International Journal of Coal Science & Technology (2025) 12:47
https://doi.org/10.1007/s40789-025-00784-3

REVIEW

A review of water-based suppressants for coal dust suppression

Fangwei Han[1,2] · Mei Liu[1] · Fuhong Hu[1] · Guirui Niu[1] · Diandian Xue[1] · Yue Zhao[1] · Shengyong Hu[3] · Hetang Wang[4]

Received: 24 September 2024 / Revised: 12 December 2024 / Accepted: 14 March 2025

Abstract

The large amount of harmful particles in coal dust not only pollutes the production environment, affects the production efficiency and resource utilization of enterprises, but also poses a risk to human health. Effectively controlling coal dust is of great significance to clean production. Water-based dust suppressants are extensively employed to mitigate coal dust. This paper provides a comprehensive review of the water-based dust suppression materials for coal dust control. According to the difference of mechanism, the dust suppressants are divided into wetting type, hygroscopic coalescence type, cohesive agglomeration type, and composite type. The evaluation methods for dust suppressants key properties such as wettability, permeability, moisture absorption and water retention, and consolidation are summarized. The review results show that coal dust suppressants are no longer limited to a single dust suppression function. For example, it is necessary to develop multi-functional coal suppressants to meet the needs for synergistic suppression both coal dust and coal spontaneous combustion. Driven by the concept of green, low-carbon and sustainable development, attention should be paid to the development of bio-based environmentally friendly coal dust suppressants. In addition, the evaluation method system for the key performance of water-based dust suppressants should also be improved, and further research is necessary.

Keywords Coal dust · Dust suppressant · Evaluation method · Environmental-friendly material

1 Introduction

Coal is an important basic energy source in the world. However, a large amount of coal dust is easily generated during coal production, storage, transportation, and use, posing significant challenges to the workers' health, working environment, safe production, etc. (Bałaga et al. 2021; Faridi et al. 2022). In terms of health risks, taking China as an example, as the world's largest coal producer, the raw coal production is 4.71 billion tons in 2023, accounting for 51.8% of global production (National Bureau of Statistics of China 2024). Accompanying this is the fact that more than half of the pneumoconiosis cases are coal workers' pneumoconiosis (National Health Commission of the People's Republic of China 2024; Cao et al. 2024; Yu et al. 2024). On the other hand, when coal dust diffuses into the air, it can not only cause environmental pollution and reduce the service life of major underground equipment, but also cause loss of coal resources (Yang et al. 2022a; Wang et al. 2022; Yu and Zahidi 2023). Additionally, coal dust will decrease visibility within workspaces and elevate the likelihood of accidents. (Liu et al. 2022c; Luo et al. 2021; Wu et al. 2023). It may even trigger explosions, leading to huge casualties and property damage (Wang et al. 2021c, 2023d; Zhang et al. 2022). It is evident that effectively controlling coal dust is essential.

To prevent and control coal dust, measures such as spraying, covering with tarpaulins, and building isolation are generally adopted in coal mining, railways, port terminals, thermal power plants, and other coal-related places.

✉ Fangwei Han
hanfangwei@lntu.edu.cn

✉ Hetang Wang
wanghetang@cumt.edu.cn

1 College of Safety Science and Engineering, Liaoning Technical University, Huludao, Liaoning Province 125105, China

2 Key Laboratory of Mine Thermodynamic Disasters and Control, Ministry of Education, Liaoning Technical University, Huludao, Liaoning Province 125105, China

3 College of Safety and Emergency Management Engineering, Taiyuan University of Technology, Taiyuan 030024, China

4 School of Safety Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China

However, there are disadvantages such as heavy water consumption, poor effect, and single function in these processes (Zhang et al. 2021a; Cheng et al. 2020). Due to the simple application process and significant dust suppression efficiency, water-based dust suppressants have gradually become an important means of coal dust control. Water-based dust suppressants use water as the main carrier and improve the dust suppression effect by adding wetting agents, moisture absorbing agents, polymers, etc. This article reasonably summarizes the dust suppression mechanism and key performance evaluation methods of water-based dust suppressants based on existing research, and offers some insights into the dust suppressants development and optimization. The aim is to explore the development potential of water-based dust suppressants in the coal dust control field. While meeting the demand for dust control, the effect will be enhanced and the environmental problems caused by coal dust will be reduced.

2 Dust suppression mechanism and dust suppressants classification

Among the current dust suppression technologies, the spray watering method is easy to operate. Nevertheless, the evaporation of water and the hydrophobicity of coal necessitate continuous spraying to enhance and sustain the dust suppression effectiveness which complicates the application process and is prone to cause water resources waste. Therefore, researchers have devised dust suppressants aimed at enhancing the dust suppression capabilities of water (Gonzalez et al. 2019; Shi et al. 2019). Dust suppressants can be classified into several types based on their mechanisms and components (Sun et al. 2018; Dong et al. 2023a). Wetting type suppressants primarily utilize surfactants to improve the water-wetting capability. Hygroscopic coalescence type dust suppressants incorporate hygroscopic inorganic salts, water-absorbing resins, and other substances to enhance moisture retention and water retention performance. Cohesive agglomeration type dust suppressants rely on petroleum by-products or polymers to strengthen the consolidation capacity. Composite type suppressants combine multiple materials to achieve synergistic effects, incorporating actions such as wetting, hygroscopic coalescence, and cohesive agglomeration for more efficient dust suppression.

2.1 Wetting type dust suppressants

Surfactants serve as the key component in wetting type dust suppressants, exerting a notable influence on enhancing the wetting effect on coal dust. Coal wetting is the process in which gas is replaced by liquid on the coal surface. The mechanism of these dust suppressants is illustrated in Fig. 1. The surfactant molecules are uniformly distributed at the gas-liquid interface, reducing the surface tension of water. When the solution comes into contact with the coal surface, the non-polar hydrophobic groups of the surfactant molecules adsorb onto the hydrophobic regions of the coal, while the polar hydrophilic groups form hydrogen bonds with water molecules. This leads to the formation of a directional molecular layer, with the hydrophobic groups facing the coal surface and the hydrophilic groups oriented towards the water, thereby facilitating the wetting process.

Water-based dust suppression technology began in the 1930s. Until the 1960s, surfactants started being utilized in coal mines (Chen 2022). Afterwards, the wetting type dust suppressant developed rapidly. Based on the ionization status of their hydrophilic groups in water, traditional surfactants can be categorized into two main types, ionic surfactants (including anionic, cationic, and zwitterionic

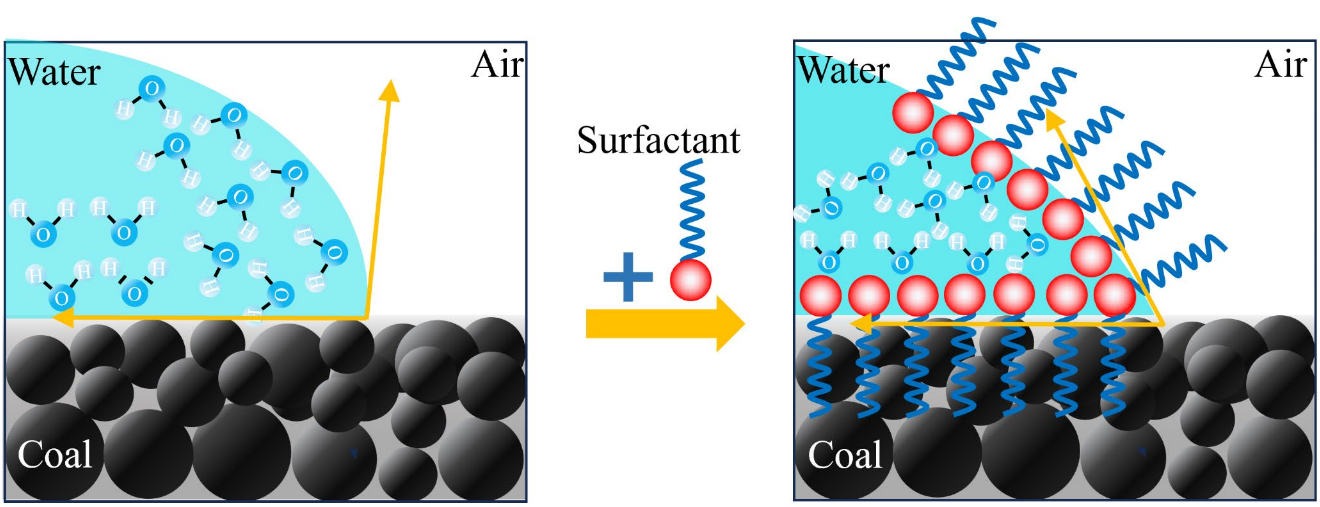

Fig. 1 Dust suppression mechanism of wetting type dust suppressants

surfactants) and non-ionic surfactants. During coal dust control procedures, it is evident that anionic and nonionic surfactants exhibit superior wetting effects on coal compared to cationic and zwitterionic (Tong et al. 2019; Wang et al. 2019). Further research has shown that the wetting effect of compounding surfactants is significantly better than that of a single component (Shi et al. 2021; Bai et al. 2023). Nie et al. (2023a) conducted a study on the binary compounding of surfactants, providing a theoretical framework for the design of high-performance dust suppressants. Meanwhile, studies have shown that adding inorganic salts can help improve the wetting performance of surfactants (Wang et al. 2023b, 2025). Based on the synergistic effect between surfactant solution and inorganic salt ions, Liu et al. (2023) formulated an optimized formula with sodium secondary alkyl sulfonate, Triton X-100 and $CaCl_2$, which exhibited excellent wetting effect. On the other hand, considering the promoting effect of magnetization treatment on wettability, some scholars have magnetized surfactant solutions and optimized the parameters. As a result, the dust control efficiency in practical dust suppression processes increased by more than 30% (Zhou et al. 2018; Pang et al. 2024).

Using inorganic chemical materials to prepare wetting type dust suppressants is easy to operate and can usually be achieved by mixing and dissolving them in water directly. However, due to the irritancy, corrosiveness, and poor degradation of some surfactants, environmentally friendly and easily degradable dust suppressants have attracted the researchers attention. Wang et al. developed two highly effective dust suppressants both demonstrated outstanding wetting capabilities, one derived from microalgae oil (MODS) and the other synthesized through *Bacillus subtilis* fermentation (Wang et al. 2021a, 2023a). Biosurfactants are a class of metabolites secreted by microorganisms in the metabolic process under specific conditions. These surfactants not only have the properties of solubilization, emulsification and wetting, but also have the advantages of non-toxicity, biodegradability, and high surface activity (Bavadi 2024; Akimbekov et al. 2024). Some researchers found that biosurfactants such as rhamnolipid and sophorolipid have good wettability in coal, offering a theoretical foundation for the widespread utilization of biosurfactants (Li et al. 2022c; Wang et al. 2023e; Niu et al. 2023). Wang et al. (2021b) prepared a green degradable composite biosurfactant. The experimental results indicated that the most effective composition comprised 0.129 mL of rhamnolipid, 0.044 mL of lactone sophorolipid, and 0.029 g of surfactin per 100 mL of dust suppressant, achieving a sinking time as short as 31.777 s. Due to evaporation and other reasons, wetting type dust suppressants typically encounter the issue of a brief wetting duration, which are often used to control floating dust. When employed to mitigate settling dust, they evaporate or lose quickly after application, leading to the potential generation of secondary dust. Therefore, many scholars often use chemical reagents with moisturizing, bonding and other properties to prepare dust suppressants with actions such as hygroscopic coalescence and cohesive agglomeration.

2.2 Hygroscopic coalescence type dust suppressants

Hygroscopic coalescence type dust suppressants are mainly composed of hygroscopic substances. Chemical moisture absorption generates hydrates through chemical reactions. Physical moisture absorption is achieved by surface adsorption and condensation. Usually, the moisture in the environment is absorbed by the deliquescence of hygroscopic substances to keep the surface wet, and at the same time, it has the effect of coalescence to capture fine dust. The mechanism of these dust suppressants involves four stages, as shown in Fig. 2. Initially, the dust suppressant comes into contact with and mixes with dust particles. Subsequently, the hygroscopic material starts to absorb water. Following this, the outer layer of hygroscopic material dissolves in the absorbed water and creates liquid films. The liquid films coalesce small particles. Finally, the majority of hygroscopic substances dissolve in the resulting solution concurrently capturing dust particles.

Inorganic salts are commonly used hygroscopic substances, which can improve the ability to absorb and retain moisture, thereby enhancing the dust control efficiency. This type of dust suppressant was first used to control road dust. In the 1960s and 1970s, regions such as the former Soviet Union and Australia began using solid $CaCl_2$ and other hygroscopic inorganic salts to treat roads for dust suppression (Peng and Wu 2005; Clark 1972). In Europe, road dust is frequently managed using calcium magnesium acetate (CMA) and $MgCl_2$ (Gulia et al. 2019). Additionally, in America, Saha and Ksaibati applied $CaCl_2$ and $MgCl_2$ to 26 gravel pavements, assessing the efficacy in mitigating dust (Saha and Ksaibati 2022). However, traditional hygroscopic inorganic salts pollute the soil and have disadvantages such as corrosiveness. Therefore, water-absorbing polymer compounds are gradually used for dust suppression. Volikov et al. (2023) proposed a dust suppressant named HS-ASQ. The HS-ASQ composition can form a gel-like substance on the mineral surface, and the concentration of PM10 and PM2.5 in the air can be reduced by 77% and 85%. The hygroscopic coalescence type dust suppressants prepared with starch (He et al. 2019), sawdust (Zhou et al. 2023c), cashew nut shell extract (Xi et al. 2023b) as the main raw materials exhibit high water absorption and good dust suppression effect. Moreover, the majority of these materials are green and

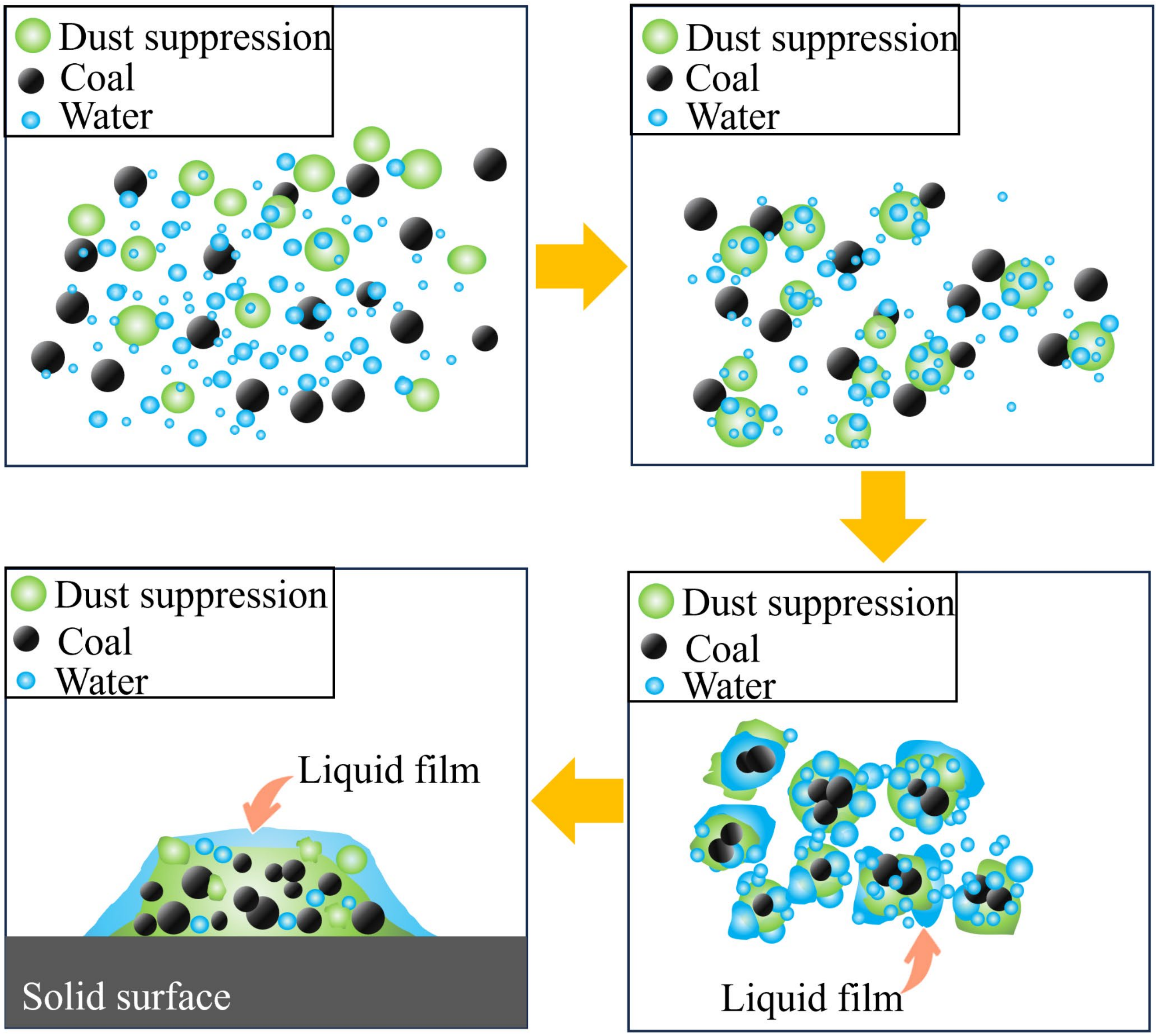

Fig. 2 Dust suppression mechanism of hygroscopic coalescence type dust suppressants

degradable, providing novel technical solutions for coal dust control, environmental protection, and resource recycling.

2.3 Cohesive agglomeration type dust suppressants

Cohesive agglomeration is a process of introducing adhesive force between fine particles and converting them into larger particles. The cohesive agglomeration type dust suppressants can form a certain strength covering layer on the coal pile surface, avoiding the fine dust from flying under airflow disturbance. The dust suppression mechanism can be divided into four steps, as shown in Fig. 3. Initially, the dust suppressant contacts and mixes with coal dust. Secondly, it begins to form bonding bridges between dust particles. Thirdly, the bonding bridges begin to solidify and form large dust clusters. Finally, the agglomeration increases to form a consolidation layer, thereby suppressing dust (Parvej et al. 2021).

Initially, asphalt emulsion was used as a cohesive agglomeration type dust suppressant for mine road dust suppression (Peng and Wu 2005). Subsequently, researchers began to pay more attention to using heavy petroleum fractions, by-products of bio-processing, high-molecular-weight polymers, and other industrial and agricultural processing by-products to solve dust suppression problems (Kondrasheva et al. 2016; Medeiros et al. 2012). These novel materials have gradually become a research hotspot because of their sustainability and environmental friendliness. The research

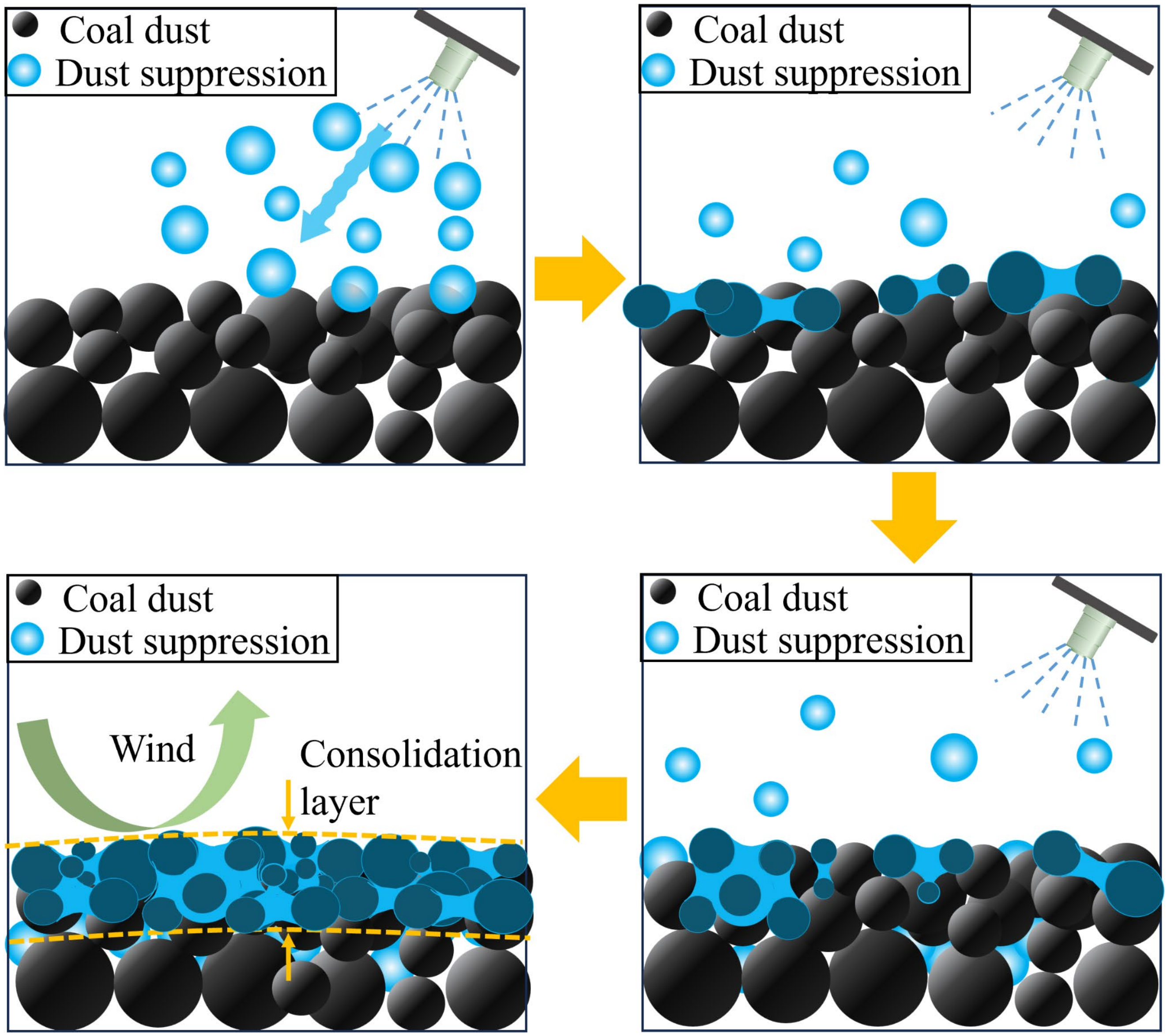

Fig. 3 Dust suppression mechanism of cohesive agglomeration type dust suppressants

of Tsogt and Oh shows that the selection of biodiesel by-product crude glycerol and bio-based materials (such as seaweed mixture, red algae, palm oil, etc.) to prepare non-toxic and degradable dust suppressants has broad application prospects (Tsogt and Oh 2021). The action of conventional cohesive agglomeration type dust suppressant is easily attenuated due to environmental impact, and high viscosity is also easy to cause weak wetting ability and permeability. These deficiencies amplify the optimization requirements for the dust suppressants. Liu et al. (2017) improved the water solubility and viscosity of dust suppressants by modifying chitosan. Additionally, Liu et al. (2020) grafted sodium alginate and hydroxypropyl methyl cellulose to improve the agglomeration performance of fine water mist. To mitigate expenses on dust suppression agents and curtail resource wastage, Li et al. utilized cellulose extracted from waste paper to synthesize sodium carboxymethyl cellulose, employing it as a matrix for a cohesive agglomeration type dust suppressant (Li et al. 2020). To enhance the adhesive properties of dust suppressants, Jin et al. (2022) modified soy protein isolate to control dust in open-pit coal mines. The foam dust suppressant developed by Xi et al. (2014) and Gan et al. (2022) can fill the pores in the coal particle layer and enhance the bonding dust performance. To enhance the environmental adaptability of dust suppressants, Xu et al. (2023) prepared a binder by oxidizing cassava starch with Cu^{2+}/ H_2O_2. This material not only helps to improve the bonding characteristics of foam dust suppressants, but also enhances the weather resistance. Zhou et al. (2022) developed a microcapsule for dust suppression based on oil, capable of creating a robust shell with dust particles and exhibiting excellent environmental adaptability. Although the raw materials of the cohesive agglomeration type dust suppressants are widely available, the cost of preparation, application and maintenance is still high, potentially constraining their widespread adoption on a large scale.

Another kind of dust suppressant is to agglomerate dust by the microbial (MICP) or enzyme induced calcium carbonate precipitation (EICP). The dust suppression mechanism is shown in Fig. 4. This type of dust suppressants utilizes urease extracted from microbial metabolism or other sources to promote urea hydrolysis. The hydrolysis product induces the precipitation of calcium carbonate, and the loosely accumulated dust particles are agglomerated into larger particles, thereby inhibiting dust flying.

The application of MICP technology has been extended to control the sandy soil consolidation, metal contaminated soil remediation and other fields (Dagliya et al. 2022; Cheng et al. 2014; Mwandira et al. 2019). *Bacillus pasteurii* is a high-yield urease bacterium commonly used by researchers. Typically, it is supplemented with a specific concentration of urea and calcium chloride solution to formulate the suppressant. This microbial agent can form a stable calcium carbonate crystal structure, effectively consolidating dust particles (Shi et al. 2019; Zhou et al. 2023b; Song et al. 2021). Furthermore, Song et al. (2019) conducted dust suppression experiments utilizing *Staphylococcus succinus J3*, isolated from the soil of a mining area. They investigated the influence of factors such as initial bacterial biomass, calcium concentration, urea concentration, and other variables on the efficacy of dust suppression. Wu et al. (2020a) developed an environmentally friendly biological dust suppressant, employing soybean urease as the primary material, and achieved a good dust-fixing efficacy. In contrast to MICP technology, EICP can reduce the time required for microorganisms to secrete urease. In theory, they can precipitate faster and exert dust suppression effects promptly. However, urease is expensive, and its production, storage, and application procedures are also quite complex. To enhance the utilization of microbial technology in dust suppression, Liu et al. (2022a) incorporated TiO_2-nanoparticles into microbial dust suppressants, which promoted bacterial growth and improved urease activity. Zhao et al. (2023) investigated the tolerance of urease-producing microorganisms communities to surfactants and conducted a microbiome analysis to discern the underlying factors influencing urease activity. In the study by Zhu et al. (2021a), introducing cocoamidopropyl betaine to mineralized bacteria exhibited a synergistic effect, leading to a substantial enhancement in the dust suppression rate. Hu et al. (2023) applied varying concentrations of extracellular polymer substances (EPS) derived from urease-producing bacteria onto coal dust to assess their efficacy. The outcomes of these experiments provide data and theoretical support for the MICP technology industrial application. Nonetheless, this technology exhibits drawbacks including limited environmental adaptability, extended consolidation duration, and a brief period effectiveness. Consequently, it becomes imperative to investigate the consolidation and dust suppression mechanisms to address the aforementioned challenges.

2.4 Composite type dust suppressants

Given the numerous drawbacks associated with single-action dust suppressants, there is a trend in the development of dust suppressants towards a composite direction. Composite type dust suppressants are often improved on the basis of a single action, so that they have two or more actions such as wetting, hygroscopic coalescence, and cohesive agglomeration. Most composite type dust suppressants contain complex mixtures of two or more components,

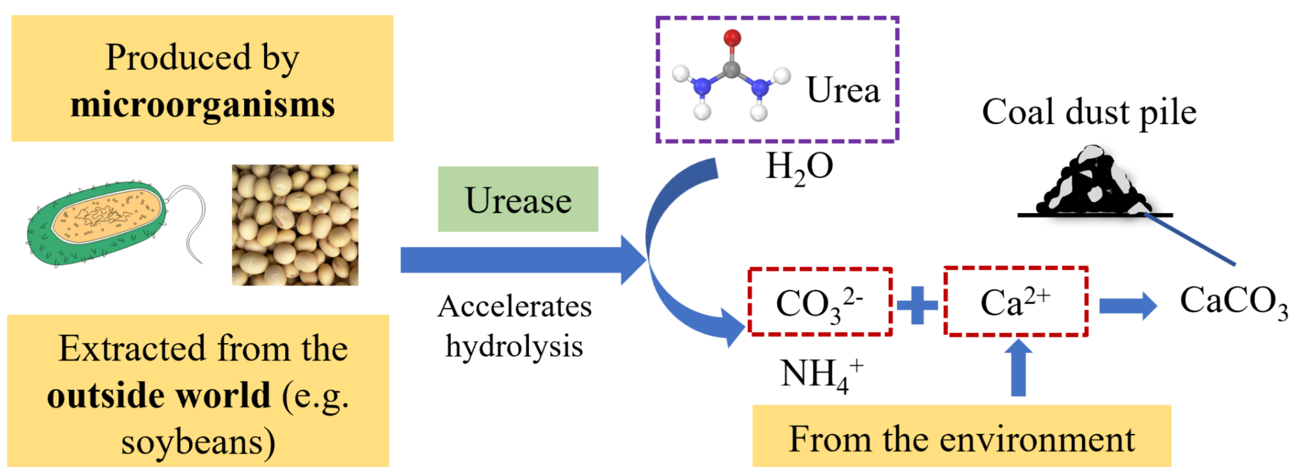

Fig. 4 Dust suppression mechanism of microbial dust suppressants (Wu et al. 2020a; Shi et al. 2022)

which are usually polymerized using physical and chemical methods.

Li et al. (2023) introduced Gemini surfactants into dust suppressants prepared from water absorbent resins and carboxymethyl starch sodium, improving the flowability and permeability of cohesive agglomeration dust suppressants. Nie et al. (2023b) added surfactants, permeate agents, hygroscopic inorganic salts, and other components to dust suppressants to improve wetting ability, permeability, and water retention properties (Yan et al. 2021). Zhang et al. (2020) added wetting agent and hygroscopic agent to hydroxypropyl guar gum, and developed a composite type dust suppressant with wetting, hygroscopic coalescence and cohesive agglomeration actions. Li et al. (2022b) synthesized a composite type dust suppressant by free radical polymerization using xanthan gum as a graft substrate. The surface tension of the dust suppressant is 29 mN/m, and the compressive strength of the consolidated body is 1.58 MPa. Ding et al. (2020) used hydroxyethyl cellulose as the main component to obtain a composite type dust suppressant with a gel structure and self-healing ability. The biological macromolecules, initiators, and cross-linking agents involved in the dust suppressant can form some network structures through free radical polymerization and other reactions. These network structures can form a denser consolidation layer with coal dust. Dong et al. (2023b) created a composite type dust suppressant featuring a gel network structure by glycosylating soy protein isolate with xanthan gum. Wu et al. (2020b) developed a composite type dust suppressant with a semi-interpenetrating network structure using a mixture of sodium alginate, polyvinyl alcohol and glycerol as substrates to control open-pit mine dust. Zhu et al. (2021b) synthesized a composite dust suppressant characterized by a porous three-dimensional network structure, using potato starch and modified sodium bentonite as the principal constituents. Xi et al. (2023a) created a three-dimensional cross-linked network composite type dust suppressant by grafting carboxymethyl starch, polyvinyl alcohol, and caprolactam.

Considering the high cost of grafting substrates mentioned above, low-cost basic materials with a wide range of sources are favored. Wang et al. (2023f) utilized pectin sourced from natural plant skins as the primary raw material. It was found that the pectin-modified dust suppressant can effectively suppress and consolidate coal dust. Zhou et al. (2021, 2023a) successively extracted substances such as chitosan and sugarcane bagasse cellulose from discarded shrimp shells and sugar making waste, and used them as a matrix to prepare composite type dust suppressants with agglomerating and wetting effects. Zhao et al. (2021b) synthesized a dust suppressant with a gel structure by recycling *Enteromorpha prolifera* near the sea area. The raw materials of composite type dust suppressants are widely available, but the complex processes involved in the preparation will lead to high costs, which is not conducive to the promotion and use of dust suppressants. At the same time, the environmental compatibility of these materials still needs to be verified.

Due to the evident size benefits, elevated surface energy, and potent adsorption properties of nanomaterials, researchers attempt to introduce nanomaterials into the dust suppressants field to prepare nano-composite type dust suppressants. In 2020, Feng et al. (2020) prepared a degradable dust suppressant composed of nanocellulose through aqueous solution polymerization. The nanocellulose used showed high hydrophilicity and biodegradability. Zhao et al. (2024) investigated the impact of SiO_2-H_2O nanofluids on the wetting behavior of coal dust and observed that these nanofluids can augment the wetting properties of coal dust. Shao et al. (2022) formulated a cohesive agglomeration type dust suppressant with low viscosity and high consolidation capacity using lignin-Ag nanoparticles (NPs). The stable agglomeration mechanism of lignin-AgNPs improved the consolidation performance. Li et al. (2022a) introduced a nano-composite dust suppressant comprising Al_2O_3 nanomaterials along with highly absorbent polymers, carboxymethyl starch sodium, and polyacrylamide as its key components. The incorporation of nanomaterials notably enhanced the dispersion, permeability, and agglomeration properties of the dust suppressant. Wang et al. (2023c) added modified hydrophilic SiO_2 nanoparticles to the foaming agent, and added silicone surfactants on this basis. It was found that the combined action of nanoparticles and surfactants resulted in the formation of long-lasting and stable foam, along with the rapid deposition of coal dust. The findings offer insights into utilizing nanoparticles and silicone surfactants for dust suppression purposes. However, the mechanism of nano-modification should be further explored to provide theoretical support for the research and application of nano-composite dust suppressants.

3 Evaluation of dust suppression performance

After spraying the dust suppressants on the storage and transportation coal pile, wetting, permeation, consolidation and other phenomena will occur. Studying these processes in coal particles is the key to controlling the spray quality and dust suppression effectiveness. Conducting a scientific and effective evaluation to the key performance of dust suppressants holds significant importance in determining parameters like spray thickness and uniformity. The performance evaluation results are helpful to put forward the optimization scheme. The key properties that affect the dust suppression effect include wettability, permeability, moisture absorption and water retention, and consolidation.

3.1 Wettability evaluation

Wettability performance refers to the ability of dust suppressants to spread and wet on the dust particles surface. It is the key performance to determine the effectiveness of wetting type dust suppressants, and it is also a crucial metric for evaluating the wetting components action within these suppressants. At present, the wettability evaluation on coal surface primarily involves experimental approaches such as measuring liquid surface tension. The other methods involve testing pertinent characteristic parameters during the gradual contact wetting between the liquid and coal. This includes measurements like surface tension, contact angle, sink tests, and more, as illustrated in Fig. 5.

Generally, lower surface tension indicates a greater propensity for effective wetting on the solid surface. When the surface tension is lower than 45 mN/m, it can spontaneously wet on the coal surface (Chen et al. 2019). The Wilhelmy plate method is commonly used in the surface tension measurement to determine the capillary rising force generated by liquid wetting on the plate. It was found that fluorocarbon surfactants exhibit a greater affinity for forming hydrogen bonds with water compared to hydrocarbon surfactants. At a concentration of 0.06% OBS, the surface tension decreases to as low as 17.6 mN/m, providing a new approach for the development of novel wetting dust suppressants (Niu et al. 2023). The surface tension measurement is highly reliable at low concentrations and the experimental operation is convenient. However, once the critical micelle concentration is exceeded, the surface tension will stabilize and no longer change significantly, making it difficult to assess the wetting

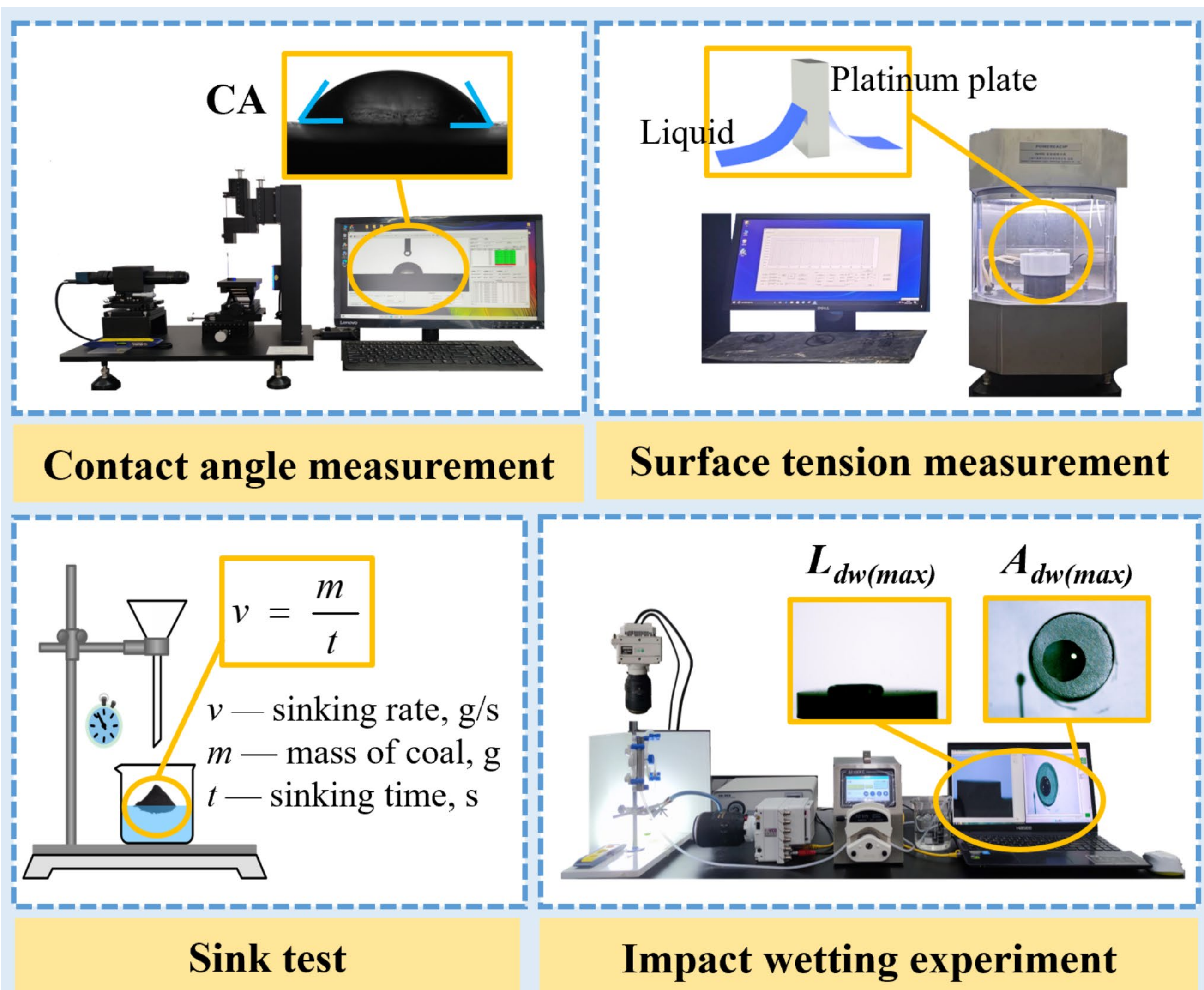

Fig. 5 Wettability evaluation methods

ability. Additionally, surface tension is an inherent physical property of the solution and cannot be used to evaluate the wetting ability on different coal samples. The contact angle measurement generally records the gas-liquid-solid three-phase contact image through an optical recording system and measures its contact angle (Erbil 2014). Liu et al. (2024a) screened surfactants with contact angle as the key index, and found that 0.4wt % dodecyl glucoside could reduce the contact angle of dust suppressant to $27.75 \pm 0.7°$ after 5s. The contact angle experiment can capture the slow wetting process of liquid droplets on the coal surface. However, when the droplet permeates quickly, the contact angle may not be captured in time. Additionally, the sink test mostly characterizes the wettability by testing the time required for quantitative dust to fully immerse in the test solution. The accuracy of the sink test results is influenced by both the particle size distribution and the uniformity of the powder. To enhance the precision, it is necessary to conduct the test repeatedly, typically ranging from three to five repetitions (Copeland et al. 2009; Zhao et al. 2021a). Chang et al. (2021) introduced a standardized sink test procedure and utilized both sink time and surface tension measurements to assess the wettability of pulverized coal in surfactant solutions. Yan (2019) used the sink time as the response value to analyze the different surfactants response surface to find the optimal combination of surfactant compounding. Hu (2014) employed the sink test to examine the impact of coal sample composition on coal wettability, and found that this method was not strong enough to distinguish coal dust with similar wettability, and could only make a rough judgment. During the dust control process, the reagent solution often impacts the coal surface at a certain speed through nozzles, exhibiting significant impact kinetic characteristics. Due to this limitation, the author's team has proposed a dynamic wetting evaluation method in recent years. This method uses high-speed camera technology to capture the droplets wetting behaviors impacting the coal surface. The characteristic parameters such as droplets dimensionless wetting length and dimensionless wetting area are extracted to effectively evaluate the wettability of dust suppressants (Han et al. 2022, 2023, 2024).

3.2 Permeability evaluation

When the dust suppressants are applied to the coal pile, it undergoes permeation. Permeability performance refers to the ability to permeate through the dust particle layer, thereby indicating the permeation difficulty level through the dust layer of dust suppressants. The dust suppression effect is significantly affected by the permeation speed and depths. The current methods for testing the permeation ability mainly include capillary rise experiments, droplet permeation experiments, CT scanning experiments, nuclear magnetic resonance experiments, etc., as shown in Fig. 6.

The capillary rise experiment assesses permeability by observing the upward movement of liquid in a glass tube containing dust particles (Galet et al. 2010; Dai et al. 2024; Zhao et al. 2011). Although this method is simple and intuitive, there are often problems such as uneven dust particle size and powder loading compactness, which seriously affect the use of this method. The purpose of the droplet permeation experiment is to measure the rate at which the solution can permeate the powder bed under gravity. Generally speaking, the shorter permeation time and the greater permeation depth means the better the permeability. Cheng et al. (2012) considered factors such as coal permeability coefficient and porosity to study the permeability effect of water injection reagents in low-permeability coal seams. Meanwhile, Zhou et al. conducted forward permeation experiments to compare the permeability of eight surfactants in lignite dust. The results showed that the permeation time after adding surfactants was less than 2347s of pure water, offering valuable insights for selecting appropriate surfactants (Zhou et al. 2019). CT scanning technology also provides an effective means to study the permeation and distribution of solution in the coal pile (Yin et al. 2018). Oostveen et al. (2015) evaluated the permeation effect of droplets on a dust bed using droplet permeation time and characterized the internal structure using CT scanning. Similarly, Wang et al. (2020a) conducted CT scanning experiments to characterize the multi-scale pore structure and examine the seepage characteristics of water within the coal samples. Furthermore, nuclear magnetic resonance experiments can also be used to study the permeation of liquids in coal particles. Based on low-field nuclear magnetic resonance experiments, Zhang et al. (2021b) and Yang, et al. (2022b) found that surfactants containing sulfonic acid, amino, and carboxyl groups readily formed hydrogen bonds with hydroxyl groups present in lignite, which is conducive to solution permeation.

3.3 Moisture absorption and water retention evaluation

Moisture absorption and water retention performance pertains to the ability to absorb water and resist evaporation after application. Dust suppressants that possess effective moisture absorption and water retention properties are able to capture coal dust more efficiently. As depicted in Fig. 7, swelling experiments and water retention experiments are commonly employed methods for assessing the moisture absorption and water retention characteristics of dust suppressants (Liu et al. 2021a, b; Guo et al. 2023; Gharekhani et al. 2017).

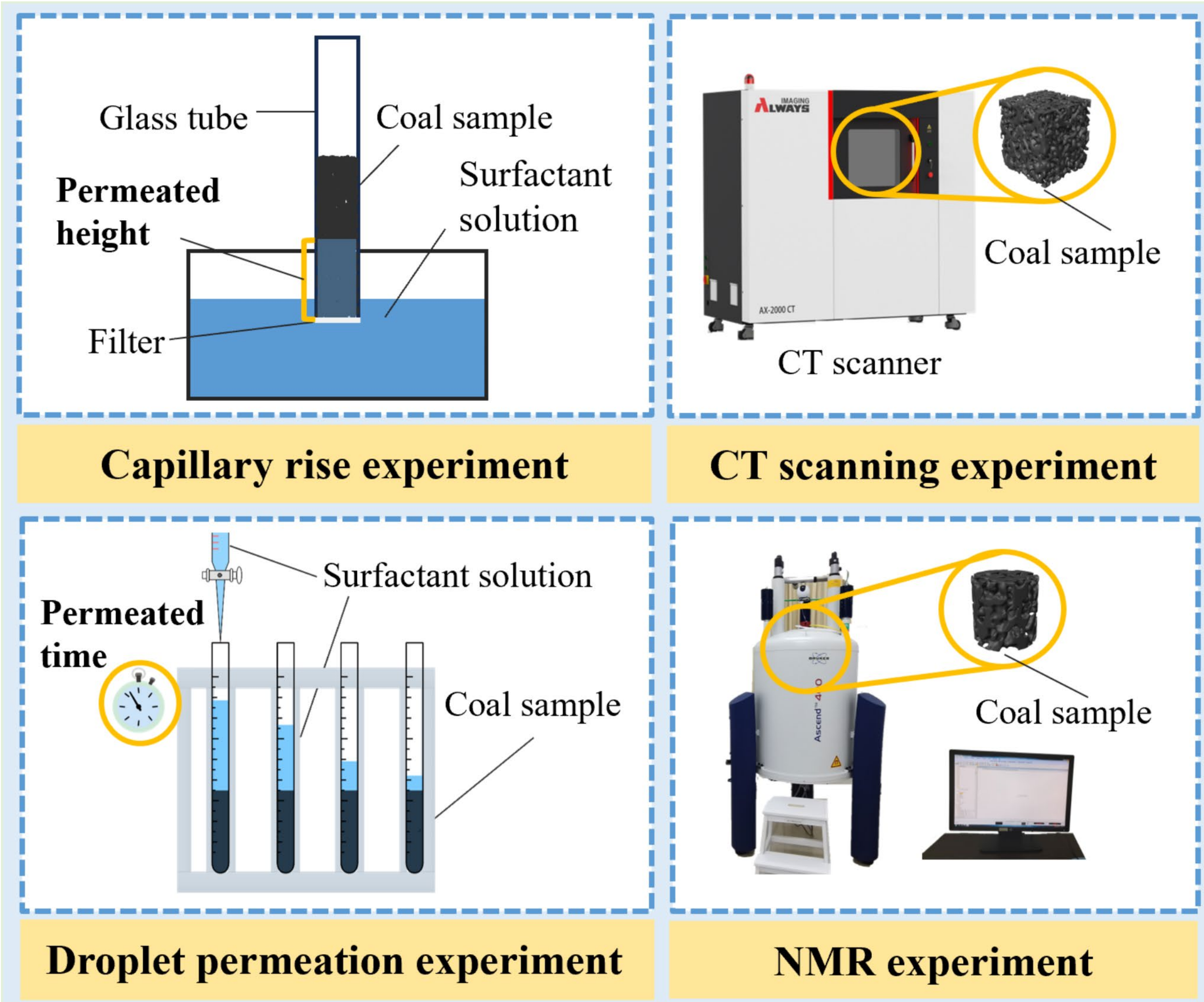

Fig. 6 Permeability evaluation methods

The swelling experiment involves analyzing the kinetic characteristics of swelling for a dust suppressant with a polymerized structure, such as gel or absorbent resin. The hygroscopicity of the dust suppressant is illustrated by plotting the swelling kinetics curve, which is derived from calculating the swelling rate of the film. For dust suppressants with hygroscopic inorganic salts as the main component, most researchers directly use water absorption rate to evaluate the hygroscopic properties (Wang et al. 2020b). The water retention experiment mainly focuses on evaluating the anti-evaporation properties of the dust suppressant. It employs parameters like the water evaporation rate to gauge the water retention efficacy. The water retention performance serves as a crucial indicator in determining the effective duration of the dust suppressant. It is employed to assess the impact of the water retention agent within the dust suppressant. A lower evaporation rate corresponds to enhanced anti-evaporation capabilities, heightened water retention capacity, and an extended duration of effectiveness for the dust suppressant (Zhang et al. 2018, 2023; Chen et al. 2023). Yu et al. (2022) assessed the water retention efficacy by calculating the water evaporation rate per unit area, and found that the water evaporation rate of dust suppressants was less than 0.02% after 20 h. Jiang et al. (2021) compared the water retention capacities of four inorganic salt solutions through water retention experiments. The results showed that after 192 h, the $CaCl_2$ sample had the highest moisture content (8.40%), providing a reference for selecting the optimal formula. The method of evaluating the moisture absorption and water retention performance of dust suppressants is relatively simple. The majority of them are measured and calculated by the weighing method, which is greatly affected by ambient temperature and humidity. In

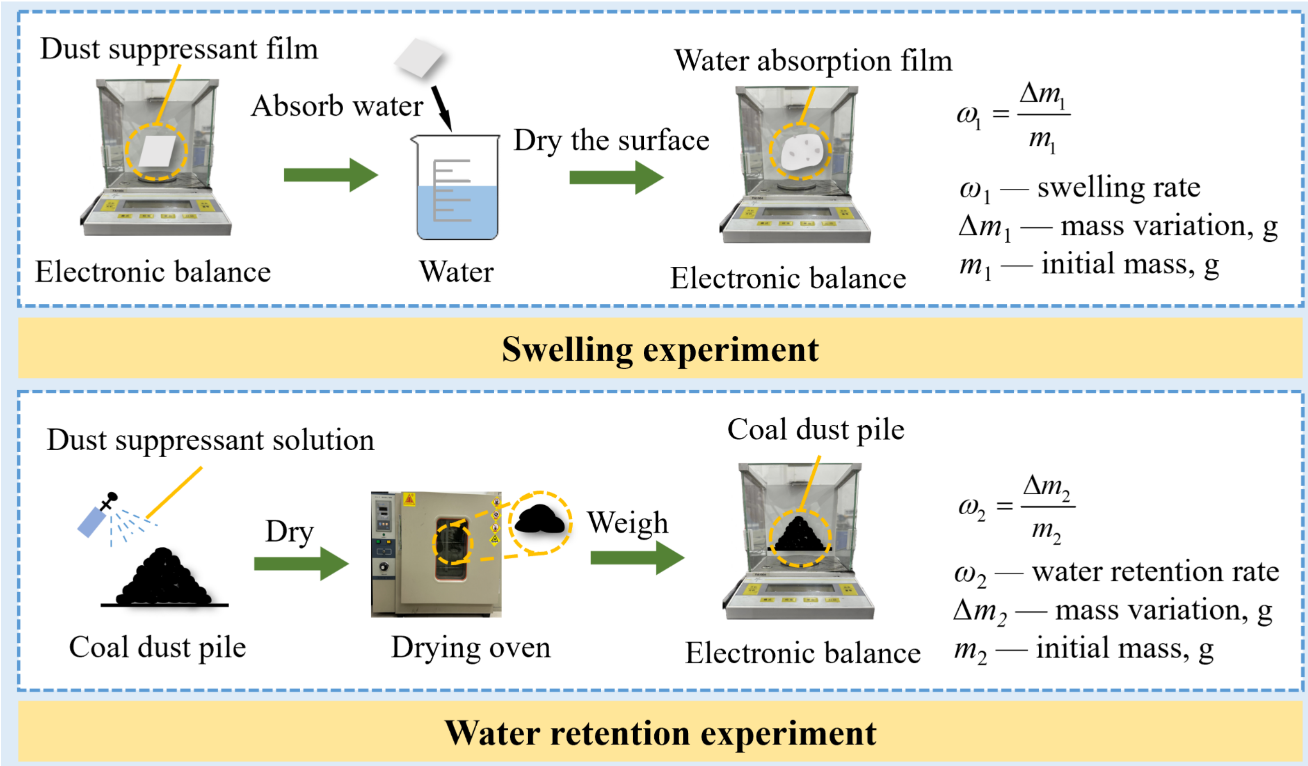

Fig. 7 Moisture absorption and water retention evaluation methods

most cases, it is used for qualitative analysis of the dust suppression effect.

3.4 Consolidation evaluation

The consolidation ability of dust suppressants is another crucial factor impacting its effectiveness in controlling dust. After the dust suppressant with cohesive agglomeration acts on the coal body, it will form a consolidation layer with the surface dust. The consolidated layer is an effective barrier, which can prevent the coal dust from escaping even under external disturbances. It can be evaluated by surface pore changes (microscopic morphology and pore structure), crystallization characteristics (XRD crystal structure, FTIR, XPS functional group structure), consolidation layer strength (hardness, thickness, mechanical resistance, wind erosion resistance, rain resistance) (Du and Jiang 2005; Luo et al. 2016; Wei et al. 2021; Wang et al. 2023 g; Jiang et al. 2024; Wang et al. 2024), as shown in Fig. 8.

Zhao et al. (2022) and Fan et al. (2018) employed scanning electron microscopy to examine the surface morphology and pore changes of the consolidated layer, and evaluate the agglomeration effect of the dust suppressant. Sieger et al. (2023) examined the effect of dust suppressants obtained from 14 types of polysaccharides and proteins. The penetrometer, as well as measurements of consolidation layer weight and thickness, were used to evaluate the strength of the consolidation layer. Sun et al. (2020) conducted wind erosion experiments and pressure tests to evaluate the consolidation layer performance. It is found that at wind speeds up to 12 m/s, the wind erosion resistance remained above 80%, with a maximum pressure of 56.35 N. Wu et al. (2022) measured the consolidation layer hardness to be 36 HA using a Shore hardness tester and calculated its degradation rate, providing a valuable reference for selecting effective cohesive agglomeration type dust suppressants. Luo et al. (2022) examined the reliability of assessment criteria for dust suppressants. The analysis findings indicated that assessing dust suppression effectiveness using solidified layer thickness, uniaxial compression strength, and wind erosion resistance yields poor results, whereas utilizing penetration resistance provides a more accurate evaluation. In summary, the current research on solidification performance has not yet established standardized experiments, and most experiments are too subjective to accurately determine the solidification and dust suppression effects.

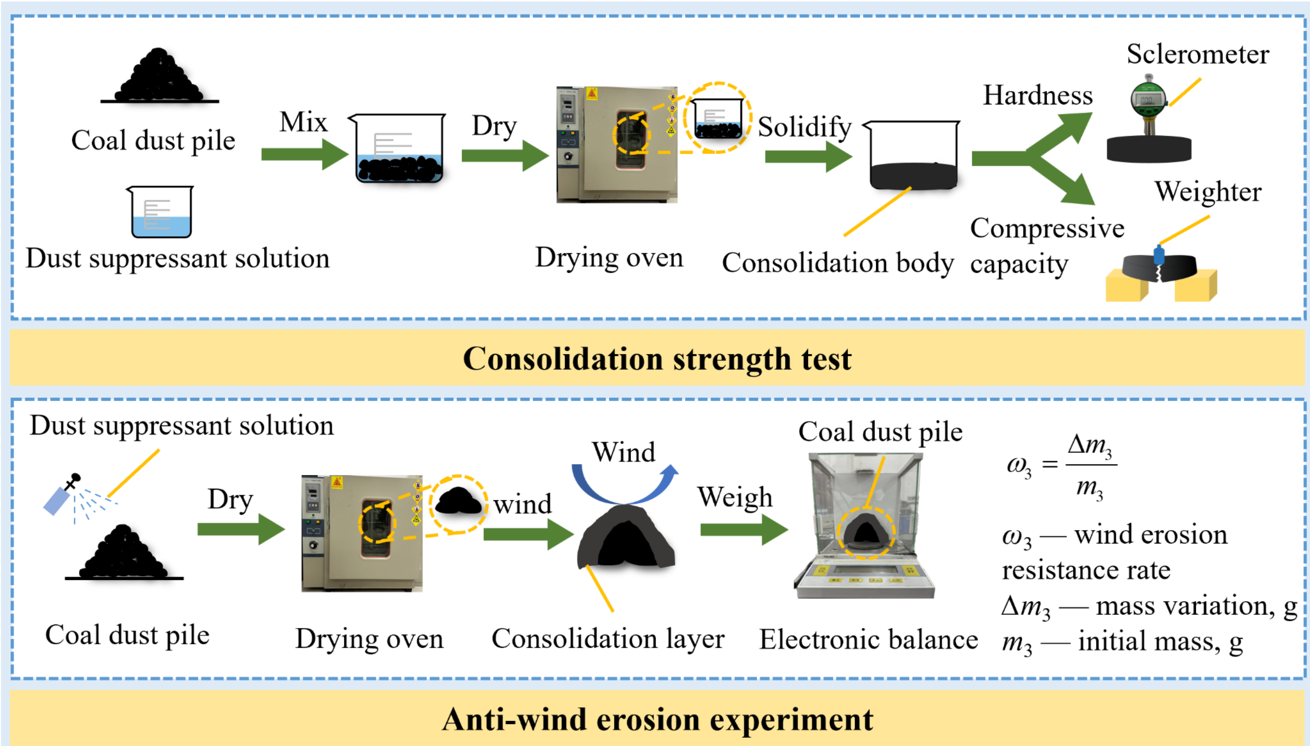

Fig. 8 Consolidation layer strength evaluation methods

4 Research results and prospects

In summary, both domestic and international researchers have made significant progress in the field of dust suppressants, particularly in the formulation and design aspects. This paper provides an overview on the dust suppression mechanisms and categorizes the dust suppressants into four types. They are wetting type dust suppressants, hygroscopic coalescence type dust suppressants, cohesive agglomeration type dust suppressants, and composite type dust suppressants. Regarding the performance evaluation, this study delves into crucial methods and evaluation criteria, including but not limited to wettability, permeability, moisture absorption, water retention, and the consolidation ability. The following are prominent findings in the literature review.

4.1 Development of new functions coal suppressants

Traditional coal dust suppressants pay greater attention to their actions such as wetting, hygroscopic coalescence, and cohesive agglomeration. However, due to the constantly changing application scenarios, it is necessary to develop more dust suppressants with new functions (Ren et al. 2022; Liu et al. 2022b). Coal suppressants have gradually developed from the initial single wetting component to complex components today, and their functions have also developed from single to diversified. For example, coal dust accumulation and spontaneous combustion are concurrent issues during storage and transportation. However, existing multi-functional coal inhibitors that can address both dust suppression and spontaneous combustion have not met engineering needs. At present, the research on the synergistic inhibition mechanism is insufficient. In order to reduce the safety risk and environmental pollution during the coal transportation and storage process, further research should be carried out on the synergistic inhibition mechanism and materials development for dust suppression and spontaneous combustion. For another example, coal dust suppressants in alpine regions need to have a certain degree of weather resistance while meeting the dust suppression function. Currently, China stands as one of the prominent coal-producing nations globally, with its primary coal-producing regions situated predominantly in the northwest. In this area, the temperature is high and dry in summer, and the temperature is low in winter. If the dust suppressant cannot have good weather resistance, it will greatly limit the application.

4.2 Development of biobased environmentally friendly coal suppressants

Most of the existing dust suppressants rely on petroleum or oil-based chemical products as the main component of wetting agents, but these chemical reagents are usually incompatible with the ecological environment, and can lead to varying degrees of harm to human health during both their preparation and application processes. Guided by the principles of promoting green, low-carbon and sustainable development, the novel coal suppressants should prioritize the utilization of bio-based materials. These materials, typically biodegradable in nature, play a significant role in easing environmental burdens throughout the coal mining, storage, and transportation processes. Compared with traditional chemical reagents, bio-based materials produce fewer harmful substances during use, which not only contributes to an enhanced working environment but also mitigates potential health hazards for workers. In the face of complex climate change, some biosurfactants can still maintain good surface activity, which is conducive to the popularization and application of bio-based materials in the dust suppression field (Wang et al. 2011; Arora et al. 2019; Dong et al. 2024). Despite the rapid development of enzymatic calcium carbonate precipitation technology and microbial dust suppression technology, the production of such dust suppressants generally has complex and harsh preparation processes and a wide range of material composition, which will lead to high costs. The production cost can be reduced through strategies such as selecting more economical raw materials (Taowkrue et al. 2024; Sen et al. 2021) or improving production processes (Liu et al. 2024b; Luo et al. 2024).

4.3 Comprehensive evaluation of coal suppressant performance

The scientific application of dust suppressants benefits from the effective evaluation. At present, most studies have separately evaluated the wetting and permeability, moisture absorption and water retention, as well as the consolidation performance of dust suppressants individually, ignoring the interrelations among these various performance parameters. A comprehensive dust suppression performance evaluation system has not yet been established, making it difficult to accurately estimate the amount and effectiveness of application. Therefore, it is necessary to establish a quantitative evaluation standard for the wetting, permeation and consolidation performance of dust suppressants. This will enable to explore the intrinsic relationships among various performance parameters, contributing to the scientific application of dust suppressants. In addition, it is necessary to evaluate the environmental safety and economic cost of dust suppressants. By selecting appropriate evaluation methods, a scientific and effective multi-dimensional comprehensive evaluation system is established to choose coal suppressants.

Acknowledgements The authors deeply appreciate the support from the staff of Key Laboratory of Mine Thermodynamic Disasters and Control. We are also grateful to the editors for their key work.

Author Contribution Fangwei Han: Conceptualization, resources, methodology, writing - original draft, writing - review & editing, project administration, funding acquisition, and supervision. Mei Liu: Formal analysis, validation, data curation, writing - original draft, and writing - review & editing. Fuhong Hu: Conceptualization, investigation, visualization, and software. Guirui Niu: Conceptualization, Writing - original draft, and methodology. Diandian Xue: Investigation, methodology, and visualization. Yue Zhao: Methodology and data curation. Shengyong Hu: Conceptualization and resources. Hetang Wang: Conceptualization and resources.

Funding This work was supported by the National Natural Science Foundation of China (52474226, 52322404), and Basic scientific research projects in higher education institutions of Liaoning Province (JYTZD2023079). The authors deeply appreciate the support from the staff of Key Laboratory of Mine Thermodynamic Disasters and Control. We are also grateful to the editors for their key work.

Declarations

Ethical approval The findings are presented transparently, truthfully, and without any form of fabrication or improper data manipulation.

Consent to participate All authors agree to continue to support the follow-up work.

Consent for publication All authors have reviewed and approved the final version of this manuscript and consent to its publication. Each author confirms that the manuscript is an original work and has not been previously published nor is under consideration for publication elsewhere.

Competing interests The authors declare no competing interests.

References

Akimbekov N, Digel I, Zhubanova A et al (2024) Biotechnological potentials of surfactants in coal utilization: a review. Environ Sci Pollut Res 31(43):55099–55118. https://doi.org/10.1007/s11356-024-34892-5

Arora P, Kshirsagar PR, Rana DP, Dhakephalkar PK (2019) Hyperthermophilic *Clostridium* Sp. N-4 produced a glycoprotein biosurfactant that enhanced recovery of residual oil at 96°C in lab studies. Colloids Surf B 182:110372. https://doi.org/10.1016/j.colsurfb.2019.110372

Bałaga D, Siegmund M, Kalita M et al (2021) Selection of operational parameters for a smart spraying system to control airborne PM10 and PM2.5 dusts in underground coal mines. Process Saf Environ Prot 148:482–494. https://doi.org/10.1016/j.psep.2020.10.001

Bai X, Yan G, Kong S et al (2023) Suppression of anthracite dust by a composite of oppositely-charged ionic surfactants with ultra-high surface activity: theoretical calculation and experiments. Fuel 344:128075. https://doi.org/10.1016/j.fuel.2023.128075

Bavadi M (2024) Generation of oil spill dispersants composed of biosurfactants and chemical surfactants: mechanism exploration through molecular dynamics simulation. J Environ Chem Eng 12(6):114249. https://doi.org/10.1016/j.jece.2024.114249

Cao Y, Xiao Y, Wang Z et al (2024) Recent progress and perspectives on coal dust sources, transport, hazards, and controls in underground mines. Process Saf Environ Prot 187:159–194. https://doi.org/10.1016/j.psep.2024.04.095

Chang P, Xu G, Chen Y et al (2021) Improving coal powder wettability using electrolyte assisted surfactant solution. Colloids Surf A 613:126042. https://doi.org/10.1016/j.colsurfa.2020.126042

Cheng L, Shahin MA, Cord-Ruwisch R (2014) Bio-cementation of sandy soil using microbially induced carbonate precipitation for marine environments. Geotechnique 64:1010–1013. https://doi.org/10.1680/geot.14.T.025

Cheng W, Nie W, Zhou G et al (2012) Research and practice on fluctuation water injection technology at low permeability coal seam. Saf Sci 50:851–856. https://doi.org/10.1016/j.ssci.2011.08.021

Cheng W, Zhou G, Chen L et al (2020) Research progress and prospect of dust control theory and technology in China's coal mine in the past 20 years. Coal Sci Technol 48:1–20. https://doi.org/10.13199/j.cnki.cst.2020.02.001

Chen X (2022) Screening and wetting characteristics study of wetting. Master thesis, Taiyuan University of Technology. https://doi.org/10.27352/d.cnki.gylgu.2021.000582

Chen X, Gao J, Deng C et al (2023) Effect of active composite ionic liquids treatment on chemical structure and wettability of coal. Fuel 337:126885. https://doi.org/10.1016/j.fuel.2022.126885

Chen Y, Xu G, Huang J et al (2019) Characterization of coal particles wettability in surfactant solution by using four laboratory static tests. Colloids Surf A 567:304–312. https://doi.org/10.1016/j.colsurfa.2019.01.068

Clark TM (1972) Australian experiences in coal dust suppression. Ann N Y Acad Sci 200:797–807. https://doi.org/10.1111/j.1749-6632.1972.tb40240.x

Copeland CR, Eisele TC, Kawatra SK (2009) Suppression of airborne particulates in iron ore processing facilities. Int J Min Process 93:232–238. https://doi.org/10.1016/j.minpro.2009.09.003

Dagliya M, Satyam N, Sharma M, Garg A (2022) Experimental study on mitigating wind erosion of calcareous desert sand using spray method for microbially induced calcium carbonate precipitation. J Rock Mech Geotechl Eng 14:1556–1567. https://doi.org/10.1016/j.jrmge.2021.12.008

Ding J, Zhou G, Liu D et al (2020) Synthesis and performance of a novel high-efficiency coal dust suppressant based on self-healing gel. Environ Sci Technol 54:7992–8000. https://doi.org/10.1021/acs.est.0c00613

Dong H, Yu H, Xu R et al (2023a) Review and prospects of mining chemical dust suppressant: classification and mechanisms. Environ Sci Pollut Res 30:18–35. https://doi.org/10.1007/s11356-022-23840-w

Dong H, Yu H, Xu R et al (2023b) Synthesis and performance determination of a glycosylated modified covalent polymer dust suppressant. Int J Biol Macromol 231:123287. https://doi.org/10.1016/j.ijbiomac.2023.123287

Dong H, Yu H, Xu R et al (2024) Research on application effect and mechanism of degradable multifunctional dust suppression foam in coal mines. J Environ Chem Eng 12:112694. https://doi.org/10.1016/j.jece.2024.112694

Du C, Jiang Z (2005) Industrial test on depression of flying dust at open coal yard by cohesive dust depressor. Met Mine 55–57. https://doi.org/10.3321/j.issn:1001-1250.2005.03.016

Erbil HY (2014) The debate on the dependence of apparent contact angles on drop contact area or three-phase contact line: A review. Surf Sci Rep 69:325–365. https://doi.org/10.1016/j.surfrep.2014.09.001

Fan T, Zhou G, Wang J (2018) Preparation and characterization of a wetting-agglomeration-based hybrid coal dust suppressant. Process Saf Environ Prot 113:282–291. https://doi.org/10.1016/j.psep.2017.10.023

Faridi S, Brook RD, Yousefian F et al (2022) Effects of respirators to reduce fine particulate matter exposures on blood pressure and heart rate variability: A systematic review and meta-analysis. Environ Pollut 303:119109. https://doi.org/10.1016/j.envpol.2022.119109

Feng J, Yan G, Wang P et al (2020) Preparation and characteristic analysis of a new degradable nano-cellulose dust suppressant. Min Res Dev 40:106–110 https://doi.org/10.13827/j.cnki.kyyk.2020.07.021

Galet L, Patry S, Dodds J (2010) Determination of the wettability of powders by the Washburn capillary rise method with bed Preparation by a centrifugal packing technique. J Colloid Interface Sci 346:470–475. https://doi.org/10.1016/j.jcis.2010.02.051

Gan J, Wang D, Xiao Z et al (2022) Synthesis and performance of a novel high-efficiency coal dust suppressant based on biopolysaccharide-xanthan gum. Fuel 329:125442. https://doi.org/10.1016/j.fuel.2022.125442

Gharekhani H, Olad A, Mirmohseni A, Bybordi A (2017) Superabsorbent hydrogel made of NaAlg-g-poly(AA-co-AAm) and rice husk Ash: synthesis, characterization, and swelling kinetic studies. Carbohydr Polym 168:1–13. https://doi.org/10.1016/j.carbpol.2017.03.047

Gonzalez A, Aitken D, Heitzer C et al (2019) Reducing mine water use in arid areas through the use of a byproduct road dust suppressant. J Clean Prod 230:46–54. https://doi.org/10.1016/j.jclepro.2019.05.088

Gulia S, Goyal P, Goyal SK, Kumar R (2019) Re-suspension of road dust: contribution, assessment and control through dust suppressants - a review. Int J Environ Sci Technol 16:1717–1728. https://doi.org/10.1007/s13762-018-2001-7

Guo F, Zhao Y, Zhao G et al (2023) Preparation and properties of chitosan-based water-absorbent resin dust-suppressing microcapsules. Saf Coal Mines 56–62. https://doi.org/10.13347/j.cnki.mkaq.2023.10.009

Han F, Liu M, Hu F et al (2022) Spreading behavior and wetting characteristics of anionic surfactant droplets impacting bituminous coal. ACS Omega 7:46241–46249. https://doi.org/10.1021/acsomega.2c04180

Han F, Peng Y, Zhao Y et al (2024) Comparative investigation of methods for evaluating the wettability of dust suppression reagents on coal dust. J Mol Liq 399:124380. https://doi.org/10.1016/j.molliq.2024.124380

Han F, Zhao Y, Liu M et al (2023) Wetting behavior during impacting bituminous coal surface for dust suppression droplets of fatty alcohol polyoxyethylene ether. Environ Sci Pollut Res 30:51816–51829. https://doi.org/10.1007/s11356-023-25991-w

He L, Fu K, Hou H (2019) Study on Preparation and dust suppression of green super absorbent resin based on starch. New Chem Mater 47:256–259. http://www.hgxx.org/CN/Y2019/V47/I2/256

Hu F (2014) Study on influence of coal composition upon hydrophilicity of coal dust. Min Saf Environ Prot 41:19–22. https://doi.org/10.3969/j.issn.1008-4495.2014.06.006

Hu X, Liu Y, Feng Y et al (2023) Study on the performance and mechanism of extracellular polymer substances (EPS) in dust

suppression. Powder Technol 419:118331. https://doi.org/10.1016/j.powtec.2023.118331
Jiang B, Liu Z, Zhao Y et al (2024) Development of an eco-friendly dust suppressant based on modified pectin: experimental and theoretical investigations. Energy 289:130018. https://doi.org/10.1016/j.energy.2023.130018
Jiang J, Wang P, Pei Y et al (2021) Preparation and performance analysis of a coking coal dust suppressant spray. Int J Coal Sci Technol 8:1003–1014. https://doi.org/10.1007/s40789-021-00406-8
Jin H, Zhang Y, Wu G et al (2022) Optimization via response surface methodology of the synthesis of a dust suppressant and its performance characterization for use in open cut coal mines. J Environ Sci 121:211–223. https://doi.org/10.1016/j.jes.2021.12.006
Kondrasheva NK, Zyrianova OV, Kireeva EV, Ivkin AS (2016) Refinery byproducts in dust suppression and the prevention of rock adhesion and freezing at mines. Coke Chem 59:338–344. https://doi.org/10.3103/S1068364X16090040
Li M, Song X, Li G et al (2022a) Experimental study on dust suppression effect and performance of new nano-composite dust suppressant. Int J Environ Res Public Health 19:6288. https://doi.org/10.3390/ijerph19106288
Li M, Yin W, Tang J et al (2023) Experimental study on ratio optimization and application of improved bonded dust suppressant based on wetting effect. J Air Waste Manage Assoc 73:394–402. https://doi.org/10.1080/10962247.2023.2189173
Li M, Zhao Y, Bian S et al (2022b) A green, environment-friendly, high-consolidation-strength composite dust suppressant derived from Xanthan gum. Environ Sci Pollut Res Int 29:7489–7502. https://doi.org/10.1007/s11356-021-16258-3
Li S, Yan D, Yan M et al (2022c) Experimental study on effect of glycolipid biosurfactant on coal wetting and microstructure. J Saf Environ 22:680–687. https://doi.org/10.13637/j.issn.1009-6094.2020.1437
Li S, Zhou G, Liu Z et al (2020) Synthesis and performance characteristics of a new ecofriendly crust-dust suppressant extracted from waste paper for surface mines. J Clean Prod 258:120620. https://doi.org/10.1016/j.jclepro.2020.120620
Liu H, Ge S, Sun L et al (2023) Study on performance of compound surfactants in synergistic with inorganic salts to wet coal dust. J Saf Sci Technol 19:60–66. https://doi.org/10.11731/j.issn.1673-193x.2023.01.009
Liu J, Feng Y, Zhao Y et al (2022a) Effect of TiO2-NPs on microbial-induced calcite carbonate precipitation. J Environ Chem Eng 10:107041. https://doi.org/10.1016/j.jece.2021.107041
Liu J, Wang J, Liu Y et al (2024a) A hygroscopic dual-porous road dust suppressant with good dust suppression prepared by the freeze-thawing method. J Clean Prod 448:141677. https://doi.org/10.1016/j.jclepro.2024.141677
Liu J, Wang S, Jin L et al (2021a) Water-retaining properties of NCZ composite dust suppressant and its wetting ability to hydrophobic coal dust. Int J Coal Sci Technol 8:240–247. https://doi.org/10.1007/s40789-020-00385-2
Liu M, Meng Q, Niu C et al (2022b) Preparation and characterization of modified dual network dust suppression gel based on sodium alginate and soluble starch. Environ Sci Pollut Res 29:69771–69784. https://doi.org/10.1007/s11356-022-20721-0
Liu M, Tu T, Li H, Song X (2024b) Production and characterization of novel/chimeric sophorose-rhamnose biosurfactants by introducing heterologous rhamnosyltransferase genes into Starmerella Bombicola. Biotechnol Biofuels Bioprod 17:133. https://doi.org/10.1186/s13068-024-02581-7
Liu R, Zhou G, Wang C et al (2020) Preparation and performance characteristics of an environmentally-friendly agglomerant to improve the dry dust removal effect for filter material. J Hazard Mater 397:122734. https://doi.org/10.1016/j.jhazmat.2020.122734
Liu Y, Nie W, Jin H et al (2017) Solidifying dust suppressant based on modified Chitosan and experimental study on its dust suppression performance. Adsorpt Sci Technol 36:640–654. https://doi.org/10.1177/0263617417713624
Liu Y, Wang R, Zhao T et al (2022c) Source apportionment and health risk due to PM10 and TSP at the surface workings of an underground coal mine in the arid desert region of Northwestern China. Sci Total Environ 803:149901. https://doi.org/10.1016/j.scitotenv.2021.149901
Liu Z, Zhou G, Duan J et al (2021b) Preparation of composite high-efficiency dust suppressant and relevant molecular dynamics simulation for wetting coal surface. Fuel 296:120579. https://doi.org/10.1016/j.fuel.2021.120579
Luo H, Zhou W, Jiskani IM, Wang Z (2021) Analyzing characteristics of particulate matter pollution in open-pit coal mines: implications for green mining. Energies 14:2680. https://doi.org/10.3390/en14092680
Luo L, Guo M, Zhang D et al (2024) Efficient isolation of rhamnolipids from fermentation broth *via* an advanced acid-induced precipitation process with heat treatment. Food Bioprod Process 148:52–61. https://doi.org/10.1016/j.fbp.2024.08.016
Luo R, Lin M, Luo Y, Dong J (2016) Preparation and properties of a new type of coal dust suppressant. J China Coal Soc 41:454–459. https://doi.org/10.13225/j.cnki.jccs.2015.1303
Luo Z, Wang D, Ding X (2022) Accuracy analysis on evaluation indexes of dust effect. China Saf Sci J 32:195–200. https://doi.org/10.16265/j.cnki.issn1003-3033.2022.01.026
Medeiros MA, Leite CMM, Lago RM (2012) Use of glycerol by-product of biodiesel to produce an efficient dust suppressant. Chem Eng J 180:364–369. https://doi.org/10.1016/j.cej.2011.11.056
Mwandira W, Nakashima K, Kawasaki S et al (2019) Solidification of sand by Pb(II)-tolerant bacteria for capping mine waste to control metallic dust: case of the abandoned Kabwe mine. Chemosphere 228:17–25. https://doi.org/10.1016/j.chemosphere.2019.04.107
National Bureau of Statistics of China (2024) Statistical bulletin of the People's Republic of China on national economic and social development in 2023. People's Daily. https://doi.org/10.28655/n.cnki.nrmrb.2024.002126
National Health Commission of the People's Republic of China (2024) Statistical bulletin on the development of health care in China in 2023. Chin J Viral Dis 14:416–424. https://doi.org/10.16505/j.2095-0136.2024.0083
Nie W, Tian Q, Niu W et al (2023a) Synergistic effect of binary mixture of anionic nonionic surfactant on inhibiting coal dust pollution: experiment and simulation. J Environ Chem Eng 11:110099. https://doi.org/10.1016/j.jece.2023.110099
Nie W, Xu C, Peng H, Zhang S (2023b) Development and research on dust suppression performance of a new type of spray dust suppressant for increasing moisturizing and accelerating coagulation in mines. Mater Rep 37:264–272. https://doi.org/10.11896/cldb.22030228
Niu W, Nie W, Bao Q et al (2023) Development and characterization of a high efficiency bio-based rhamnolipid compound dust suppressant for coal dust pollution control. Environ Pollut 330:121792. https://doi.org/10.1016/j.envpol.2023.121792
Oostveen MLM, Meesters GMH, Van Ommen JR (2015) Quantification of powder wetting by drop penetration time. Powder Technol 274:62–66. https://doi.org/10.1016/j.powtec.2014.09.021
Pang J, Xie J, Zhao Z et al (2024) Study on improving the wettability of anthracite dust by surfactant-magnetized water. Trans Beijing Inst Technol 44:83–90. https://doi.org/10.15918/j.tbit1001-0645.2023.064
Parvej S, Naik DL, Sajid HU et al (2021) Fugitive dust suppression in unpaved roads: state of the Art research review. Sustainability 13:2399. https://doi.org/10.3390/su13042399

Peng X, Wu C (2005) Progress of chemical dust suppressants and their applications. J Saf Sci Technol 05:46–49. https://doi.org/10.3969/j.issn.1673-193X.2005.05.010

Dai J, Zhang Y, Yang J et al (2024) Effect of alkali activated potassium persulfate solution immersion on wettability and pore structure of coking coal. J China Coal Soc 49(S2):1090−1103. https://doi.org/10.13225/j.cnki.jccs.2023.0845

Ren B, Yuan L, Zhou G et al (2022) Effectiveness of coal mine dust control: A new technique for Preparation and efficacy of self-adaptive microcapsule suppressant. Int J Min Sci Technol 32:1181–1196. https://doi.org/10.1016/j.ijmst.2022.09.006

Saha P, Ksaibati K (2022) Effectiveness of the two chemical treatments (CaCl2 and MgCl2) as dust suppressants on gravel roads. Int J Pavement Eng 23:332–339. https://doi.org/10.1080/10298436.2020.1745799

Sen S, Borah SN, Sarma H et al (2021) Utilization of distillers dried grains with solubles as a cheaper substrate for sophorolipid production by Rhodotorula Babjevae YS3. J Environ Chem Eng 9:105494. https://doi.org/10.1016/j.jece.2021.105494

Shao Z, Dong H, Cheng W et al (2022) Preparation of mussel-inspired stable-bonding dust binders for fugitive dust control. ACS Appl Polym Mater 4:5341–5354. https://doi.org/10.1021/acsapm.2c00367

Shi G, Han C, Wang Y, Wang H (2019) Experimental study on synergistic wetting of a coal dust with dust suppressant compounded with noncationic surfactants and its mechanism analysis. Powder Technol 356:1077–1086. https://doi.org/10.1016/j.powtec.2019.09.040

Shi G, Qi J, Teng G et al (2022) Influence of coal properties on dust suppression effect of biological dust suppressant. Adv Powder Technol 33:103352. https://doi.org/10.1016/j.apt.2021.11.004

Shi G, Qi J, Wang Y, Shen H (2021) Synergistic influence of noncationic surfactants on the wettability and functional groups of coal. Powder Technol 385:92–105. https://doi.org/10.1016/j.powtec.2021.02.056

Sieger JL, Lottermoser BG, Freer J (2023) Evaluation of protein and polysaccharide biopolymers as dust suppressants on mine soils: laboratory experiments. Appl Sci 13:1010. https://doi.org/10.3390/app13021010

Song C, Zhao Y, Cheng W et al (2021) Preparation of microbial dust suppressant and its application in coal dust suppression. Adv Powder Technol 32:4509–4521. https://doi.org/10.1016/j.apt.2021.10.001

Song W, Yang Y, Qi R et al (2019) Suppression of coal dust by microbially induced carbonate precipitation using Staphylococcus succinus. Environ Sci Pollut Res Int 26:35968–35977. https://doi.org/10.1007/s11356-019-06488-x

Sun J, Zhou G, Gao D et al (2020) Preparation and performance characterization of a composite dust suppressant for preventing secondary dust in underground mine roadways. Chem Eng Res Des 156:195–208. https://doi.org/10.1016/j.cherd.2020.01.030

Sun Y, Zhu X, Yuan H et al (2018) The Preparation and performance test of a new type of water-absorbent resin dust suppressant with cation. IOP Conf Ser 199:032085. https://doi.org/10.1088/1755-1315/199/3/032085

Taowkrue E, Songdech P, Maneerat S, Soontorngun N (2024) Enhanced production of yeast biosurfactant sophorolipids using yeast extract or the alternative nitrogen source soybean meal. Ind Crops Prod 210:118089. https://doi.org/10.1016/j.indcrop.2024.118089

Tong R, Cao Q, Wang S (2019) Study on wettability of coal dust based on surface active agent. Coal Technol 38:118–120. https://doi.org/10.13301/j.cnki.ct.2019.04.041

Tsogt B, Oh S (2021) Preparations and application of dust suppressants from biomass-based materials. J Air Waste Manage Assoc 71:1386–1396. https://doi.org/10.1080/10962247.2021.1942320

Volikov A, Karpukhina EA, Larionov KS et al (2023) Humic-based polyelectrolyte complexes for dust suppression. Polym 15. https://doi.org/10.3390/polym15061514

Wang G, Han D, Qin X et al (2020a) A comprehensive method for studying pore structure and seepage characteristics of coal mass based on 3D CT reconstruction and NMR. Fuel 281:118735. https://doi.org/10.1016/j.fuel.2020.118735

Wang H, Cheng S, Wang H et al (2023a) Synthesis and properties of coal dust suppressant based on microalgae oil extraction. Fuel 338:127273. https://doi.org/10.1016/j.fuel.2022.127273

Wang H, He S, Zhang Q, Zhao X (2021a) Experimental study on synthesis of biological dust suppressant by microbial fermentation. J China Coal Soc 46:477–488. https://doi.org/10.13225/j.cnki.jccs.XR20.1962

Wang J, Ji G, Tian J et al (2011) Functional characterization of a biosurfactant-producing thermo-tolerant bacteria isolated from an oil reservoir. Pet Sci 8:353–356. https://doi.org/10.1007/s12182-011-0152-y

Wang K, Zhang Y, Cai W et al (2021b) Study on the microscopic mechanism and optimization of dust suppression by compounding biological surfactants. Colloids Surf A 625:126850. https://doi.org/10.1016/j.colsurfa.2021.126850

Wang P, Jiang Y, Liu R et al (2020b) Experimental study on the improvement of wetting performance of OP-10 solution by inorganic salt additives. Atmos Pollut Res 11:153–161. https://doi.org/10.1016/j.apr.2020.02.023

Wang P, Liu Y, Cui Y et al (2023b) Effect of inorganic salt additives on wetting coal dust with SDBS solution. J Saf Environ 23:1935–1943. https://doi.org/10.13637/j.issn.1009-6094.2022.1893

Wang Q, Geng X, Li Y et al (2023c) Effect of nanoparticles and silicone surfactants on the foam properties and wettability of dust removal foam. Chem Eng Sci 281:119147. https://doi.org/10.1016/j.ces.2023.119147

Wang Q, Zhang X, Wang W et al (2025) Effect of fluorocarbons and inorganic salts on wetting and foaming characteristics of hydrocarbon surfactants. Colloids Surf A 704:135416. https://doi.org/10.1016/j.colsurfa.2024.135416

Wang S, Ding H, Xie J et al (2023d) A review on the suppression mechanism of typical flame retardants on the explosion of mine dust. Powder Technol 427:118762. https://doi.org/10.1016/j.powtec.2023.118762

Wang S, Zheng Y, Jiang B et al (2023e) Effect of sophorolipid adsorption on the coal microstructure: experimental and wettability mathematical model discussion. Langmuir 39:14173–14188. https://doi.org/10.1021/acs.langmuir.3c02308

Wang X, Dai H, Liang G et al (2021c) Flame propagation characteristics of mixed pulverized coal at the atmosphere of gasification. Fuel 300:120954. https://doi.org/10.1016/j.fuel.2021.120954

Wang X, Jiang B, Zhao Y et al (2023f) Effect of pectin-modified dust suppressant with different methoxy levels on wetting and agglomeration of coal: experimental and theoretical discussion. Fuel 352:129134. https://doi.org/10.1016/j.fuel.2023.129134

Wang X, Yang J, Li X (2023g g) Study on characteristics and microscopic mechanism of composite environment-friendly dust suppressant for urban construction site soil fugitive dust based on response surface methodology optimization. Environ Sci Pollut Res 30:41954–41969. https://doi.org/10.1007/s11356-023-25224-0

Wang X, Yang J, Shi Y et al (2024) Study on the mechanism of polymer inhibiting purplish soil fugitive dust at macro-micro scale in Southwest China. J Mol Liq 396:123928. https://doi.org/10.1016/j.molliq.2023.123928

Wang X, Yuan S, Jiang B (2019) Wetting process and adsorption mechanism of surfactant solutions on coal dust surface. J Chem 2019:9085310. https://doi.org/10.1155/2019/9085310

Wang Z, Zhou W, Jiskani IM et al (2022) Annual dust pollution characteristics and its prevention and control for environmental protection in surface mines. Sci Total Environ 825:153949. https://doi.org/10.1016/j.scitotenv.2022.153949
Wei J, Zhao Y, Yu S et al (2021) Environment-friendly dual-network hydrogel dust suppressant based on Xanthan gum, Polyvinyl alcohol and acrylic acid. J Environ Manage 295:113139. https://doi.org/10.1016/j.jenvman.2021.113139
Wu G, Xu C, Yang Y, Yang Y (2022) Development of hydrogel biological dust suppressant based on formula optimization. Environ Sci Technol 45:148–154. https://doi.org/10.19672/j.cnki.1003-6504.0711.22.338
Wu M, Hu X, Zhang Q et al (2020a) Preparation and performance evaluation of environment-friendly biological dust suppressant. J Clean Prod 273:123162. https://doi.org/10.1016/j.jclepro.2020.123162
Wu M, Hu X, Zhang Q et al (2020b) Study on Preparation and properties of environmentally-friendly dust suppressant with semi-interpenetrating network structure. J Clean Prod 259:120870. https://doi.org/10.1016/j.jclepro.2020.120870
Wu Y, Meng X, Zhang Y et al (2023) Experimental study on the suppression of coal dust explosion by silica aerogel. Energy 267:126372. https://doi.org/10.1016/j.energy.2022.126372
Xi Z, Jiang M, Yang J, Tu X (2014) Experimental study on advantages of foam-sol in coal dust control. Process Saf Environ Prot 92:637–644. https://doi.org/10.1016/j.psep.2013.11.004
Xi Z, Wang C, Xia T, Suo L (2023a) Synthesis of a new three-dimensional cross-linked network dust suppressant and its mechanism of coal-dust Inhibition. Powder Technol 430:118976. https://doi.org/10.1016/j.powtec.2023.118976
Xi Z, Xia T, Shen L, Suo L (2023b) Synthesis of cardanol grafted hydrophilic polymers and its mechanism of coal dust Inhibition. Fuel 345:128112. https://doi.org/10.1016/j.fuel.2023.128112
Xu R, Yu H, Dong H et al (2023) Preparation and properties of modified starch-based low viscosity and high consolidation foam dust suppressant. J Hazard Mater 452:131238. https://doi.org/10.1016/j.jhazmat.2023.131238
Yang F, Li X, Ge F, Li G (2022a) Dust prevention and control in China: A systematic analysis of research trends using bibliometric analysis and bayesian network. Powder Technol 411:117941. https://doi.org/10.1016/j.powtec.2022.117941
Yang H, Liu Z, Zhao D et al (2022b) Insights into the fluid wetting law and fractal characteristics of coal particles during water injection based on nuclear magnetic resonance. Chaos Solitons Fractals 159:112109. https://doi.org/10.1016/j.chaos.2022.112109
Yan J (2019) Study on wettability of coal dust based on its surface properties. PhD dissertation, China University of Mining and Technology, Beijing. https://doi.org/10.27624/d.cnki.gzkbu.2019.000092
Yan J, Nie W, Xiu Z et al (2021) Development and characterization of a dust suppression spray agent based on an adhesive NaAlg-gln-poly/polysaccharide polymer. Sci Total Environ 785:147192. https://doi.org/10.1016/j.scitotenv.2021.147192
Yin S, Wang L, Chen X et al (2018) Seepage law of solution inside ore granular under condition of different heap constructions. J Cent South Univ (Sci Technol) 49:949–956. https://doi.org/10.11817/j.issn.1672-7207.2018.04.024
Yu H, Zahidi I (2023) Environmental hazards posed by mine dust, and monitoring method of mine dust pollution using remote sensing technologies: an overview. Sci Total Environ 864:161135. https://doi.org/10.1016/j.scitotenv.2022.161135
Yu X, Tao X, Yu L et al (2024) Gut Microbiome and metabolome profiling in coal workers' pneumoconiosis: potential links to pulmonary function. Microbiol Spectr 12:e00049–e00024. https://doi.org/10.1128/spectrum.00049-24
Yu X, Zhao Y, Feng Y et al (2022) Synthesis and performance characterization of a road coal dust suppressant with excellent consolidation, adhesion, and weather resistance. Colloids Surf A 639:128334. https://doi.org/10.1016/j.colsurfa.2022.128334
Zhang F, Lu Y, Wang Y et al (2022) Study on air curtain cooperative spray dust removal in heading face based on swirl theory. J Environ Chem Eng 10:108892. https://doi.org/10.1016/j.jece.2022.108892
Zhang F, Lu Y, Wang Y, Jiang Z (2023) Study on synthesis of environmentally-friendly polymer dust suppressant based on graft modification. Powder Technol 423:118436. https://doi.org/10.1016/j.powtec.2023.118436
Zhang H, Han W, Xu Y, Wang Z (2021a) Analysis on the development status of coal mine dust disaster prevention technology in China. J Healthc Eng 2021:5574579. https://doi.org/10.1155/2021/5574579
Zhang H, Nie W, Wang H et al (2018) Preparation and experimental dust suppression performance characterization of a novel Guar gum-modification-based environmentally-friendly degradable dust suppressant. Powder Technol 339:314–325. https://doi.org/10.1016/j.powtec.2018.08.011
Zhang H, Nie W, Yan J et al (2020) Preparation and performance study of a novel polymeric spraying dust suppression agent with enhanced wetting and coagulation properties for coal mine. Powder Technol 364:901–914. https://doi.org/10.1016/j.powtec.2019.10.082
Zhang Q, Zhou G, Hu Y et al (2021b) Microwetting dynamic behavior and mechanism for coal dust based on low field NMR method - A case study. Fuel 297:120702. https://doi.org/10.1016/j.fuel.2021.120702
Zhao B, Li S, Lin H et al (2022) Experimental study on the influence of surfactants in compound solution on the wetting-agglomeration properties of bituminous coal dust. Powder Technol 395:766–775. https://doi.org/10.1016/j.powtec.2021.10.026
Zhao J, Tian S, Zou Q et al (2024) Effect of SiO2-H2O nanofluids on wettability of pulverized coal and the modification mechanism. Fuel 359:130396. https://doi.org/10.1016/j.fuel.2023.130396
Zhao Y, Liu W, Hu X et al (2023) Effect of surfactant on urease-producing flora from waste activated sludge using microbially induced calcite precipitation technology to suppress coal dust. Environ Res 237:116941. https://doi.org/10.1016/j.envres.2023.116941
Zhao Z, Chang P, Xu G et al (2021a) Comparison of the coal dust suppression performance of surfactants using static test and dynamic test. J Clean Prod 328:129633. https://doi.org/10.1016/j.jclepro.2021.129633
Zhao Z, Yang C, Sun C, Shu X (2011) Experimental study of coal dust wettability. J China Coal Soc 36:442–446. https://doi.org/10.13225/j.cnki.jccs.2011.03.029
Zhao Z, Zhao Y, Hu X et al (2021b) Preparation and performance analysis of enteromorpha-based environmentally friendly dust suppressant. Powder Technol 393:323–332. https://doi.org/10.1016/j.powtec.2021.07.071
Zhou G, Wang C, Li S et al (2021) Preparation and characteristics analysis of an ecoenvironmental protection Cyclic solidification dust-fixing agent extracted from waste shrimp shells to suppress dust in coal resource-based cities. J Environ Manage 296:113224. https://doi.org/10.1016/j.jenvman.2021.113224
Zhou G, Xing Z, Tian Y et al (2022) An environmental-friendly oil-based dust suppression microcapsules: structure with Chitosan derivative as capsule wall. Process Saf Environ Prot 165:453–462. https://doi.org/10.1016/j.psep.2022.07.013
Zhou G, Xu Y, Wang Q et al (2023a) Wetting-consolidation type dust suppressant based on sugarcane Bagasse as an environmental material: preparation, characterization and dust suppression

mechanism. J Environ Manage 330:117097. https://doi.org/10.1016/j.jenvman.2022.117097
Zhou G, Xu Y, Wang Y et al (2023b) Study on MICP dust suppression technology in open pit coal mine: Preparation and mechanism of microbial dust suppression material. J Environ Manage 343:118181. https://doi.org/10.1016/j.jenvman.2023.118181
Zhou G, Zhang X, Li S et al (2023c) New type of sawdust-based dust suppressant during tunnelling and underground space: preparation, characterization and engineering application. Constr Build Mater 365:130085. https://doi.org/10.1016/j.conbuildmat.2022.130085
Zhou L, Yang S, Wu X et al (2019) Enhancing suppression performance of spray on lignite fine particles by adding surfactant. J Southeast Univ 49:280–287. https://doi.org/10.3969/j.issn.1001-0505.2019.02.012
Zhou Q, Qin B, Wang J et al (2018) Effects of Preparation parameters on the wetting features of surfactant-magnetized water for dust control in Luwa mine, China. Powder Technol 326:7–15. https://doi.org/10.1016/j.powtec.2017.12.002
Zhu S, Zhao Y, Hu X et al (2021a) Study on Preparation and properties of mineral surfactant - microbial dust suppressant. Powder Technol 383:233–243. https://doi.org/10.1016/j.powtec.2021.01.053
Zhu Y, Cui Y, Shan Z et al (2021b) Fabrication and characterization of a multi-functional and environmentally-friendly starch/organo-bentonite composite liquid dust suppressant. Powder Technol 391:532–543. https://doi.org/10.1016/j.powtec.2021.06.050