear energy they produce and reduced coal mining [23]. The report of the Nineteenth National Congress of the Communist Party of China pointed out that economic development must realize that “clear waters and verdant mountains are invaluable assets” and that economic development must promote the harmonious coexistence of man and nature [24].

- (4) There have been technical advances in gas extraction. As set out in the 13th Five-year Plan of the Development and Utilization of Coalbed Methane, the extraction of coalbed methane (CBM) is expected to reach 24 billion m³ by 2020, 10 billion m³ from surface CBM wells and 14 billion m³ from coal mines. This gas extraction will contribute, in part, to the expected 15% decrease in the number of deaths from coal mine gas accidents compared with the number of deaths from that type of accident in 2015. This increase in CBM extraction is possible because researchers in China and abroad have developed several enhanced coalbed methane recovery techniques including protective layer mining [25], hydraulic technologies like hydraulic fracturing and hydraulic slitting [26], shock wave cracking [27], liquid CO₂ blasting [28], and other fracture-generating techniques. These procedures can be used along with heat injection, microwave heating, acoustic wave treatments, displacement desorption, and other methods to enhance gas desorption [29] and to improve CBM extraction efficiency.

By the end of 2020, there were still 840 high-gas coal mines and 719 coal mines with coal and gas outburst across the country. Moreover, with the continuous increase of the mining depth, some low-gas coal mines have evolved into high-gas and outburst coal mines. Therefore, the prevention and control of gas explosion accidents should not be slackened. In summary, the positive changes in coal mine safety during 2010–2020 are closely related to changes in China’s National administrative regulations, economic structure, and industrial technology. Thus, the government can control gas accidents through policies and regulations and can gradually reduce the number of gas explosion accidents.

4.1.2. Accident Distribution by Calendar Quarter

As shown in Figure 2, approximately 20–30% of the gas explosion accidents occur in each quarter of the year. The second and fourth quarters have a slightly higher incidence of gas explosion accidents and there are fewer accidents in the first and third quarters. The variation in the number of gas explosion accident deaths is like the variation in the number of accidents. Both of those statistics increase in the first and second quarters, decrease during the spring and early summer, but increase again in the third and fourth quarters—although the numbers are somewhat volatile. These changes in the number of accidents and deaths may be related to seasonal changes in coal production pressures. The fourth quarter is the worst with 32.51% of deaths. It is followed by the first and second quarters with 21.43% and 25.91% of the gas explosion-related deaths, respectively.

In the fourth quarter, as the year-end approaches and winter coal demand rises, coal mine enterprises bear great pressure from production, economic, and safety indicators. Under this stress, both managers and front-line workers are prone to unsafe behaviors during production. Especially in December, to meet workload, progress, and task requirements, enterprises mine blindly, ignoring safety and heightening risks from illegal and reckless operations. Meanwhile, as coal production ramps up for supply in the critical stage, overcapacity, overwork, and overstaffing lead to equipment overload, making gas explosion accidents highly likely. In contrast, in the first quarter, enterprises have less production pressure. Safety lessons from the previous year improve employees’ awareness of safe production, so the number of gas explosion accidents and deaths is relatively low.

4.1.3. Accidents and Mine Shift Times

It can be seen from Figure 3 that the number of gas explosion accidents and deaths in the early shift is the largest, followed by the middle and late shift. Liu (2019) found that the miners reach their sleep point after six hours of work in the morning shift and five hours of work in the middle shift [30]. During the night shift, the miners' physiological functions are at their lowest level between midnight and 4:00 a.m. Most of miners feel extremely tired in the first four hours and are prone to unsafe behavior. However, the number of night shift accidents and fatalities is the lowest (Figure 3) and this is inconsistent with circadian rhythm theory. Therefore, combining this observation with observations from case analyses suggests two possibilities. ① The handover time for early shift production and maintenance is around 11:00 a.m. At this time, some equipment is shut down for maintenance, and changes in underground conditions and airflow may cause gas to accumulate in local areas. The unsafe behavior of mine personnel during maintenance can lead directly to a gas explosion. ② More than 90% of the mines with high accident rates are township enterprises (small mines controlled by the local village or township governments) or privately-owned mines that produce less than 600,000 t of coal per year. These mines tend to have chaotic management, may mine illegally, and shift times may not be managed according to the three-eight system.

4.2. Geographic Distribution of Accidents

The regional distribution of the larger and more serious gas explosion accidents in China from 2010 to 2020 is shown in Figure 4. The number of accidents and deaths in the Sichuan, Guizhou, and Heilongjiang provinces is very high. Yunnan, Hunan, and Liaoning provinces have a high number of accidents but a relatively low number of deaths, whereas Chongqing, Shanxi, and Jilin have a low number of accidents but a high death toll. Zhou et al. (2016) compiled statistics on the average gas content of the coal in coal mines in a number of provinces in China [31]. In 2012, 3284 high-gas mines and mines that experienced coal and gas outbursts were counted in 26 larger coal-producing provinces. These provinces are mainly in the southwestern and the central-eastern parts of the country. Of those 3284 mines, 2865 are in Guizhou, Sichuan, Hunan, Shanxi, Yunnan, Jiangxi, Chongqing, Henan, and some other provinces. These mines account for 87.2% of the total and they include the majority of the high accident/high death toll mines in the areas. Heilongjiang province is a "double-high accident" province, but the proportion of low-gas mines in this area is very high, indicating that low-gas mines can also be affected by gas explosions. The mines in Heilongjiang province emphasize the point that complete gas monitoring and management systems should be installed in low-gas mines as well as in high-gas mines.

4.3. Patterns of Gas Explosion Causes

4.3.1. Gas Accumulations and Ignition Sources

Appendix A was screened for credible data to establish any recognizable patterns for accidental gas explosions gas accumulations or ignition sources. Reliable data for 106 reasons for the gas accumulation before an explosion and reports on 99 substantiated explosion ignition sources were found. These data were used to construct Figure 4. It can be seen in Figure 4a that gas accumulations caused by insufficient air volume (including operating without ventilation and sufficient airflow) account for the highest proportion of gas accumulations, followed by ventilation system mix-ups, ventilator failure, and blind lanes in the goaf. Together, these errors accounted for 84.91% of the total accidents. Based on the four main causes of explosive gas accumulation tabulated from Appendix A and

published accident investigation reports, Table 2 was prepared to summarize the direct causes of explosive gas accumulations [32,33].

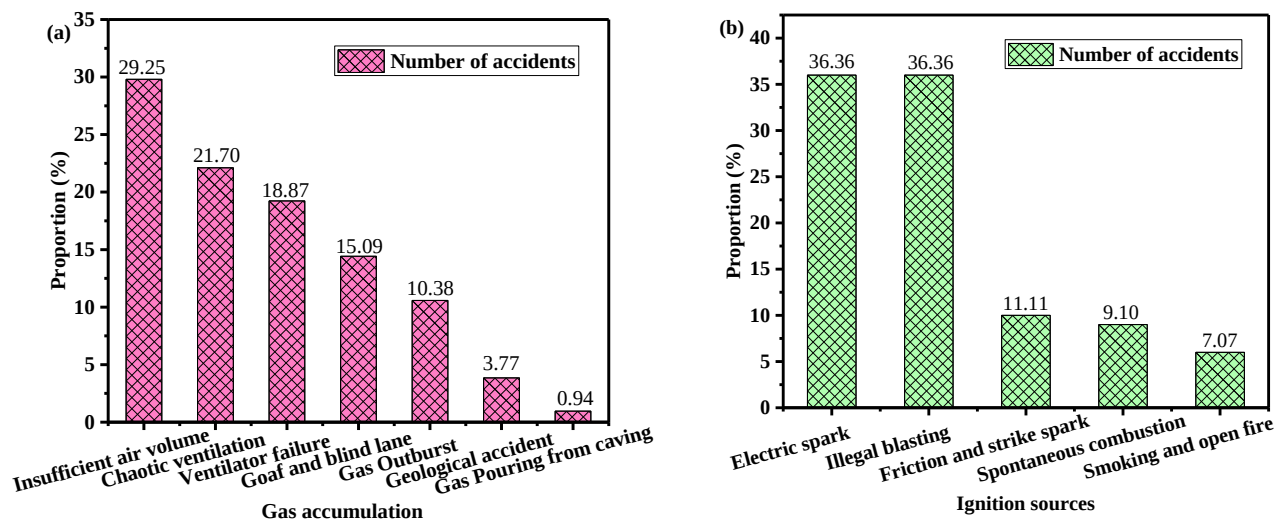


Figure 4. Causes of gas accumulations (a) and ignition sources (b) for gas explosions in coal mines.

Table 2. Direct causes of explosive gas accumulations.

Category	Direct Cause
Insufficient air volume or no wind	Local fan can be stopped at will.
	Air volume not distributed as required.
	Roadway caving block leads to short circuit of air current.
	Air duct broken, disjointed, pressed and other treatment is not timely.
	The air duct mouth is too far away from the heading face, so that air volume is too small and wind speed is low, resulting in the breeze operation of the heading face.
Chaotic ventilation facilities management	Poorly managed mines form tandem wind, diffuse wind, circulating wind, etc.
	Goaf and blind lanes are not handled and closed in time.
	No ventilation system for super-layer cross-border mining.
	Coal mines that have been closed produce without permission.
Chaotic gas inspection system	Insufficient inspection personnel caused missed inspections.
	Tile inspection personnel responsibility is not strong, and there is a false phenomenon.
	Mine gas monitoring and control system installation is unreasonable or maintenance is not timely.

As shown in Figure 4b, electrical sparks and flames from blasting are the main ignition sources for gas explosion accidents, these two sources account for 72.72% of the accidents. The number of explosions ignited by friction, sparks from metal striking metal or rock, and coal spontaneous combustion are nearly the same. Smoking and open flames ignited the fewest explosions. The ignition sources reported by the accident investigation reports consulted for this study are summarized in Table 3 [34–36].

To summarize, it is clear that there are human factors involved in both the ignition sources and the gas accumulations, and that these accidents are the result of illegal actions by staff or illegal orders by management. Chen et al. (2013) have confirmed this view through statistical accident analysis [11]. Moreover, Chen et al. (2012) found that 98% of coal mine accidents are caused by unsafe actions by people [37]. It can be inferred that unsafe acts by mine personnel and unsafe management practices are the main causes

of gas accumulations and the ignition sources for explosions. Therefore, reducing the number of accidents and improving safety can only be achieved by systematically reducing unsafe behavior.

Table 3. Ignition sources for gas explosion accidents.

Category	Direct Cause
Electric sparks	Underground lighting does not meet regulations. The power supply of the mechanical equipment does not comply with the regulations. The electrical installation does not comply with the regulations. Electrical equipment exploded. Live work produces electric sparks.
Illegal blasting	The system of “one shot and three checks” was not implemented during blasting operations. The blast hole is not or less loaded with mud or replaced with combustible materials such as coal powder. Insufficient minimum resistance line or multi bus blasting. Blasting of exposed bus or continuous blasting.
Friction and strike sparks	Metal strike spark. Rock strike spark. Metal friction spark. Machine friction.
Coal spontaneous combustion	Coal spontaneous combustion in goaf. Coal spontaneous combustion in roadway. Airtight management is not strict, fire area reignites.

4.3.2. Accident Locations

Gas accidents can occur wherever a gas accumulation can form. Common gas explosion sites include coal faces, headings, roadways, the goaf, blind alleys, and enclosed spaces. To quantify initial gas explosion locations, 97 sets of reliable explosion location data were selected from Appendix A; these locations are shown in Figure 5. Coal faces, headings, and roadways account for around 90% of the initiation locations for gas explosions. Coal faces and heading faces are the locations where coal is first extracted from the coal seam and gas accumulation in these areas is mainly determined by the both the amount of gas desorbed from the seam and the efficiency of local ventilation. Gas accumulation in roadways is predominantly affected by the efficiency of whole-mine ventilation. Therefore, to minimize gas accumulations, reasonable management measures should be taken at important sites and corresponding factors in daily mining.

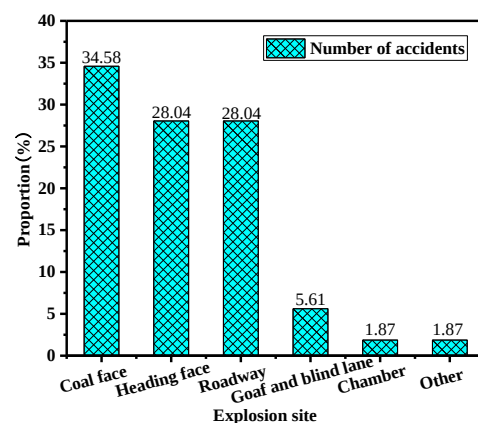


Figure 5. Number of coal mine gas explosion accidents classified by location in the mine.

4.3.3. Coupling Relationships for Gas Explosion Accidents

As can be seen in Figure 4, electric sparks and flames from blasting are the main gas explosion ignition sources. As described in Figure 6a, if the proportion of the coupling between the gas accumulation and the ignition source is more than 8%, the gas accumulation correspondence to an electrical spark is the highest but the correlation between gas accumulations and flames from blasting is relatively low. The reasons for the above relationships are related to the sites. Blasting is mainly concentrated at the working face in the heading, but electrical sparks can be generated anywhere electricity is used underground. To reduce or prevent gas accidents, it is necessary to analyze the sites that meet two conditions: they are likely to host a gas accumulation and they have an ignition source (see Figure 6b). Coal faces, working faces, and roadways under construction are locations with high incidences of gas explosion accidents (Figure 4). The main causes of gas accumulations near coal faces are haphazard ventilation, insufficient air volume, and faces in the goaf or in blind lanes. Accident investigation and analysis has shown that the coal mines that have haphazard ventilation systems and insufficient air flow are mainly privately-owned mines and “township” mines. In addition, many of these “accident mines” engage in illegal practices such as mining beyond their license boundary and mining without permission in closed or restricted coal mines. The main reason for gas accumulations in roadways is ventilation failure. This conclusion is consistent with the analysis presented in Section 4.3.2. It is clear that proper ventilation system management can effectively reduce gas explosion accidents in roadways.

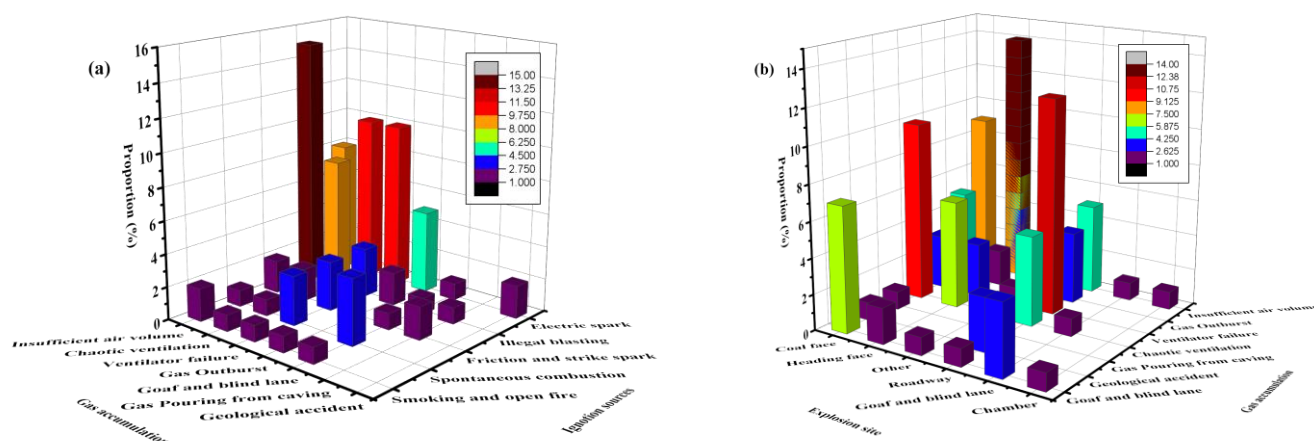


Figure 6. Coupling relationships for Chinese coal mine gas explosion accidents: (a) gas accumulation cause vs. ignition source; (b) explosion site vs. gas accumulation cause.

Gas explosion accidents is caused by the coupling effect of risk factors. From the perspective of the necessary and sufficient conditions for the occurrence of gas explosion accidents, the coupling chemical reaction of gas concentration overrun, ignition source, and oxygen lead to explosion accidents. The factors that cause gas concentration overrun and ignition source involve the coupling effect of inherent, human, equipment, environment, management, and other factors in time and space. Most gas explosion accidents are the result of multi-factor local coupling. The more factors involved, the more complex the coupling path, and the greater the probability of accidents.

5. Preventing Gas Explosion Accidents

The following suggestions can be made to prevent gas explosion accidents.

- (1) Cracking down on illegal mine production and development

Severely crack down on the “five fakes and five supers”, namely the “five fakes” of fake rectifications, fake seals, fake data, fake drawings, and fake reports; the “five supers” of super-capacity, super-strength, super-layer cross-border, and over-licensing. In addition to daily inspections, additional methods such as unannounced visits and unannounced inspections must be taken to maintain pressure and force the mine operators to halt illegal production. It is necessary to improve joint law enforcement under the leadership of the local government and ensure that all relevant departments participate. All departments should recognize their respective responsibilities and form a joint force to investigate and deal with legal and regulatory violations. Regarding the “five fakes and five supers”, measures such as maximum penalties, suspension of production, mine closure, criminal prosecution, and legal liability should be imposed. The units and personnel who organize production in violation of laws and regulations and cause accidents should be punished and their names should add to a “blacklist” that records instances of illegal mine production and mines with a bad safety record.

(2) Close illegal and antiquated mining operations

Small coal mines that have had larger accidents and coal mines that use mining methods prohibited by the State must be closed if their operations cannot be modernized. Coal mines that have experienced major disasters, have essentially exhausted their reserves, have inadequate storage, use non-mechanized mining, or have a production capacity less than the prescribed requirements should be closed. Coal mines listed in the capacity reduction plan should be shut down immediately. Plans and safety procedures should be formulated for equipment reassignment or disposal and special personnel should be deployed to strictly observe and guard against illegal production while the mine is being deactivated and closed. When a decision has been made that a coal mine should be closed it should be closed immediately. Coal mines that have been shut down for a long time should be closed in an orderly manner in accordance with State regulations. Coal mines whose safety permits have expired should have their safety production permits cancelled if they have not applied for an extension. Management at mines with expired safety permits should prevent illegal production by limiting the power supplied to the mine and stopping the procurement, distribution, and use of blasting supplies.

(3) Promote larger gas disaster prevention and encourage gas control technological innovations

Coal mine management should always regard gas accident prevention as a top priority and earnestly implement “Coal Mine Safety Regulations”. They should strive for “reliable ventilation, extraction compliance, effective monitoring, and site management”. It is necessary for both management and miners to believe that “a gas overrun is an accident” and aim for zero coal mine gas overruns. Coal mines should only operate when ventilation systems can ensure that air volumes meet requirements and air circulation is sufficient. If gas prevention measures are not in place and working properly, the ventilation system is not adequate, and if the safety monitoring and control system cannot operate normally, the mine should stop production until the situation is rectified and the mine air can meet regulatory requirements. In addition to gas explosion prevention, management should pursue enhanced coalbed methane recovery to improve gas drainage efficiency.

(4) Strict investigation of ultra-production

Overcapacity production from coal mines should be prevented and mines should produce coal in strict accordance with their designed production capacity. If a coal mine is found to be producing more coal than their production capacity, the company should be ordered to suspend production until the situation is rectified. If the annual raw coal output

from a mine exceeds 110% of the mine's designed production capacity or the monthly output exceeds 10% of the designed annual capacity, the mine should also be ordered to stop production. If major dangers cannot be eliminated after rectification, the mine should be closed.

(5) Strengthen ventilation management and improve gas extraction

Based on the mine's geological conditions and mining layout, a scientific and rational ventilation system must be designed to ensure stable airflows, sufficient air volume, and proper air distribution. Regularly inspect, maintain, and service ventilation equipment such as ventilators and air ducts to keep them performing well and operating reliably. Set up a strict ventilation management system and assign professional staff. Strengthen daily inspections and monitoring of the ventilation system. Use the ventilation monitoring system to track parameters such as wind speed, air volume, and gas concentration in real time, and address any problems promptly. For high-gas and gas outburst mines, establish a complete gas drainage system to extract gas from coal seams in advance, reducing gas content and pressure. Adopt advanced drainage equipment and technologies to improve gas drainage efficiency and concentration.

(6) Annually prepare an achievable production plan and follow that plan

External factors beyond the enterprises' control mean that an enterprise commonly fails to meet production requirements in the first three quarters of the year. When this occurs, it is expedient to increase coal production in the fourth quarter. The annual plan should take this into account and ensure that safe production throughout the year is achievable. If necessary, production during the fourth quarter should be adjusted and safety procedures should be strengthened the fourth quarter to prevent accidents.

(7) Improve safety management

Flames from blasting and electrical sparks are the main ignition sources for gas explosion accidents. Therefore, coal mines should improve their management procedures for explosives and blasting supplies and implement a system for their procurement, distribution, storage, and use. The checking of gas concentration before charge and initiation, as well as after blasting, and the adoption of an interlocked blasting system should be used when blasting. In addition, mechanical and electrical operator management should be improved and working with electricity illegally should be prohibited.

(8) Enhance safety culture

To improve employee skills and risk identification capabilities, coal mines should conduct regular safety training classes, carry out safety drills, and ensure that employees are aware of their safety compliance responsibilities. Through safety lectures and professional skills training, management and front-line employees' sense of their own responsibilities are heightened; illegal commands and illegal operations are eliminated, and unsafe behavior in the mine is reduced. This can reduce coal mine gas explosion accidents.

6. Conclusions

- (1) From 2010 to 2020, there were 125 larger and above gas explosion accidents in China, with 1092 deaths. Compared with the previous decade, the situation of coal mine safety production has been greatly improved, the number of gas explosion accidents and deaths have shown a fluctuating downward trend, and the number of extraordinarily severe gas explosion accidents has decreased significantly. In addition, the number of larger gas explosion accidents in this decade is the largest, accounting for 72%, but the number of deaths caused by larger gas explosion accidents is the largest, accounting for 43.68%.

- (2) Unsafe behavior by mine personnel and management failures are the main reasons that gas is allowed to accumulate and ignite. Therefore, the most effective way to reduce accidents and improve safety is to reduce unsafe behavior and practices and correct management errors.
- (3) More than 90% of the accidental gas explosions are initiated by sources in the coal face, heading, or roadway. Coal mines that experience accidents at a coal mining face or heading are mainly township or village enterprises or privately-owned mines. All of these mines engage in illegal practices, such as mining beyond their license boundary, mining without permission in closed or restricted mines, and roadway mining. The main cause of gas accumulations in roadways is ventilation system failure; these failures can be reduced with improved ventilation system management.
- (4) From 2010 to 2020, the number of gas explosion accidents and related deaths in the Sichuan, Guizhou, and Heilongjiang provinces was very high, but many of the coal mines in Heilongjiang province are low-gas mines. These data imply that low-gas mines can suffer as many accidental gas explosions as high-gas mines. Daily gas monitoring and gas management in low-gas mines are just as important as they are in high-gas mines, and if the monitoring and management are deficient, they need to be improved.
- (5) The number of gas explosion accidents in China and how that number changes over time are closely related to national policies and regulations. The quarterly distribution of accidents in any specific mine is related that mine's coal production. In addition, the distribution of accidents during the "three-eight system" workday is directly related to the mental status of the miners. Based on these and other data, seven gas accident prevention measures have been proposed. These measures provide theoretical support for mine gas accident prevention.

Through the statistical analysis of gas explosion accident cases, the occurrence characteristics and laws of gas explosion accidents can be obtained. However, with the innovation of technology and the changes in complex conditions, the occurrence patterns and characteristics of gas explosion accidents will change. Regarding the occurrence of gas explosion accidents, it is necessary to analyze the causation mechanisms, evolution paths, intelligent early warning, and preventive strategies from different perspectives, so as to continuously reduce the gas explosion accidents.

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Appendix A

Table A1. Gas Explosion Accidents in Chinese Coal Mines, 2010–2020.

Accident Time	Province	Death Toll	Explosion Site	Gas Accumulation	Ignition Source
7 January 2010	Hubei	4	Roadway	Ventilator failure	Electric spark
19 January 2010	Hunan	3	Roadway	Ventilator failure	Electric spark
22 January 2010	Hunan	4	Heading face	Chaotic ventilation	Electric spark
7 February 2010	Chongqing	5	Heading face	Gas Outburst	/
3 March 2010	Hunan	7	Coal face	Gas Outburst	Electric spark
4 March 2010	Guizhou	4	/	/	/
5 March 2010	Heilongjiang	4	Chamber	Insufficient air volume	/
25 March 2010	Hubei	11	Coal face	Goaf and blind lane	Illegal blasting
10 April 2010	Liaoning	6	Roadway	Ventilator failure	Friction and strike spark
25 April 2010	Liaoning	3	Heading face	Insufficient air volume	Illegal blasting
2 May 2010	Guizhou	7	Coal face	Gas Outburst	Electric spark
8 May 2010	Hubei	10	Coal face	Chaotic ventilation	Electric spark
11 May 2010	Gansu	9	Roadway	Gas Outburst	Illegal blasting
18 May 2010	Shanxi	11	Goaf and blind lane	Insufficient air volume	/
18 July 2010	Liaoning	4	Coal face	Insufficient air volume	Spontaneous combustion
5 September 2010	Hebei	11	Heading face	Insufficient air volume	/
9 September 2010	Yunnan	7	Coal face	Gas Outburst	/
27 September 2010	Jiangxi	9	Heading face	Insufficient air volume	Illegal blasting
7 December 2010	Henan	26	Coal face	Chaotic ventilation	Illegal blasting
24 February 2011	Jilin	5	Coal face	Insufficient air volume	Electric spark
3 March 2011	Hunan	6	/	Ventilator failure	Electric spark
5 March 2011	Liaoning	5	Coal face	/	/
11 March 2011	Hunan	7	Roadway	Gas Outburst	/
12 March 2011	Guizhou	19	/	/	/
17 March 2011	Liaoning	4	Roadway	Insufficient air volume	Illegal blasting
24 March 2011	Jilin	13	Roadway	Gas Outburst	Electric spark
3 April 2011	Yunnan	6	Heading face	Chaotic ventilation	Electric spark
15 April 2011	Yunnan	12	Roadway	Ventilator failure	Electric spark
26 April 2011	Heilongjiang	9	Coal face	Chaotic ventilation	/
29 April 2011	Qinghai	5	/	/	/
13 May 2011	Heilongjiang	4	Heading face	Insufficient air volume	Smoking and open fire
22 May 2011	Sichuan	6	Coal face	Gas Outburst	Electric spark
4 June 2011	Sichuan	4	Coal face	Ventilator failure	Spontaneous combustion
5 June 2011	Jilin	4	Roadway	Ventilator failure	Smoking and open fire
12 July 2011	Inner Mongolia	3	Goaf and blind lane	Goaf and blind lane	Smoking and open fire
12 July 2011	Chongqing	4	Coal face	Chaotic ventilation	Electric spark
17 July 2011	Chongqing	3	Heading face	Ventilator failure	Illegal blasting
29 September 2011	Hunan	7	Heading face	/	/
16 October 2011	Shaanxi	11	/	/	/
17 October 2011	Chongqing	13	/	Chaotic ventilation	Electric spark
9 December 2011	Heilongjiang	7	Heading face	Gas Outburst	Illegal blasting
3 February 2012	Sichuan	13	Roadway	Ventilator failure	Spontaneous combustion
14 February 2012	Xinjiang	6	/	/	/
22 March 2012	Liaoning	5	Goaf and blind lane	Chaotic ventilation	Spontaneous combustion
23 April 2012	Inner Mongolia	9	Heading face	Insufficient air volume	Illegal blasting
15 May 2012	Xinjiang	6	/	/	/
12 June 2012	Jiangxi	5	Roadway	Gas Outburst	Electric spark
26 July 2012	Shanxi	7	Coal face	Ventilator failure	Illegal blasting
29 July 2012	Liaoning	3	/	/	/
13 August 2012	Jilin	20	Roadway	Geological accident	Friction and strike spark
28 August 2012	Xinjiang	6	/	/	/
29 August 2012	Sichuan	48	Heading face	Insufficient air volume	Electric spark
2 September 2012	Jiangxi	15	Coal face	Goaf and blind lane	Illegal blasting
10 October 2012	Anhui	6	Heading face	Insufficient air volume	Illegal blasting
17 December 2012	Hunan	7	Heading face	/	/
7 January 2013	Shanxi	7	Goaf and blind lane	Goaf and blind lane	Friction and strike spark

Table A1. Cont.

Accident Time	Province	Death Toll	Explosion Site	Gas Accumulation	Ignition Source
1 March 2013	Yunnan	8	Heading face	/	/
29 March 2013	Jilin	36	Coal face	Goaf and blind lane	Spontaneous combustion
12 April 2013	Guizhou	7	Coal face	Chaotic ventilation	Illegal blasting
20 April 2013	Jilin	18	Coal face	Chaotic ventilation	Illegal blasting
10 May 2013	Guizhou	12	Heading face	Chaotic ventilation	Electric spark
11 May 2013	Sichuan	28	Coal face	Insufficient air volume	Illegal blasting
2 June 2013	Hunan	10	Heading face	Insufficient air volume	Electric spark
2 July 2013	Hubei	4	Roadway	Geological accident	Friction and strike spark
23 July 2013	Sichuan	7	Roadway	Ventilator failure	Spontaneous combustion
17 October 2013	Guizhou	4	Roadway	Ventilator failure	Electric spark
2 November 2013	Yunnan	3	Roadway	Chaotic ventilation	Friction and strike spark
5 December 2013	Jiangxi	7	Heading face	Insufficient air volume	Illegal blasting
13 December 2013	Xinjiang	22	Coal face	Goaf and blind lane	Illegal blasting
21 December 2013	Qianxi	6	Heading face	Chaotic ventilation	Electric spark
12 March 2014	Anhui	3	Heading face	Goaf and blind lane	Spontaneous combustion
31 March 2014	Yunnan	5	Roadway	Chaotic ventilation	Electric spark
21 April 2014	Yunnan	14	Coal face	Chaotic ventilation	Illegal blasting
8 May 2014	Yunnan	3	Coal face	Insufficient air volume	Electric spark
13 May 2014	Jilin	4	Roadway	Goaf and blind lane	Illegal blasting
3 June 2014	Chongqing	22	Coal face	Goaf and blind lane	/
13 August 2014	Guizhou	3	Roadway	Chaotic ventilation	Electric spark
4 September 2014	Heilongjiang	4	Roadway	Chaotic ventilation	Smoking and open fire
27 November 2014	Guizhou	11	Heading face	Chaotic ventilation	Friction and strike spark
14 December 2014	Heilongjiang	10	/	/	/
15 December 2014	Shandong	3	Roadway	Insufficient air volume	Electric spark
27 April 2015	Sichuan	8	Roadway	Ventilator failure	Friction and strike spark
1 May 2015	Sichuan	4	Inclined shaft	Ventilator failure	Electric spark
19 June 2015	Liaoning	3	Heading face	Ventilator failure	Electric spark
9 October 2015	Jiangxi	10	Coal face	Goaf and blind lane	Spontaneous combustion
31 October 2015	Liaoning	5	Heading face	Chaotic ventilation	Illegal blasting
17 November 2015	Shanxi	5	Vertical shaft	Insufficient air volume	Electric spark
23 March 2016	Shanxi	20	Coal face	Gas Pouring from caving	Illegal blasting
15 April 2016	Hubei	3	Roadway	Chaotic ventilation	Electric spark
22 April 2016	Heilongjiang	4	Roadway	Ventilator failure	Friction and strike spark
3 May 2016	Yunnan	6	Heading face	Ventilator failure	Electric spark
18 June 2016	Yunnan	3	Coal face	Goaf and blind lane	Illegal blasting
18 July 2016	Shaanxi	6	/	/	/
27 September 2016	Ningxia	20	Heading face	Insufficient air volume	Illegal blasting
13 October 2016	Guizhou	7	Coal face	Insufficient air volume	Illegal blasting
29 October 2016	Heilongjiang	21	Coal face	Insufficient air volume	Illegal blasting
31 October 2016	Chongqing	33	Heading face	Insufficient air volume	Illegal blasting
20 November 2016	Hunan	4	Roadway	Insufficient air volume	Electric spark
25 November 2016	Sichuan	4	Chamber	Goaf and blind lane	Illegal blasting
25 November 2016	Hunan	4	/	/	/
29 November 2016	Heilongjiang	22	Coal face	Chaotic ventilation	Illegal blasting
3 December 2016	Inner Mongolia	32	Roadway	Ventilator failure	Electric spark
6 February 2017	Liaoning	4	Roadway	Insufficient air volume	Smoking and open fire
14 February 2017	Hunan	10	/	/	Smoking and open fire
27 February 2017	Guizhou	9	Coal face	Gas Outburst	Smoking and open fire
3 August 2017	Guizhou	5	Roadway	Insufficient air volume	Electric spark
13 September 2017	Heilongjiang	10	Roadway	Ventilator failure	Illegal blasting
2 October 2017	Sichuan	4	Coal face	Chaotic ventilation	Illegal blasting
15 October 2017	Hubei	5	Heading face	Insufficient air volume	Friction and strike spark
3 December 2017	Heilongjiang	17	Coal face	Ventilator failure	Electric spark
8 December 2017	Hunan	4	Coal face	Geological accident	Electric spark
13 December 2017	Guizhou	6	Coal face	Insufficient air volume	Illegal blasting
26 January 2018	Chongqing	5	Heading face	Insufficient air volume	Illegal blasting
10 April 2018	Hubei	4	Heading face	Goaf and blind lane	Illegal blasting
9 May 2018	Hunan	5	Coal face	Insufficient air volume	Illegal blasting

Table A1. Cont.

Accident Time	Province	Death Toll	Explosion Site	Gas Accumulation	Ignition Source
10 October 2018	Jilin	3	/	/	/
15 October 2018	Chongqing	5	Vertical shaft	Goaf and blind lane	/
25 October 2018	Sichuan	4	/	/	/
24 December 2018	Shaanxi	5	Goaf and blind lane	Goaf and blind lane	Electric spark
30 April 2019	Shandong	9	Heading face	Insufficient air volume	Friction and strike spark
28 July 2019	Sichuan	3	Coal face	Insufficient air volume	Illegal blasting
31 July 2019	Guizhou	7	Roadway	Geological accident	Electric spark
28 September 2019	Xinjiang	4	Goaf and blind lane	Goaf and blind lane	Spontaneous combustion
18 November 2019	Shanxi	15	Coal face	Chaotic ventilation	Illegal blasting
20 October 2020	Shanxi	4	Roadway	Closed wall air leakage	Friction and strike spark

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