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# Technologies For Mitigating Spontaneous Combustion: A Systematic Review And Meta-Analysis

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***Abstract:*** The spontaneous combustion of coal presents serious dangers in mining operations, resulting in loss of life, financial setbacks, and harm to the environment. This systematic review assesses the efficacy of different technologies designed to prevent and manage spontaneous combustion, concentrating on research published in Fuel, Energy, and Applied Energy from 2000 to 2025. A comprehensive analysis was conducted on 29 articles, focusing on various technologies including gels, gel foams, inhibitors, inert gas injection, and aqueous solutions. Notable findings reveal that gels, especially those enhanced with polymers such as konjac glucomannan (KGM) and expandable graphite (EG), demonstrate enhanced thermal stability and effective oxygen barrier properties. Gel foams, such as gel-stabilized and three-phase varieties, exhibit superior fire suppression capabilities due to their enhanced film-forming properties and water retention. However, challenges with stability persist. Methods involving inhibitors and gas injection demonstrate potential, particularly as the depth of nitrogen injection plays a crucial role in regulating temperature within coal gobs. The review emphasizes progress in material science, showcasing polymer-modified gels and high-water-retaining foams as the leading solutions. Nonetheless, the practical use and enduring reliability necessitate additional exploration. This research brings together current insights, highlights areas needing further exploration, and suggests directions for upcoming studies aimed at enhancing technologies for preventing spontaneous combustion in coal mining**.**

***Keywords* -** Spontaneous combustion, coal mining, fire prevention, gel technology, foam suppression, meta-analysis.

## I. INTRODUCTION

The risks associated with the mining of coal are enormous, with most being related to explosions or ignitions at the mines, which result in fatal injuries and the loss of many lives. This explains why the spontaneous combustion of coal is one of the main threats in coal mining [1-3]. Coal fires not only burn coal resources, in addition the injuries and causalities, economic losses, and the release of harmful greenhouse gases polluting the environment [4]. In China, statistics show that about 170 people died and 70 people were injured due to spontaneous combustion-related accidents in the past 10 years which resulted in negative economic and social implications [5]. Thus, the prevention of spontaneous combustion in the coal mines is essential for the protection of the lives of the miners as well as the environment. However, to prevent the cause of spontaneous combustion the cause of the phenomenon needs to be investigated to provide a gateway for the solution to the problem. Many studies have been conducted to investigate the mechanism underlying spontaneous combustion. The vast research indicates the interaction between oxygen and coal at low temperatures was the main reason for spontaneous combustion hazards [6, 7]. The quest to solve this problem has necessitated for the invention of new ways and technologies to prevent and control the ignition of coal at the mines.

The expanse of literature has indicated a lot of technologies by different authors which aimed to develop an effective method to prevent and control spontaneous coal combustion. Some of these technologies include gel foams [1, 3, 7-9], three-phase foams [10-12], grouting [13-15], inert gas injection [16, 17], and inhibitors [18-20]. It is worth noting that these technologies were all effective and efficient at the times that they were proposed or developed. However, with more advancements in technology, some technologies were deemed more efficient and effective in preventing spontaneous combustion than others. Some authors argued that the introduction of a gelatinizing agent, such as a Water Glass and a coagulant $NaHCO_3$, into the surfactant solution was very effective in the prevention of spontaneous combustion [9]. However, others also posit the addition of more polymers to a gel, making it very effective in the prevention of spontaneous combustion [3].

Given that there has been a lot of research work on the development of technologies that can reduce spontaneous combustion in coal mines, it is imperative to assess the overall effectiveness of these strategies. Since there is no prior research on a systematic review and meta-analysis of such data, this helps to integrate all the findings and propose efficacies in these reports. This systematic review, for the first time, summarized the published reports of spontaneous combustion technologies in three notable journals, Fuel, Energy, and Applied Energy journals, because of their known credibility of publishing quality data on safety engineering-related discourse. The purpose of this review is to establish the most effectiveness technology based on its characteristics and efficiency. Thus, the methodological qualities of the papers were also evaluated

### 1.2 PICO Framework

The literature searches form the underlying basis of systematic reviews, and its quality is crucial to the overall quality of the systematic review [21]. The use of the four-part PICO model to facilitate searching for a precise answer is recommended [22]. A clinical question (clinical in this context does not apply to medical study, it refers to a scientific endeavor) must be focused and well-articulated for all four parts: the population or problem (P), the intervention or exposure (I), the comparison intervention or exposure (C), if relevant, and the outcome of interest (O). In this study, the PICO element was used as the framing model for the search.

#### 1.2.1 Participants (P)

The characteristics of coal mines are susceptible to spontaneous combustion, considering factors such as coal type, geological conditions, and mining methods.

#### 1.2.2 Interventions (I)

Systematically review and analyses existing technologies employed for mitigating spontaneous combustion in coal mines, including but not limited to monetization, ventilation strategies, and monitoring systems

#### 1.2.3 Comparisons (C)

Compare the efficacy of different technologies in preventing and controlling spontaneous combustion incidents within coal mines, considering variations in scale, cost, and environmental impact.

#### 1.2.4 Outcome (O)

Assess the effectiveness of the identified technologies in reducing the occurrence and severity of spontaneous combustion events, with a focus on safety improvements, operational efficiency, and environmental sustainability.

## II. METHODS

### 2.1 Data sources and searches

The search for data was conducted on the Scopus database because of its vast database and connection with a wide of engineering journals. The search terms linked terms related to technologies for spontaneous coal combustion and preventive technologies. The search terms which was used included; ( TITLE-ABS-KEY ( "spontaneous coal combustion" OR combustion OR ignition OR explosion OR "coal explosion" OR "Spontaneous ignition" ) ) AND ( TITLEABS-KEY ( "Technologies" OR gels OR foams OR "gel foams" OR "Polymer gel foam" OR grouting OR "three-phase foam" ) ) AND ( TITLE-ABS-KEY ( "prevention" OR "Curb" OR "Control" OR "Suppression" ) ) AND PUBYEAR > 2000 AND PUBYEAR < 2024 AND ( LIMITTO ( LANGUAGE, "English" ) ) AND ( LIMIT-TO ( EXACTSRCTITLE, "Fuel" ) OR LIMIT-TO ( EXACTSRCTITLE, "Energy" ) OR LIMIT-TO ( EXACTSRCTITLE, "Applied Energy" ) ). In addition to the search results that were received, the references list of the articles was searched to find other works that fit the main objective.

### 2.2 Eligibility Criteria

This review sorted for primary research studies that prepared and experimented with technologies that can be used for the prevention and control of spontaneous combustion in coal mines. Thus, the eligibility criteria were studies published in English from 2000 to 2024 which were published in the following journals: Fuel, Energy and Applied Energy. The studies also need to assess the quality of the technology by evaluating its characteristics against the various characteristics of spontaneous combustion. This study excluded papers on the reviews and secondary data analysis of technologies used to prevent spontaneous combustion. Finally, the included papers examined the thermal ability, the water retention rate, the inhibition characteristics, and the viscosity of the technology that was experimented with. This provided the ground to thoroughly compare the studies against each other to identify the efficacies of all the papers and makes substantive future directions for new experiments and technologies. Figure 1 illustrates the systematic process used in the data collection process. A total of 29 published articles [1-9, 12, 23-42] were included in the study.

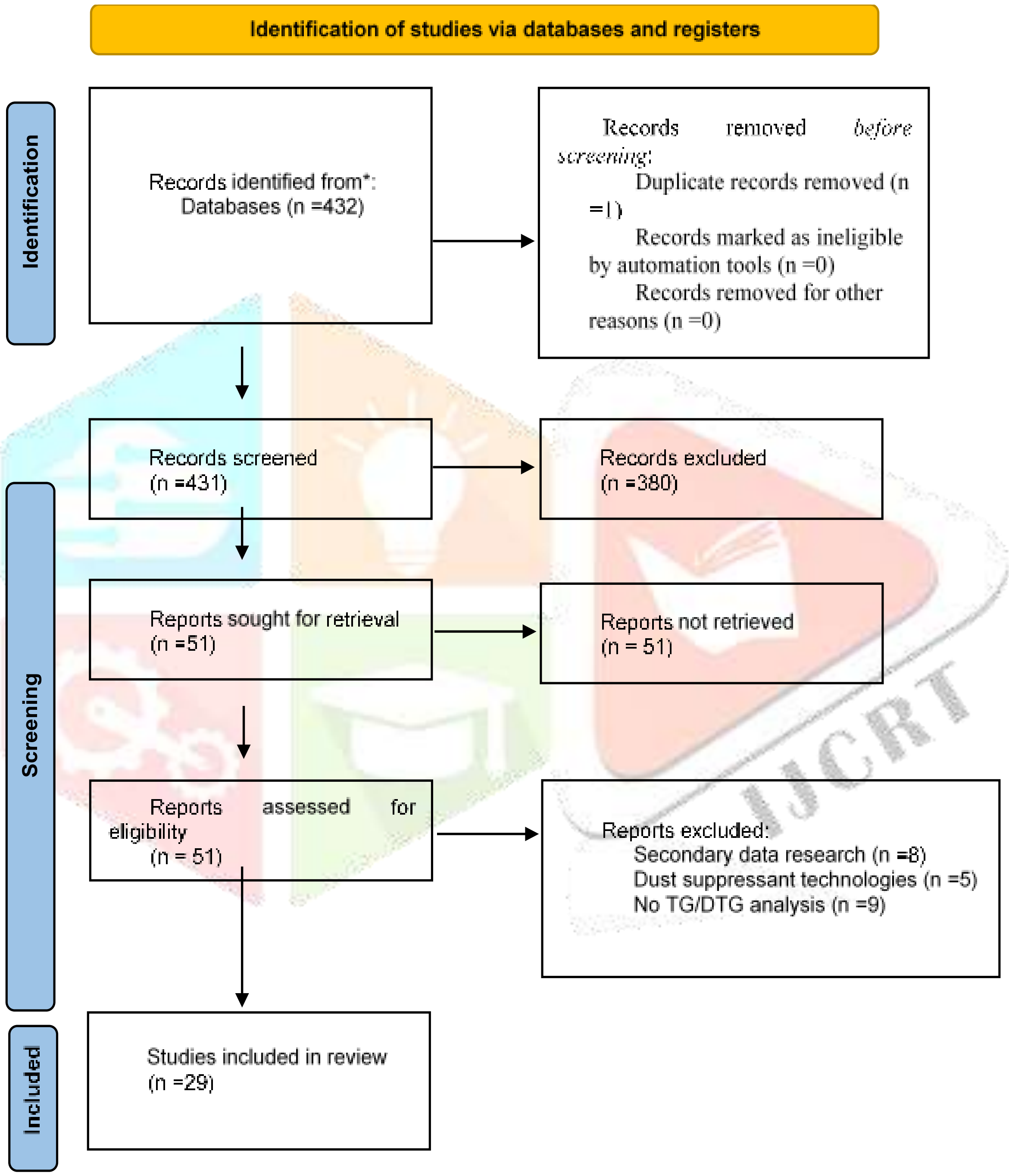


Figure 1: Preferred Reporting Items for Systematic Reviews and Meta-Analyses Flowchart from Record Identification to Study Inclusion

## 2.3 Data Management

A major purpose of this systematic review is to assess the quality of data published in the field of spontaneous combustion thus, it is imperative to thoroughly outline the steps employed by the researcher to ensure validity and reliability of this study. Search results were exported from Scopus to the Ryyan reference manager where duplicates were removed. The author screened the articles unbiased and extracted data from all the studies that were included in the study as shown in Table 1. The methodological quality of the included data was further assessed.

## III. RESULTS

### *Summary of Key Findings*

This review included 29 selected articles which reported on the technologies that have been used to prevent and control spontaneous combustion in coal mines. This review combined narrative writing and meta-analysis; seven articles focused on gels [1, 24, 28, 32, 35, 36, 40], fourteen studies on gel foams and gel-stabilized foams [2, 4-9, 12, 25, 30, 33, 38, 39, 41], three studies on inert gas and aqueous solution injection [29, 34, 37, 42], four studies on inhibitors [23, 26, 27, 31], and one study on three phase foam.

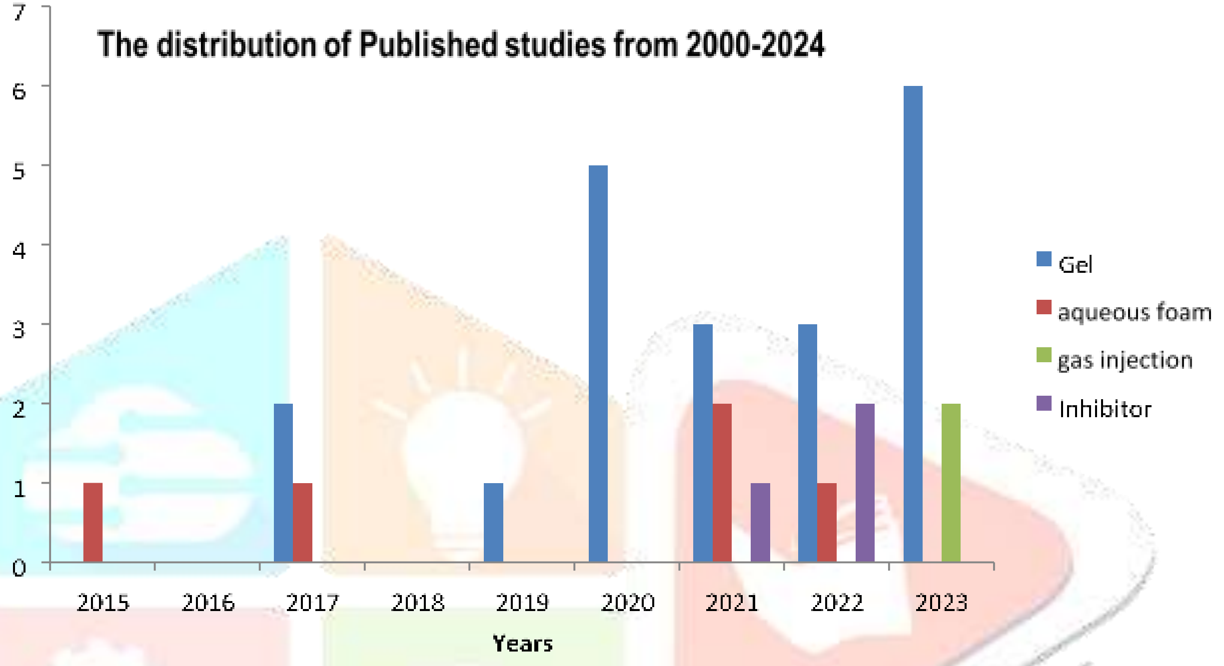


Figure 2: The distribution of published studies from 2000 to 2024

There have been enormous studies on the technologies used to prevent spontaneous however, there is a lot of focus on gels as illustrated in Figure 2. Thus, the discussion is made on these themes; gels, gel foams and gel stabilized foams, inert gas and aqueous solution, inhibitors, and three-phase foams.

## IV. DISCUSSION

### 4.1 Gels

Gels have been proven in the expanse of literature to be a great technology that can be used to prevent spontaneous combustion in coal mines. However, the efficiency of each gel is dependent on the content of the gel. The studies that were included in this review indicated that the addition of polymers with a high thermal stability among other factors improves the prevention of spontaneous coal combustion. The microstructure of the konjac glucomannan (KGM) and expandable graphite (EG) prepared by Yu et al. [40] presents a homogeneity among the networks which in tend makes it denser as shown in Figure 3. The density and the physical strength created by this network are what help them gel to isolate oxygen and the carbon monoxide concentration. In the preparation of a composite gel by Wang et al [36], the gel was similar to that of Yu et al, except for the differences in the added polymer. The authors who propose the use of gels instead of three–phase foams think that the three-phase foam is poorly stable and cannot withstand heat supplied by surrounding rocks [43]. The microstructure of the KGM@FA gel, as illustrated in Figure 3 b, shows a strong interconnected network and a high level of homogeneity. These characteristics of gels help in the creation of a colloid which prevents the contact of the coal with enough oxygen to prevent spontaneous combustion and other mine-related ignition at the coal mines. Also, the evenly distributed pore diameters in the microstructure of the gel create high water retention capabilities of the gel thus, it does not change its structure easily to expose the coal enough to dangerous gases such as methane [24, 28].

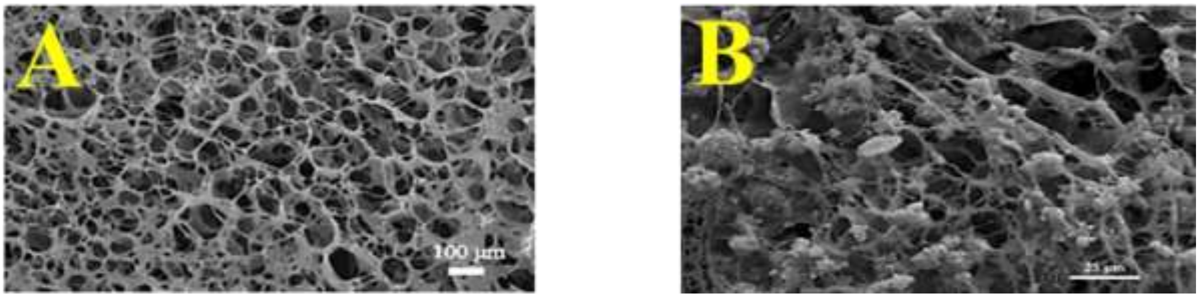


Figure 3:(a) microstructure of KGM@EG [40]; (b) microstructure of KGM@FA gel[36]

The emission of oxygen by the mined coal and the potential oxidation process is a major chemical reaction that results in spontaneous combustion. The CO concentration of the coal after the application of the technology was examined in the studies. The differences in the concentration of CO in the samples explain the efficiency of different technologies. At 2000C, MS/CMC-Al3+ gel [32] which was produced with Sodium carboxymethyl cellulose, Coal mine sludge and Polyaluminium chloride, had the lowest concentration of CO as illustrated in figure 4. This result, however, does not lead to the conclusion of the best method for the prevention of spontaneous combustion it rather gives an idea of how each technology can isolate CO. Other important indicators such include thermal stability of the method, the peak variations of the isolation of other gases and the temperature variations. As much as the gel technology showed a great way of preventing spontaneous combustion, there were some weaknesses in these technologies. KGM @ EG [40] had a reduced viscosity under high shear stress which can cause the exposure of the coal when it is not restored on time. KGM@FA [36] on the other had a relatively higher viscosity under high stress however the gelation time was longer than KGM @ EG.


Figure 4: CO concentration in Coal Samples and Gel Technologies in 200 °C

This means that the gel might not be ready on time when not prepared early after the coal is mined. Also, if it is prepared earlier than expected then it might be as effective as the other ones. Fan et al [3] discovered that when coagulant and polymer plasticizer is added to surfactants the gelation time decreases. The plastogel prepared by Fan et al [3] which included adding coagulant, polymer plasticizer, and bentonite into the water glass solution was among the gels with lower CO concentration compared to other studies with CO concentration below 10 ppm and the temperature was controlled at 27–29 °C, which ensured a safe rack-withdrawal procedure of the working surface. About other studies, the outcome of this study was tested in the working face of the mine Shandong Longyun Coal Industry [3]. The P(AA-co-AM)/WG gel [28] can also gelate rapidly using the high ground temperature. Gelating time has been one of the setbacks in the preparation of gel foams, however, current studies have solved this with the addition of other polymers that catalyze gelation. A typical example of the gelation process and how gels prevent spontaneous combustion is illustrated in Figures 5 and 6.

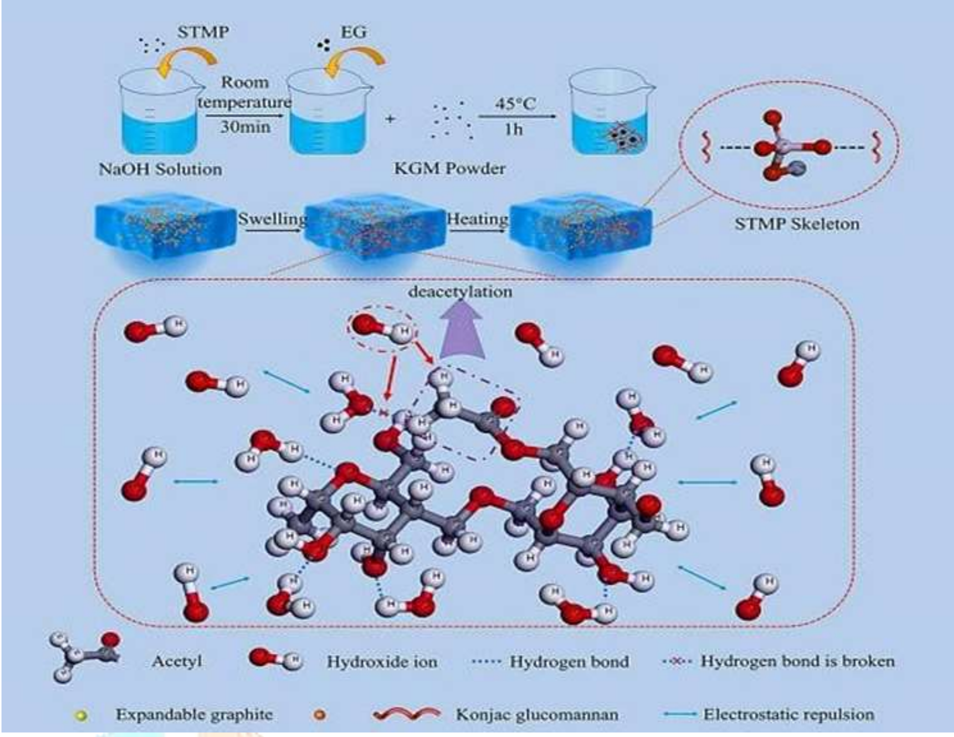


Figure 5: Detailed procedures and specific preparation processes of the KGM@EG gel [40]

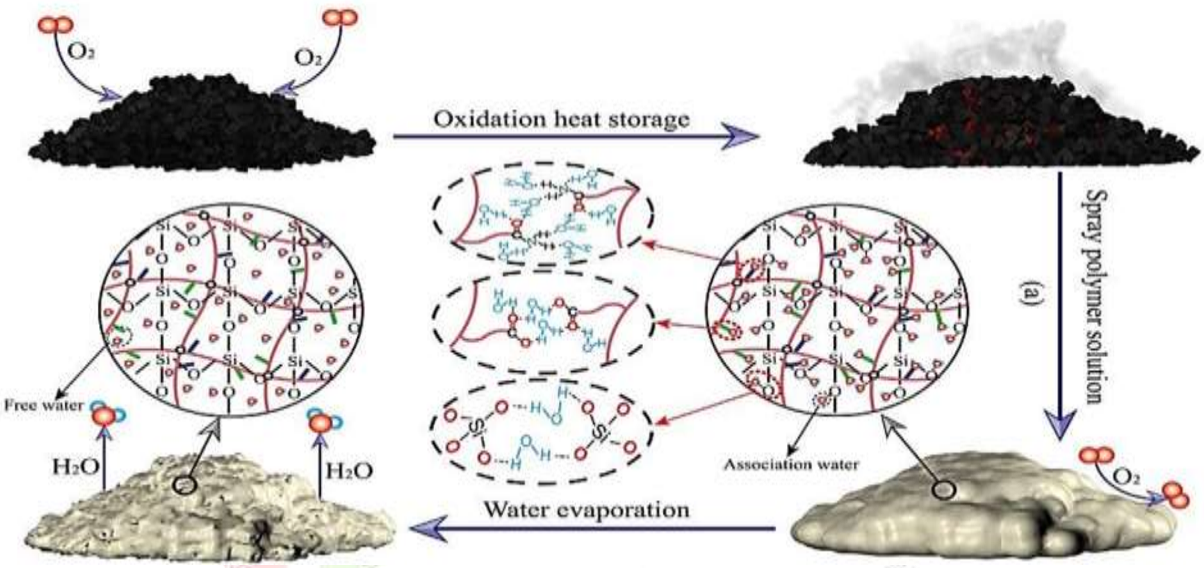


Figure 6: Flame retardation process of mechanism of P(AA-co-AM)/WG gel [28]

### 4.2 Gel foams and gel-stabilized foams

Gel foams are differentiated from gels in this write-up based on how both of them are prepared and the expectations of each researcher. As discussed in the previous section, gels only focus on the dense colloid that is formed after the chemical combination of foaming agents (FA) foaming stabilizers which are often polymers and cross-linking agents. However, gel foams are also focused on the foams formed after the mixing of materials. This review identified fourteen published papers that prepared gel foams, gel-stabilizer foams, and three-phase foams [2-9, 12, 25, 33, 38, 39, 41]. The literature on gel foams and for that matter gel-stabilized foams and three-phase foams, the foam itself is a thermodynamically unstable system, and there is still the problem of foam rupture and water loss, which weakens the long-term coverage and suppression effect of the gel foam on the coal [3]. Thus, there is the need for scientists to increase the time of gel foam acting on coal to improve the performance of gel foam and develop gel foam with stability and film-forming properties and a good inhibition effect which is seen as idle to prevent and control spontaneous combustion. The efficiency of the gel foams is dependent on the film formed after the production of the foam as illustrated in Figure 7.

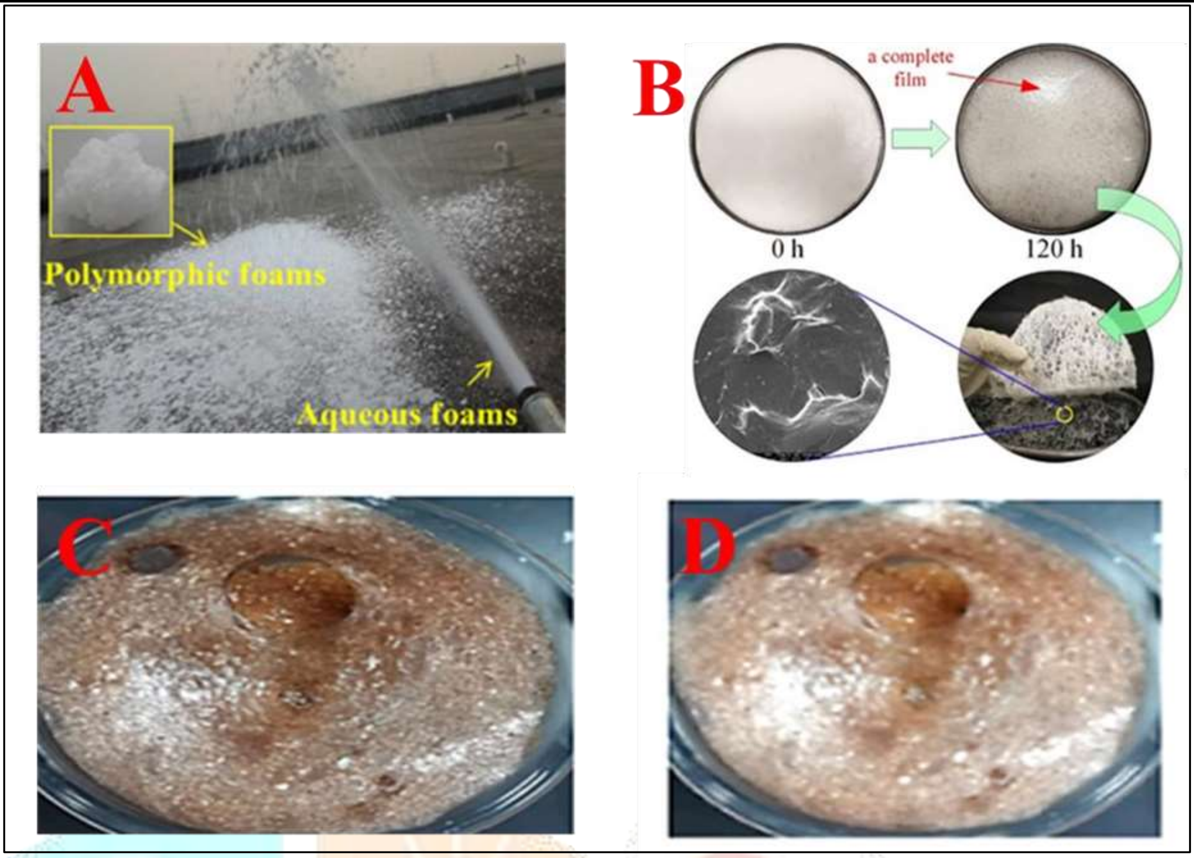


Figure 7: (a) Aqueous foam [2] (b) gel-stabilized foam [4] (c) anti-oxidant gel foam [7] and (d) three-phase foam [3]

From Figure 7, we deduced that gel foams are classified under four sub-themes: aqueous foams, gel-stabilized foams, gel foam and three-phase gel foams. The pictorial similarity between the antioxidant gel foam and three-phase foam can be attributed to the presence of Polyacrylamide (HPAM). The colloid that each foam produces in the gelation process is what covers the coal and isolates it from oxygen and carbon monoxide to prevent it from spontaneous combustion. Polymorphic foam (PF) was proven to inhibit the formation of new –CH2/CH3 and –OH functional groups in the process of coal low-temperature oxidation. This is because is well known that the 3700–3100 cm–1 region corresponds to the –OH vibration peak for alcohols, water, carboxylic acids and phenols, and the 2975–2820 cm–1 region corresponds to the – CH2/CH3 vibration peak [2]. However, the PF technology indicated almost no alkyl and hydroxyl groups as compared to raw coal at 120 and 1500. One major similar finding that runs through all the studies includes the higher thermal stability and great water retention rate which was a result of higher crossing point temperature, and lower emission of carbon monoxide and ethylene for treated coal by gel-stabilized foam [4].

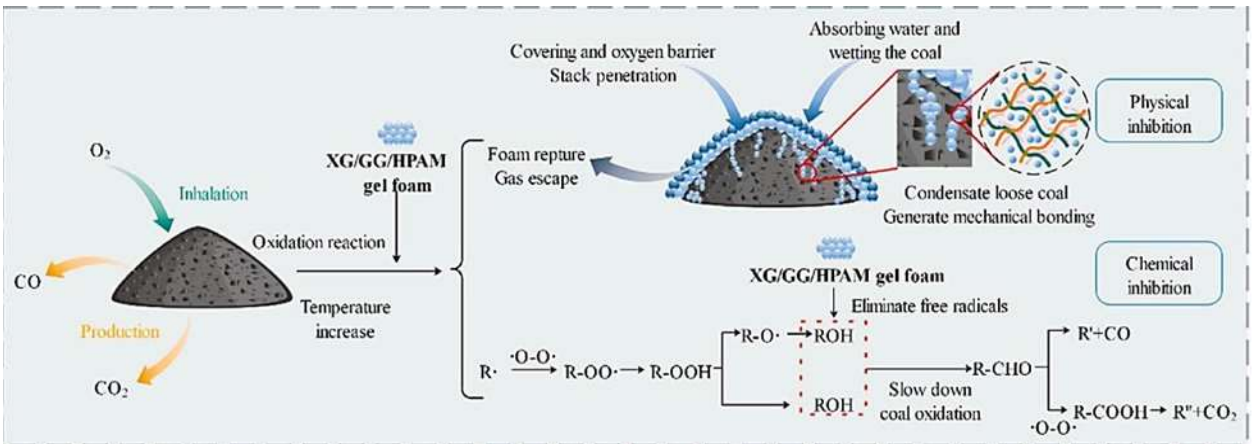


Figure 8: Schematic diagram of the process of suppressing coal spontaneous combustion by XG/GG/HPAM gel foam [3]

### 4.3 Inhibitors

Thermo-gravimetric analysis (TG) and Differential Thermo-gravimetric analysis are the main analyses used to examine the thermal stability of inhibitors as demonstrated in the articles reviewed in this section. The analysis is always conducted between raw coal and raw technology to assess the efficiency of the inhibitor [23, 26, 27, 31].

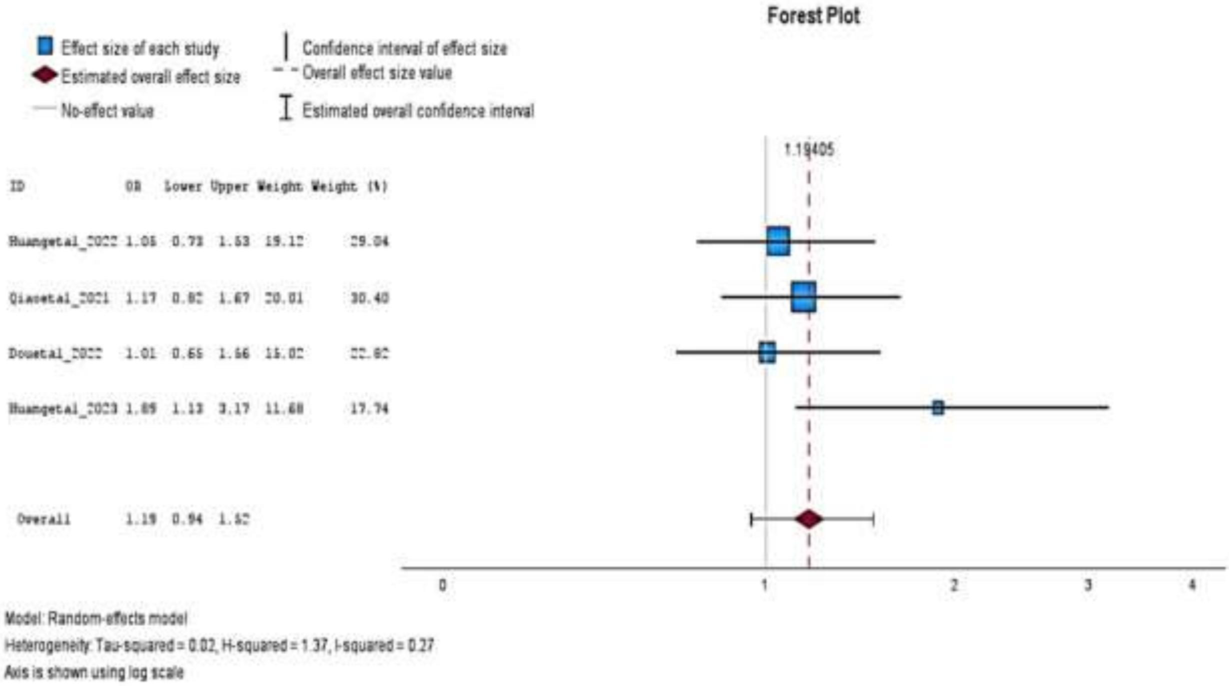


Figure 9: A forest plot of inhibition technology for spontaneous combustion

The figure above shows heterogeneity between the studies that as conducted on inhibition technologies to prevent spontaneous combustion. The I2 =0.27 indicates the internal variability of the inhibitor to prevent spontaneous combustion, however, because the I2 is less than 50% it means its impact and variability is not high. Also, all the studies were pooled around 1.00 (94% Cl: 1.19-1.52) which indicates a high accuracy in the replicability of the findings and the appropriateness in the use of the model. Furthermore, it can be argued that the studies do not overlap and that the conditions in one study are different from the other which influenced the use of the random effect method (REM). The next section focused on gas and solution injection technologies.

### 4.4 Gas and Aqueous Injection

This review found four articles [29, 34, 37, 42] that prepared and experimented with the use of gas and aqueous injection technologies to prevent spontaneous combustion. Xi et al [37] argued that solid particles in the foam could not hold water efficiently, and the half-life of three-phase foam was below 10 h, causing the loss of water easily during foam diffusion. Thus, the backdrop to introduce polymers and water glass into foam as stabilizers to lengthen the half-life and water retention time was to build a system more efficient than the solid particles. Below is an example of an aqueous solution injected into coal

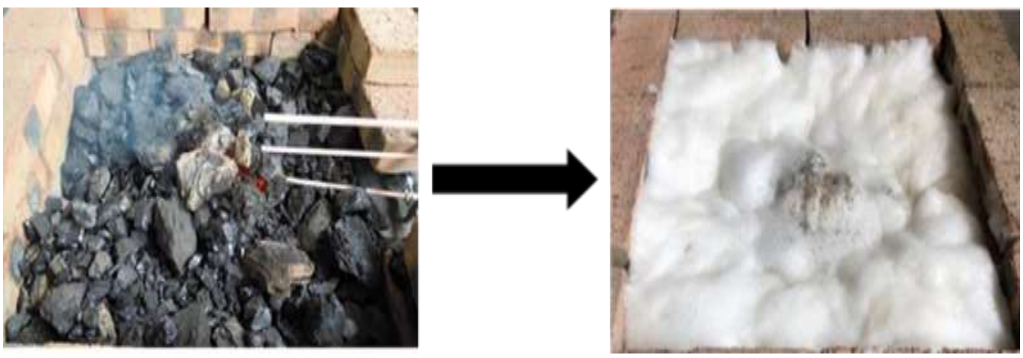

Figure 10: Coal-fire extinguishment performance of high-water-retaining foam [37]

Figure 10 shows high water-retaining foam covering the burning coal pile completely after an hour of injection. This implies that the aqueous solution added to water glass foam could still be alive to shield the coal even after 1 h, which revealed the significant stability of the high water-retaining foam.

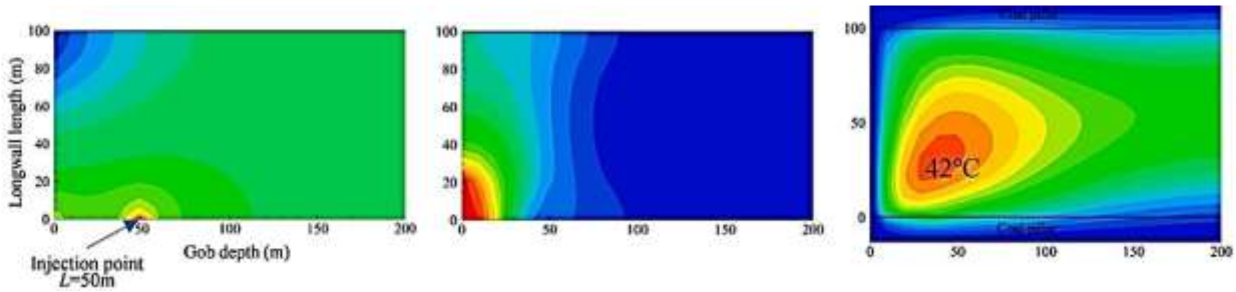


Figure 11: Effects of nitrogen injection depth (L) on the evolution of each physical field (QN = 700 m3 /h, T0 = 5 ◦C

The development of the pressure field, oxygen concentration field, and solid skeleton temperature field are shown as functions of nitrogen injection depth (L) in Figure 11. The size of the high oxygen concentration zone on the air intake side of the gob shows a tendency of first reducing and then growing as the nitrogen injection depth rises. A similar pattern of change is also seen in the highest temperature of the gob region. The highest temperature (Tmax) in the gob, for instance, is 44.2 $^{o}$C when L = 10 m; it climbs to 41.1 $^{o}$C when L = 30 m, and then to 42.7 $^{o}$C if L goes to 50 m. It suggests that the maximum amount of suppression of the rise in coal temperature may be achieved by nitrogen injection at a theoretically ideal depth [29]. The aqueous technique and gas injection are the two main injection technologies used in this area to avoid spontaneous coal combustion.

## V. Conclusion and Recommendation

The study highlights the several methods that have been presented in the literature, such as inhibitors, inert gas injection, gel foams, and three-phase foams. The main goals are to understand the mechanics driving spontaneous combustion and creating solutions through these technological developments. Notably, the write up recognizes how technological progress has led to the gradual discovery of increasingly effective techniques. Gels are emphasized as useful tools for averting spontaneous combustion, particularly those that include polymers with strong heat stability. Expandable graphite [21] and konjac glucomannan (KGM) are two examples of gels whose microstructure is essential for forming a thick colloid that separates coal from oxygen and carbon monoxide. The write up also explores gel foams, separating them from gels according to expectations and preparation. The review suggests that in order to improve gel foams' capacity to prevent spontaneous combustion, their stability and film-forming qualities should be strengthened. The efficiency of gel foams is related to the film that forms after manufacture.

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**Table 1: Summary of included studies**

| Author, Year | Technology type | Materials | Outcome |
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| Fan et al.,2020 [24] | gel | Plastogel (bentonite with MW = 360.31, coagulant with content ≥ 99.5%, pH value (50 g/L, 25 °C) ≤ 8.6, and water insoluble matter ≤ 0.01%) | Compared with the conventional water glass gel, the plastogel had better viscoelasticity, which is beneficial for enhancing the adhesion of plastogel on the surface of the coal body and strengthening the protection of plastogel on the coal body. |
| Li et al., 2020 [28] | gel | P(AA-co-AM)/WG gel (acrylic acid (AA, analytically pure), content≥99.5%; acrylamide (AM, analytical pure), molecular weight: 71.08, and content: 99.0%; potassium per sulfate (KPS, analytically pure), molecular weight: 270.32, and content: 99.5%; sodium hydroxide (NaOH, analytically pure), molecular weight: 40.00, and content: 96.0% | The rheological experiment results indicate that the elasticity of the P(AA-co-AM)/WG gel was greatly enhanced so that it could move with the coal seam and automatically deform according to the shape of the cracks; thereby, accomplishing the longterm plugging for the fracture between the coal seams |
| Han et al., 2022 [25] | gel | Sodium alginate (SA, 90 wt%) Calcium Llactate (CL, USP), Tea saponin (TS, industrial grade, content ≥ 98 wt%), Alkyl Glycoside (APG, Industrial Grade). The coal sample is obtained from Ningxia Wangwa Coal Co., Ltd. | SC-GF has an excellent isolation effect; it can impede the contact of carbon radicals and oxygen-containing functional groups with oxygen during the coal chain reaction. Meanwhile, SC-GF has high water retention, and it can effectively reduce the temperature of coal. Therefore, SC-GF shows excellent fire prevention and extinguishing properties. |
| Wang et al, 2021[36] | gel | Konjac glucomannan (KGM) is a natural water-soluble macromolecule that is extracted from the tubers of Amorphophallus | The KGM@FA gel presents excellent fire extinguishing properties and is low-cost and environmentally benign, showing |

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| | | konjac, which is native to China. Sodium trimetaphosphate (STMP) is a cyclic phosphate that cans crosslink hydroxyl groups on the KGM molecule chains | great potential as a novel material for the prevention coal spontaneous combustion and the extinguishment of coal fires. |
| Xue et al., 2023 [38] | gel | The diameter of the particles of hydrophobic nano-silica was less than 30 nm (H18, Shanghai Macklin Biochemical Co., Ltd. China). Polyvinyl alcohol is a white powdered solid (PVA-1788, [–CH2CHOH–]n, degree of alcoholysis: 87.0–89.0% (mol/mol), Portland cement (PC, Qingdao Shanshui Innovative Cement Co., Ltd.) and ordinary grade II fly ash (FA, Gongyi Yuanheng Water Purification Material Factory). Sodium silicate (WG, Baume: 40, modulus: 3.3, and content: 34%, Shandong Yousuo Chemical Technology Co., Ltd.) | The H18 particles have high pozzolanic activity and react with calcium hydroxide to form C–S–H, which improved the compressive strength of JCSF. However, due to resource constraints, JCSF is currently in the laboratory research stage, and its field applications will be the focus of future research. |
| Cheng et al., 2017[1] | gel | AA: acrylic acid; KPS: potassium persulfate; MBA: N, N-methylenebisacrylamide. AA (g) 6, MBA/ AA (%) 0.8, Na2CO3 (g) 0.25, KPS/ AA (%)1.5, Neutralization value (%) 70. | The gel effectively reduced the thermal radiation as well as the amount of CO generated and prevented re-ignition. Compared to TSG, PAM, and water, IG exhibited distinct firefighting advantages, making it ideal fire prevention and extinguishing material. |
| Xi et al., 2017 [2] | gel | Industrial-grade polycaprolactone (PCL; Letai chemical, particle sizes<38.5 lm); industrial-grade polyethylene oxide (PEO, Letai chemical, particle size <38.5 lm); sodium silicate solution (Na2O,10.6%, SiO2, 26.5%, Letai | The C–O and C@O are the main functional groups of PF, which may make PF surface much more hydrophilic. PF inhibits the formation of new –CH2/CH3 and –OH functional groups in the process of coal low-temperature oxidation |

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| | | chemical); sodium dodecyl sulfate(SDS; Aladdin, 99%); industrial-grade organic acid (Letai chemical, 85%); distilled water and the coal sample (Nanjing Wharf, Tianjin Port, China, particle size <0.15 mm). | |
| Liu et al ., 2023[29] | gas injection | The high purity nitrogen produced by the generator was cooled to − 30 ◦C and then injected into the gob area, which played the role of fast cooling and inerting the high-temperature coal. This technology had successfully applied in Zhuxianzhuang (ZXZ) Coal Mine in China, with remarkable fire prevention effect on-site. | A reasonable increase in nitrogen injection volume and an appropriate decrease injected nitrogen temperature can improve the fire prevention effectiveness, but there is an optimal depth of nitrogen injection point that most effectively inhibits the CSC. |
| Shi et al., 2022 [33] | gel stabilized foam | The gel-stabilized foam fluids were mainly composed of thickening agent (TA), crosslinking agent (CA), foaming agent (FA), and Water. | For the hidden coal fire inside the porous media, the temperature decreased quickly without obvious rebound phenomenon after contacting the foam fluids, which revealed the good prospect of gel-stabilized foam to prevent and control coal fire in coal mines. |
| Fan et al., 2023[3] | three phase foam | Surfactants were used as foaming agents (FA). Anionic polysaccharide xanthan gum (XG) and galactomannan guar gum (GG) were compounded as foam stabilizer (FS). Metal cross-linker and gelling agent polyacrylamide (HPAM) were used as the gel system. Lab-made inhibitor. The ordinary foam used contains only FA; gel foam-A adds FS to foam; gel foam-B adds gel system to foam; XG/GG/HPAM gel | XG/GG/HPAM gel foam can effectively inhibit coal spontaneous combustion. It reduces coal-oxygen contact by covering oxygen insulation and condensation plugging. After XG/GG/HPAM gel foam treatment, the CO release during low-temperature oxidation of coal is significantly reduced. The inhibition rate is 74.48% at 100 ◦C, which is 43.63% higher than that of ordinary foam. |

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| | | foam adds FS and gel system to foam. To further improve the inhibitory effect of XG/GG/HPAM gel foam, the lab-made inhibitor was added. | |
| Yu et al., 2023[40] | gel | A neoteric irreversibly thermo-sensitive composite gel based on konjac glucomannan (KGM) and expandable graphite (EG) was elaborately synthesized for preventing SCC disasters and coal fires. | Temperature programming experiment and fire extinguishing experiment suggest that the KGM@EG composite gel could effectively inhibit the increase in coal temperature, heat buildup, and CO formation over the oxidation and combustion process of coal, which would lower the possibility of SCC and coal fires. |
| Shi et al., 2019[4] | gel-stabilized foam | Microbial polysaccharide XG and galactomannan biopolymer HPG were used to prepare the synergistic polymer as thickening agent (TA). Crosslinking agent (CLA) with the delayed crosslinking characteristic was mainly composed of organic boron. Foaming agent (FA) was home-made by China University of Mining and Technology, mainly including the sodium alpha-olefin sulfonate surfactant and fatty alcohol polyoxyethylene ether surfactant, and the optimal concentration of foaming agent was 3 g/L in the gel stabilized foam system. | Gel-stabilized foam demonstrated excellent water-retaining property and film-forming characteristic, which would form a complete film to cover the coal. It also could form a layer of gel to fill the pores and cracks on the surface of coal to isolate coal from the oxygen, and further inhibited the lowtemperature oxidation reaction of coal. The simulation experiment of spontaneous combustion of coal verified the better efficiency for gelstabilized foam to inhibit spontaneous combustion, which could be revealed by higher crossing point temperature, lower emission of carbon monoxide and ethylene for treated coal by gel-stabilized foam compared to traditional foam. |

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| Sun et al., 2022[34] | solution injection | The inhibitor solution is prepared by mixing the surfactant and inhibitor. The specific process is as follows. To prepare the surfactant solution, weigh 0.25 g of SDS powder, slowly pour it into a beaker containing 500 mL of distilled water, and stir well. To prepare the inhibitor solution, add MgCl2.6H2O, NH4H2PO4, NH4, Hn+2PnO3n+1, and CaCl2 into a beaker of 100 mL distilled water respectively, stir well, and formulate the inhibitor solution according to the desired concentration. | When the concentration of the inhibitor solution is constant, the contact angle of the inhibitor solution with a 1:1 proportion of NH4H2PO4 and SDS reaches the lowest value of 21.9◦, which is significantly the lowest among the four solutions. This shows that the addition of SDS improves the fluidity and injection effect of the inhibitor solution, enabling the prevention and control of spontaneous coal combustion. |
| Xue et al., 2020[9] | gel-stabilization foam | Water glass (WG, 40 Baume degree, a modulus of 3.3 and 34% content. NaHCO3 with the purity ≥ 99.5%, pH value (50 g/L, 25 °C) ≤ 8.6, and water insoluble matter ≤ 0.01% (analytically pure, Yantai Shuangshuang Chemical Co., Ltd., China). Hexadecyl trimethyl ammonium bromide (CTAB) (analytically purity, Chengdu Cologne Chemicals Co., Ltd., China). Modified alkyl glycoside (APG) with the purity of 50% (Shanghai Fakai Chemical Co., Ltd., China). Carboxymethylcellulose (CMC) with the sodium content: 6.5–8.0, pH value: 6.5–8.0 (analytically pure, Tianjin Kaitong Chemical Reagent Co., Ltd., China). Polyethylene glycol (PEG1500, analytically pure, Shandong West Asia Chemical Co., Ltd., | The results from the inhibition tests indicate that, compared with the other coal samples, those treated with GSF have lower released amount of CO and heating rate. During the fire extinguishing process, GSF exhibits good fluidity and accumulation, allowing penetration into the cracks of loose coal body, thus uniformly covering the surface of burning coal body, plugging the air leakage passage and blocking the air. In addition, the GSF was characterized by good fireextinguishing performance, fine cooling effect, excellent thermal insulation property and smaller CO release. |

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| | | China). Modified silicone polyether emulsion (MPS, with the purity of 55%, Linyi lvsen Chemical Co., Ltd., China). Fatty alcohol polyoxyethylene ether sodium sulfate (AES, with the purity of 70%, Linyi lvsen Chemical Co., Ltd., China). Sodium dodecyl sulfate (SDS, analytically pure, Linyi lvsen Chemical Co., Ltd., China). | |
| Huang et al., 2023[26] | Inhibitor | We dissolved 1 g nano-ATP in 100 ml of ethanol solution with 90% concentration, which we placed in a KQ-50E ultrasonic cleaner for ultrasonic dispersion for 10 min. We added 2 ml of KH-570 into the nanoATP solution, and the modified nan- ATP solution was obtained after continuous stirring for 2 h with a DF-101S magnetic agitator. Then, a 2- 16R centrifuge was used to centrifuge the modified nano-ATP solution for 10 min (rotation speed 2000 rpm; centrifugal force 390 g), and the supernatant of the centrifuge tube was filtered. The separated modified nano-ATP was placed in a DH- 101 drying oven, dried at 100 °C for 5 h, the modified nano-ATP powder was then obtained by grinding with a Retsch PM100 ball mill | The environmental performance of the composite inhibitor was studied with gas analysis. The results showed that the composite inhibitor effectively reduced the production of CO, CO2 and CH4 during spontaneous coal combustion. The microscopic inhibition mechanism of the composite inhibitor was analyzed by diffuse reflection infrared spectroscopy, and it was proved that the composite inhibitor effectively passivated the free hydroxyls of the active groups in the coal. Additionally, the composite inhibitor inhibited the consumption of aliphatic hydrocarbon in the coal, reduced the generation of carbonyl groups, and effectively promoted the formation of stable functional group ether bonds in the coal. |
| Qin et al., 2015[12] | aqueous foam | FA particles used in the present experiments were supplied by the Chaili coal mine Co. Ltd. Sodium dodecyl sulfonate (SDS, surfactant) was obtained from Sinopharm | The coal acceleration oxidation experimental results showed that these Pickering foams can improve the coal thermal stability and effectively inhibit the coal oxidation |

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| | | Chemical Reagent Co. Ltd. and used without further purification. Freshly distilled water (twice distilled) was used in all solution preparation. Coal samples were collected from the Liangbaosi Colliery in Shandong Province, which were processed to remove the surface layers and crushed in an oxygen-free glove box. The crushed coal samples were then sieved to control the particle size between 0.25 mm and 0.8 mm. The sieved coal particles were kept under an inert atmosphere before use. | process by increasing CPT and reducing CO emission. In conclusion, the prepared FA-stabilized Pickering foams effectively inhibited the coal oxidation process. This suggests that the aqueous, low-cost and nontoxic FA-stabilized Pickering foams have application potentials in coal spontaneous combustion prevention and control |
| Qiao et al., 2021[31] | Inhibitor | Analytically pure Anhydrous calcium chloride (CaCl2) was bought from Tianjin Bailunsi Biotechnology Co., Ltd.), while span 80 with a content ≥ 99% was obtained from Shandong Yousuo Chemical Technology Co., Ltd. Ethyl cellulose (EC) with the viscosity of 9–11 mPa·s was obtained from Shanghai Aladdin Biochemical Technology Co., Ltd. Analytically pure ethyl acetate (CH3COOC2H5, purity ≥ 99.5%, molecular weight : 88.11) was purchased from Tianjin Guangfu Technology Development Co. Ltd. Food grade gelatin was obtained from Shandong Yousuo Chemical Technology Co., Ltd, while chemically pure sodium dodecylsulfate (SDS, MW 288.38) | SDS-CCMC had good inhibitory properties and was superior to the untreated SDS-Ca. It could inhibit the oxidation of methyl and methylene groups in the low-temperature oxidation stage. At the same time, the characteristic temperature of the coal sample treated with SDS-CCMC was higher than those of the SDS-Ca sample and the raw coal sample. The inhibitory rate could reach 83.8%, which is higher than 70.7% for SDSCa |

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| | | was bought from Tianjin Bailunsi Biotechnology Co., Ltd. | |
| Dou et al., 2022[23] | inhibitor | The majority of reagents used (including N-isopropyl acrylamide (NIPAm, A.R. grade), acrylic acid (AA, A.R. grade), lignin, N, N, N′, N′ - tetramethylethylenediamine (TEMED, A.R. grade), ammonium persulphate (APS, A.R. grade), N, N′ -methylene diacrylamide (MBA, A.R. grade) and sodium hydroxide (NaOH, A.R. grade) were purchased from local medical stations. | This paper analyzed the application of lignin to coal mineral hydrogels to prevent fire, and furthermore, realized the highvalue utilization of lignin in terms of improving the fire extinguishing performance of the hydrogel, and the findings may serve as a reference for the development of new types of hydrogel fire-extinguishing materials in future research. |
| Ma et al., 2023[7] | gel foam | Surfactant: Alpha olefin sulfonate (AOS, with the purity of 92 %). Sodium dodecyl sulfate (SDS, analytically pure). Cetyltrimethylammonium bromide (CTAB, analytically pure). Dodecyl dimethyl betaine (BS-12, 30 % aqueous solution). Caprylyl glucoside (APG, 50 % aqueous solution). All purchased at Shanghai Eon Chemical Technology Co. Foam stabilizer: Xanthan gum (XG). Guar gum (GG). All purchased at Shanghai Eon Chemical Technology Co. (3) Gel system: Polyacrylamide (HPAM, technical grade, Shandong Yusuo Chemical Technology Co.). Aluminum citrate (AlCit, technical grade, Shandong Yichen Biotechnology Co.). (4) Inhibitor: Super absorbent polymer (SAP, with the purity ≥ 94 %). Procyanidin (OPC, with the purity of 95 %). All purchased at | The temperature of coal samples treated with antioxidant gel foam entering the rapid oxidation stage is 30 ◦C higher than that of raw coal. The oxygen consumption rate is reduced by 69 %, and the inhibition rate can reach 74.48 % at 100 ◦C. At 120 ◦C, the CO and CO2 production rates are reduced by 72.43 % and 78.53 %, respectively. |

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| | | Shandong Yusuo Chemical Technology Co. | |
| Qiao et al., 2022[8] | gel foam | Polyvinyl alcohol (PVA1788, industrial grade), Sodium tetraborate ($Na2B4O7$ $10H2O$, industrial grade), Sodium bicarbonate ($NaHCO3$, analytically pure), Nanometer silica (H18), Sodium dodecyl sulfate (SDS, Chemical pure), Carboxymethyl cellulose (CMC, analytically pure). Sodium alginate (SA, analytically pure), Calcium Lactate (CL, analytically pure), Tea saponin (TS, industrial grade, content ≥ 98%) and Alkyl Glycoside (APG, industrial grade). | It was found that PGF could significantly inhibit the formation of methyl and methylene groups and reduce the consumption rate of active functional groups such as hydroxyl groups. In the fire extinguishing experiment, PGF can effectively extinguish coal flame by isolating the contact between coal and oxygen and can effectively avoid the resignation of coal after the fire extinguishing, and greatly prolong the time of fire prevention. Therefore, PGF is an ideal fire prevention material. |
| Zhang et al., 2021[41] | aqueous foam | Nano-ATH with an average particle size of 50 nm. The purity of MgCl2 is more than 98%, The coal samples were collected from 11 to 2 Coal of Zhujixi Coal Mine in Anhui Province, and smashed in a coal mill, then sieved until coal powder with a particle size of 0.15–0.55 mm was obtained. 11–2 Coal is gas-fat coal, its spontaneous combustion tendency grade is class II, and the shortest spontaneous combustion period is 58 days. | Compared with traditional retardants, the nano-ATH foam lengthened the TTI values of the coal samples to 176s. Moreover, the time of sustained combustion was shortened to 211 s, the peak heat release rate declined to 58 kW/m2 , and the peak smoke production rate declined to 0.0049 m2 /s, demonstrating the good flameretardant and smoke-suppression properties of the retardants. |
| Zhang et al., 2021[6] | gel foam | All six foaming agents (A–F) were surfactants with a mass fraction of active substances higher than 90%. They were all produced by Sinopharm Chemical Reagent Co., Ltd (Shanghai). Specifically, A, B, and C were anionic surfactants; D | The THR of coal samples with foamed gel is the lowest (28.87 kW/m2) within 1,200 s; meanwhile, the THR of coal samples with MgCl2 and raw coal samples is 45.46 and 49.97 kW/m2, respectively. Therefore, coal |

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| | | was a cationic surfactant; E was a nonionic surfactant; and F was a zwitterionic surfactant. | samples with foamed gel have outstanding retardation performance, which is related with the lower maximum HRR and THR in comparison with traditional retardants |
| Shi and Batao, 2021[5] | gel stabilized foam | The TA was composed of the synergistic polymer, while the CA was an organic complex. In addition, the FA was home-made in the laboratory and its optimal concentration was 3 g/L. The concentration of the FA used in gel-stabilized foam was 3 g/L. In addition, the effects of TA concentrations from 0−4 g/L and CA concentrations from 0−3 g/L on the film-forming properties of foam were analysed in this paper. | Experimental results indicated that the strong chemical reaction between the TA and CA in gelstabilized foam could provide the favorable conditions for foam to form the dense coverage film. This was mainly ascribed to the excellent water retention and long-term stability of gel-stabilized foam, which would delay the liquid drainage process to provide enough time for foam to form a thin film. |
| Wang et al., 2023[35] | gel | Hydroxypropyl methyl cellulose (HPMC) can be used to prepare temperature–sensitive hydrogels, depending on the internal hydrophilic and hydrophobic groups. Chitosan (CS) can increase the water content of the gel. Meanwhile, F-36 expansion microspheres (EM) can expand at 70–120 °C. Therefore, EM, HPMC, CS were selected to prepare inflatable temperature–sensitive hydrogel (HPMC–CS–EM). | The high temperature decomposition of the A50 gel ensured that more carbon residue covered the coal body, which had a strong oxygen isolating effect and inhibited in the slow oxidation stage. Finally, the ignition temperature was delayed (8.49 °C), increasing the apparent activation energy. |
| Ren et al., 2020 [32] | gel | Coal mine sludge (MS) was provided by Shandong Lilou Coal Industry Co. Ltd. The reagents used were Polyaluminium chloride (analytical grade, Tianjin Damao | The preparation of MS/ CMCAl3+ reused MS, which can reduce the pollution and cost, and the prepared gel has an excellent fire prevention performance. Therefore, it is an ideal |

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| | | Chemical Reagent Factory), Citric acid monohydrate (C6H8O7·H2O, analytical grade, Tianjin Hengxing Chemical Reagent Manufacturing Co., Ltd.), NaOH (analytical grade, Laiyang Economic and Technological Development Zone Fine Chemical Plant), sodium carboxymethyl cellulose (CMC) (analytical grade, Tianjin Kaitong Chemical Reagent Co., Ltd.), Gluconate-δ-Lactone (GDL, Anhui Xingzhou Pharmaceutical Food Co., Ltd.), and pulverized coal (120 mesh, high ash bituminous coal, Shandong Lilou Coal Industry Co., Ltd.) | novel type of clean, fire-fighting material. |
| Xi and Shi, 2021[37] | aqueous foam | Polymer composite (PC), a mixture of the microbial polysaccharide and galactomannan biopolymer, was used as thickening agent to stabilize the liquid foam. To further enhance the water-retaining property of foam, an organic boron complex (OBC) as crosslinking agent was employed to crosslink the solution in foam film to form the gel to hold the water. The above materials were provided by Guangpu Natural Products Co., Ltd., and used as received. Moreover, the home-made foam agent prepared form | Compared with traditional aqueous foam, high-water-retaining foam could hold water in film much longer time, which was more beneficial to for high-waterretaining foam to wet coal and control its spontaneous combustion. As a result, high-water-retaining foam showed the excellent fire extinguishment performance by fully covering the burning coal and extinguishing quickly, decreasing the temperature of burning coal from around 700◦C to 34.7 ◦C within 30 min. |
| Zhao et al., 2023[42] | gel stabilized foam | The cement used for the experiments was PO42.5 cement with a specific surface area of 360 m2 /kg and a density of 3.12 g/cm3. The chemical composition and physical properties | In this paper, a new method of synthesizing ultrastable PF using XG is presented. The results show that XG forms copolymerization network structure through hydrogen |

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| | | of the PO42.5 cement can be found in a previous study.32 The details about the foaming agent can also be found in a previous study.33 Xanthan gum (XG, USP grade) was obtained from Shanghai Maclean Biochemical Technology Co., Ltd., China, whereas fly ash was procured from Gongyi Yuanheng Water Purification Material Plant (China) | bonding, which can resist the thermodynamic instability of bubbles. The stability of PF was positively correlated with the XG content. However, the refinement of the XG on the bubble size became less and less pronounced as the XG content increased from 0.3 to 0.5 wt %. |
| Huang et 2022[27] | | The physical inhibitor polyacrylamide (PAM) and the nanomaterial silica aerogel powder (SA) were selected to intercalate a composite inhibitor. The product was a polymer-based composite (PAM/SA). Thereafter, PAM/SA was combined with the chemical inhibitor Ca(OH)2 to form a polymer-based composite inhibitor. | The idea of using nanomaterial to modify physical inhibitor and then compound with chemical inhibitor has a certain reference role in the Coal industry. However, due to the limited laboratory conditions and the Complexity of coal mine site, some new inhibitors has not been effectively applied. Therefore, if further research can optimize the process flow and reduce the preparation cost of new inhibitors, it will be Conducive to the progress of the industry. |