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A Comparative Assessment of On-Site Application Effects of Mine Dust Prevention and Control Technology

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Abstract

Prolonged exposure to coal dust leads to various lung disorders, including incurable coal workers' pneumoconiosis (CWP), and endangers miners' health in underground mines. This article summarizes the latest research progress in dust control technology, including chemical dust suppressants, foam dust removal, ultrasonic atomization, magnetized water dust suppression, double curtains of wind and fog, biological nano-film, and emerging microbial dust suppressants in the field of dust. The actual application compares and analyzes the advantages and disadvantages of different dust removal technologies. The current three directions of mine dust prevention and control are pointed out: the prevention and control of respirable dust, hydrophobic dust, and secondary dust, and the prospects for future development trends. Given the treatment of respirable dust, it is necessary to strengthen the research on the dust generation mechanism under different working conditions and to explore the migration and settlement laws of respirable dust by constructing a numerical model of dust dynamics; for the treatment of hydrophobic dust, further research on the microphysical and chemical properties of coal dust is needed. The relationship between wettability and continuously optimizing the wetting agent; for the prevention and control of secondary dust in coal mines, emerging microbial dust suppression technologies need to be developed to explore the micro-action between microorganisms and coal dust molecules to achieve green prevention and control of dust.

Keywords

Dust Control, Hydrophobic, Reduction Efficiency, Surfactant, Wettability

1. Introduction

Coal is a primary energy source that plays a significant part in China's energy production and consumption (Hao, Song, Feng, & Zhang, 2019). However, it has caused immeasurable harm to the environment and workers' health for the past decades, borne out of the excessive dust pollution exerted during the coal mining process. Industrial mine dust-related accidents and other health issues are caused by the enormous amount of coal dust created during coal extraction, transportation, and storage. By the end of 2018, China has reported more than 800,000 cases of occupational pneumoconiosis, with the coal industry contributing to even more than 60% of those cases (Doney et al., 2020; Kurth, Laney, Blackley, & Halldin, 2020; Zhang, Zhang, Liu, & Meng, 2020c). Furthermore, the increased coal dust concentration enhanced the dangers of coal dust explosions in underground coal mines. For instance, 29 persons were killed on April 5, 2010, in a methane and coal dust explosion in the Upper Big Branch mine south of Charleston, United States (Davis, Engel, & van Wingerden, 2015). As a result, coal dust has become an important issue in the coal sector, substantially affecting company safety procedures, workers' lives, and properties.

In many mining countries, laws and guidelines on coal dust concentration limits have been developed to provide a safe and healthy workplace in underground mines. For instance, according to China's "coal mine safety rules," the maximum allowable quantities of total dust and respirable dust were 10 mg/m^3 and 3.5 mg/m^3, respectively. In 2016, these limits were adjusted to 4 mg/m^3 and 2.5 mg/m^3, respectively (Li, Sui, Liu, & Zhao, 2019a). In the US, the Mine Safety and Health Administration (MSHA) established the permissible exposure limit for respiratory coal dust at 2 mg/m^3, which was subsequently decreased to 1.5 mg/m^3 in August 2016 (Xu, Chen, Eksteen, & Xu, 2018). However, the technologies now used to control coal dust scarcely satisfy the stated standards. According to an examination of compliance dust samples taken over five years between 2000 and 2004 by MSHA inspectors and mine operators, 15% and 14% of the samples from the two groups exceeded the exposure limit (Weeks, 2006).

Many technologies, including coal seam water injection and water spray, have previously been investigated to reduce coal dust pollution (Liu & Wang, 2019; Liu, Cao, Guo, & Li, 2018a). Laumann and Ren discovered that a coal seam's water content could be significantly increased to decrease the dust produced when coal is broken. They demonstrated this by increasing the water content by 0.7%, and the dust concentration in the Bulli coal seam was reduced by 30% to 50% (Laumann et al., 2011; Ren, Plush, & Aziz, 2011). Liu studied the impact of the coal body's pore structure and permeability on how well water infusion suppressed dust. It was discovered that the fissure is well formed in the stress relief zone, the borehole's stress along its depth was significantly concentrated in the stress concentration region, and the influence of coal seam water injection gradually weakened (Liu, Yang, Wang, Cheng, & Xin, 2018b). Although coal seam water injection provides the benefit of pre-wetting the coal body, the majority of coal seams in China have low permeability, making it challenging to accomplish the desired impact.

Currently, water spray dust control technology is the most widely employed in the coal mining process (Kou et al., 2015; Li, Zhou, & Li, 2017). This technology has helped to improve the underground working environment, protect workers' health, and avoid mine dust accidents. In order to effectively capture coal dust, Klima created a water curtain. He discovered that when the novel device was used with a 75˚ spray angle and a 1.37 m spray distance, respirable dust concentration at the upwind splitter arm and drum centerline locations was significantly reduced (Klima, Reed, Driscoll, & Mazzella, 2021). In addition, Ren created a dust removal spray system to control downhole dust particles by simulating the distribution rules of the spray field along the wind flow in the fully mechanized face (Ren, Wang, & Cooper, 2014a). However, while water spray has many benefits, including affordability, ease of acquiring spray mediums, and a simple operation process, it also has disadvantages, including poor wettability for coal dust and high water consumption, with a total dust control efficiency of less than 50%, particularly in respirable dust (Tessum, Raynor, & Keating-Klika, 2014; Wang, Jiang, Chen, Chen, & Wang, 2019b).

Given the aforementioned, many existing literature (Chen et al., 2019; Csavina et al., 2012; Rees & Murray, 2020; Sarver, Keleş, & Afrouz, 2021; Vanka et al., 2022) have tried to examine the mechanisms of industrial mine dust, dust-associated hazards as well as mine dust control and prevention mechanisms, and have proposed new prevention and control methods for mine dust prevention. However, these technologies still have limitations (Kong, Li, Yang, Liu, & Yan, 2017).

According to the research above, coal dust is still a substantial threat to the coal industry, and efficient technologies are required to minimize coal dust concentrations to satisfy the stated requirement and protect coal workers from dust hazards. Therefore, this article comparatively assesses mine dust prevention and control technologies, evaluates technical research status and development trends, summarizes the latest research results, and compares the application of dust removal technologies.

The rest of the paper is structured in the following way Section 2 details prior studies within the scope of the study; Section 3 comparatively analyses on-site application effects; Section 4 details the development direction of dust prevention and control and finally, Section 5 concludes the work.

2. Research Status of Coal Mine Dust Prevention Technology

2.1. Chemical Dust Suppressant

Chemical dust suppression is to form a polymer network structure through cross-linking in which dust particles are captured, adsorbed, and agglomerated in the network structure through the attraction of ionic groups to the charged particles (Jin et al., 2022; Zhou, Ma, Fan, & Wang, 2018). A chemical dust suppressant is a technology used to manage fugitive dust by combining water with an ideal volumetric concentration of surfactants such as lignosulphonates, salts, petroleum products, and polymer emulsion products. However, China did not start to apply chemical dust suppressant to mine dust until the 1960s (Xu et al., 2018). Currently, chemical dust suppressants are mainly divided into wetting, foaming, crust, and agglomerating agents (Liu, Zhou, Wang, Jiang, & Wei, 2020).

Wetting agents are surfactant formulations that increase water's capacity to wet and agglomerate small particles. Particle capture, bulk aggregation, and surface stabilization are the main methods for suppressing moist dust. Particle capture involves contacting, wetting, and capturing suspended dust particles with liquid droplets. Spread and capillary wetting processes are involved in the wetting of bulk solids to control dust. In addition, it is effective in containing highly concentrated floating dust (Cui et al., 2019; Zhou et al., 2022).

Foaming agents are substances used to turn water and air into foam. Dust control foam has the consistency of shaving cream and is dry, stable, and small-bubbled. Foaming agents are primarily high-foaming surfactants with the addition of wetting and binding agents. Dust control foam works the same way liquid spray wet suppression does by wetting and agglomerating small particles. The benefits of foam over liquid sprays include better liquid dispersion, which results in lower liquid feed rates, and better fine particle capture, which decreases breathable dust (Fan, Zhou, & Wang, 2018; Yu et al., 2021). Crusting agents are long-term surface stabilization binding agents. The best qualities for a particular application vary, although elastic properties are usually the most significant for maintaining a continuous crust during pile sinking, expansion and contraction, and light loads. Tensile strength, flexibility, and weather resistance are crucial features of pile crusting (Mugahed Amran, Alyousef, Rashid, Alabduljabbar, & Hung, 2018). Binding/agglomerating agents provide long-term residual dust control distinct from water or foam suppression. Binding agents are broadly classed as a humectant and sticky formulations. Humectants like magnesium and calcium chloride absorb and retain surface moisture, keeping the dust moist. In the absence of surface moisture, adhesives successfully include fine particle agglomerates (Ma, Zhou, Ding, Li, & Wang, 2018).

With the development of science and technology, China's dust suppressant requirements are becoming more stringent. Therefore, the primary development trend is an environmentally friendly dust suppressant for mines (Jin et al., 2022). **Table 1** summarizes the research results of dust suppressant in recent years. The chemical dust suppressant is evaluated for its effect on economic viability and environmental-friendliness. Furthermore, it functions efficiently on open dust sources, implying that it has a large potential for future growth.

2.2. Foam Dust Reduction

In the 1950s, Britain first discovered that the foam produced by water, compressed air, and foaming agents could effectively control dust (Price, 1946). In the early 1980s, the US Bureau of Mines produced a compressed air foam generator

Table 1. Research results of chemical dust suppressant.

Types of Suppressant	Name	Formula	Advantage	Dust suppression performance		Years	Literature
				Total dust	Respirable		
Wetting Dust Suppressant	Coagulation-type coal mine spray dust suppressant	0.3%SDS + 0.25%BS-12 + 0.1%NaCl + 0.8% Hydroxypropyl guar	Improve wettability and coagulation performance	83.94%	84.08%	2020	Zhang (Zhang et al., 2020a)
	Preparation of Wetting Dust Suppressant from Papermaking Waste	Sodium lignosulfonate grafted polyacrylamide branched chain (SLS-PAM):SDBS = 1:1	Shield metal ions, not affected by hard water downhole	——		2019	Li Shufang (Li, Tian, Xie, & Mang, 2019b)
	New type coal dust chemical dust suppressant	0.20% polyacrylamide + 0.15% sodium alginate + 0.20% fatty alcohol polyoxyethylene ether + 0.09% lauryl trimethyl ammonium bromide + 0.01% tallow amine	High safety, low corrosion, PM2.5 dust removal rate is 77.3%	90.0%	82.4%	2020	Zhang Jiangshi (Zhang, Liu, & Fan, 2020b)
Crust Dust Suppressant	Microwave polymerization compound dust suppressant	Bentonite 1.0%, Tween-800.7%, Borax 1.0%, reaction temperature 35˚C	High wind erosion resistance, high total dust suppression rate	92.96%	84.62%	2019	Wang Zhenyu (Wang, 2019)
	Dust suppressor for crusting in an open-pit coal mine	Hydroxyethyl cellulose: acrylamide: acrylic acid 1:2:6 initiator 1.0 mol%, crosslinking agent 0.8 mol% temperature 65˚C	Good environmental adaptability, cheap raw materials, simple preparation	84%		2018	Ma (Ma et al., 2018)
	Modified Chitosan Cured Dust Suppressant	0.025% quaternary ammonium salt modified chitosan (HTCC)	High water solubility, viscosity, and durability	82.30%		2017	Liu (Liu et al., 2017)

for dust suppression (Wang et al., 2015). More recently, research in China Wang et al. (2013) created a Venturi-type foam device developed and tested in coal mines, generating good outcomes.

With the rapid development of the surfactant industry, scientists can continuously improve the performance of foaming agents according to the requirements of different dust sources (Wang, Wei, Du, & Wang, 2019a). Wang et al. (2015) found that adding carboxymethyl cellulose can optimize the shape of the foam and increase its uniformity. As a result, the average particle size is reduced, which is more favorable to the wetting of coal dust. Adding a foam agent to the water can minimize the contact angle with coal dust by 67%, according to the foam performance test, and the wetting rate is higher than that of pure water. Increase by 30 times. In highly mechanized underground coal mines, foam dust suppression is frequently employed (Wang, Lu, Wang, & Chen, 2016), as shown in **Table 2**. The key to creating a high-performance foam is to produce a foaming agent and foam generator that are well-suited to coal dust control. Ren, Wang, Guo, and Zuo (2014b) showed some of the benefits of using foam

Table 2. Application of foam dust reduction.

Application	Water consumption m^3/h	Input cost yuan/m^3	Dust removal rate	
			Total dust	Respirable dust
Jinjia Coal Mine	1 - 1.5	12.2	66.39%	71.25%
Hujiahe Coal Mine	1 - 2	13.4	76	76
Binhu Coal Mine	1 - 2	15	80	80

technology to manage dust in coal mines effectively: good coverage, a large surface area, a fast wetting rate, and strong adhesion. These qualities allow for effective dust control, resulting in rapid improvements in coal mines. However, in underground applications, problems include small foam nozzle coverage, large foam diameter, and poor adhesion (Ren et al., 2014a). In the future, it is necessary to continuously improve the structure of the foamer, the foaming method, and the equipment application technology and optimize the foam dust reduction technology.

2.3. Dust Reduction by Active Magnetized Water

Magnetization improves water wetting properties and is a more cost-effective and ecologically friendly way of coal dust suppression (Nakhaei Pour, Gholizadeh, Housaindokht, Moosavi, & Monhemi, 2017; Pang, Deng, & Tang, 2012). Surface tension, viscosity, and other properties of water can be reduced by magnetization (Cai, Yang, He, & Zhu, 2009). After magnetization, the polarity of water molecules increases, and it is easy to form physical bonds with coal surface substances to produce adsorption, thereby increasing the wettability effect (Lee, Jeon, Kim, & Lee, 2013). To further ensure that the droplets can efficiently capture suspended fine dust, Jing, Ren, and Ge (2019) studied the wettability of coal dust under different magnetic field strengths based on the coupling modification mechanism of surfactants and magnetic fields. They observed significant sedimentation effects on the coal dust and concluded that the magnetization effect produces an optimum result when the magnetization intensity reaches 500 mT (Wu, Deng, Wang, Mao, & Ding, 2015). Magnetized water is a new and efficient dust reduction method currently used in other coal mines in China (Zhou, Qin, Ma, & Jiang, 2017) (see **Table 3**).

2.4. Ultrasonic Atomization (Dry Mist) Dust Removal

Acoustic atomization dust removal uses ultrasonic waves to break and decompose liquid droplets into fine droplets (Zhang, Wang, Chi, & Hu, 2018). In the late 1970s, American researchers proposed that using fine water mist to catch dust could better remove respirable dust. However, the effect of spraying to remove respirable dust is not an ideal technique because the size of the droplets is too large, and it is difficult to capture the dust (Liu & Author, 2002; Zhang et al., 2018).

Table 3. Summary of the application of magnetized surfactant spray dust reduction technology.

Coal mine	Preparation of active magnetized water			Application effect				Literature
				Dust concentration mg/m³		Dust removal efficiency%		
	Active agent	Magnetic field intensity mT	Magnetization time	Total	Respirable	Total	Respirable	
Zhangcun Coal Mine	0.15%LDLC	1200	60	49.8	42.3	76.5	70	Wang Yongzhen (Wang, 2016)
Zouzhuang Coal Mine	0.03%SDBS/FMEE	300 - 350	-	79.78	45.53	82.21	80.87	Zhou Qun (Zhou, Qin, Ma, & Jiang, 2017)
Luwa Coal Mine	0.03%SDBS/FMEE	350	-	31.1	19.1	84.75	83.54	Wang Huaizeng (Wang, Li, & Ding, 2018a)

Wang, Nie, Cheng, Liu, and Jin (2018b) effectiveness of high-pressure atomization for dust removal in deep coal mines was investigated under the assumption that the water supply pressure is constant and fractional efficiency improves with the number of nozzles. Furthermore, when the number of nozzles remains constant, the fractional efficiency rises as the water supply pressure rises. Wang, Tan, Cheng, Guo, & Liu, (2018c) devised an ultrasonic dust suppression system that uses compressed air and water to create micron-sized droplets that successfully suppress respirable coal dust.

The principle is to use compressed air to impact the water flow in the resonant cavity to generate ultrasonic resonance, which intensifies the water flow into mist particles with a diameter of only 1 - 10 μm (Li, Gang, & Chao, 2015). Ultrasonic atomization consumes very little water, about 1% of the water consumption of ordinary spray. Therefore, it is a practical and widely used dust reduction method. **Table 4** summarizes the current application of ultrasonic atomization. Since the conditions of the tunneling faces of various coal mines are different, it is necessary to change the optimal parameters of ultrasonic atomization for different working faces to achieve better dust control effects.

2.5. Wind and Fog Double Curtain Dust Collection

Researchers have presented a wind and fog double curtain dust collecting system based on ventilation dust removal and spray dust reduction research. It consists of a three-way cyclone air curtain device, a high-efficiency wet dust removal fan, a quantitative moisturizer addition device, an excavation face synergistic efficiency and dust control technology (Li, Hu, Hao, & Qu, 2020; Yin et al., 2021).

This technology can achieve dual capture of water curtain and air curtain. The water mist curtain first captures dust, then the escaping dust is controlled by effective technologies such as air curtains and dust removal fans. Hua et al. (2018)

Table 4. Application of ultrasonic atomization dust reduction technology.

Application	Features	Dust concentration mg/m³		Dust removal rate	Cost $/t
		Before use	After use		
Waste silo	A dry, windy climate affects a large amount of dust produced by vibration and impact.	174.2	13.8	92.12%	0.030
Coal preparation plant	Floating dust below 10 μm is generated during crushing, screening, and scraper transfer.	366.71	9.27	95%	0.031
Fully mechanized excavation face	The coal seam has a low water content; the minimum amount of rock dust to inhibit coal dust explosion is 55%, and the volatile content is 38.35%. Therefore, coal dust has the risk of explosion.	88	41.82	65.34%	0.021

and others used FLUENT software to simulate the formation of multi-radial swirling air numerically. The wind and fog double curtain is a more advanced prevention and control technology for treating respirable dust on the tunneling face. However, the air curtain dust collection method still has the disadvantages of long forming distance and difficulty covering the roadway section completely. Therefore, to achieve the wind and fog double curtain for the best dust removal effect, it is important to expand the study of dust flow laws on various working surfaces and under various conditions and continuously enhance the best parameters of the dust control air curtain through numerical simulation (Table 5).

2.6. Biological Dust Suppression

2.6.1. Biomembrane Dust Reduction

Bio-nanofilm dust reduction technology is a new type of dust prevention method based on aerodynamic principles and dust aggregation theory. It is currently used in domestic mines, quarries, ironworks, and construction sites (see Table 6). Nano-biomembrane is a double ionospheric membrane with a water film spacing at the nanometer level. Then gravity settles after its weight increases. Bio-nano-membrane technology conforms to national environmental protection, energy saving, and emission reduction policies but has not been applied to underground mining work. In the future, it is necessary to summarize the experience further, continuously optimize process parameters, and expand the scope of the application.

2.6.2. Microbial Solidification and Dust Suppression

In 2004, Whiffin (2004) researched an emerging soil reinforcement and improvement technology-microbial induced $CaCO_3$ precipitation (MICP). Most of the microorganisms used in MICP technology are urease-producing bacteria (mainly Bacillus pasteurii), which secrete urease to hydrolyze urea to produce carbonate ions combined with calcium ions with calcium chloride and calcium nitrate as the main calcium source precipitation. The mineralization product has gelling properties, can solidify and cement loose particles with microorganisms as nodule sites, and effectively improve the stiffness, strength, and wind erosion resistance of sand, thereby effectively inhibiting the rise of dust.

Table 5. Field application of wind and fog double curtain.

Coal mine	Applicable place	Air curtain parameters	Dust removal efficiency		Literature
			Total	Respirable	
Tangkou Coal Mine	Low gas or no gas full rock machine face excavation	When the air pressure port is 30 m away from the tunnel head, an air curtain of 1.62 Pa can be formed at a position 8.7 m away from the tunnel head	95.1%	96.1%	Nie Wen (Nie et al., 2012)
A mine of Jinmei Group	Fully mechanized excavation face	The jet outlet wind speed should be 10 m/s - 20 m/s. The jet outlet slot width should be 6 mm - 20 mm	86%	90%	Li Yucheng (Li, 2010)

Table 6. On-site application of bio-nano-membrane technology.

Application	Dust characteristics	Operating cost $/t	Dust reduction rate
Lime ore	The discharge port and the transportation roadway produce a large amount of dust	0.028	90%
Andesite Mine	The dust concentration is very high; the visibility is within 1 m	0.047	96.2%
iron ore	The concentration of particles is high, the distribution is uneven, and the airflow is turbulent and difficult to collect	0.063	99%
Gold mine	There are many dust-generating spots in the open air, and the dust dispersion is high	0.062	95%

The microscopic cementation mechanism is shown in **Figure 1**. However, the hydrolysis of urea will produce ammonia gas and cause environmental pollution, and the CO_2 hydration reaction process is relatively slow, affecting the deposition of mineralized products. Carbonic anhydrase can capture CO_2 in the air as a carbon source, promote the hydrolysis of CO_2 to increase the content of mineralized products, have a better curing effect, and be more environmentally friendly (see **Figure 1** and **Figure 2**). Based on the above theory, Jiang, Huang, Zhang, and Zhang (2018) developed the Bacillus Pasteurella dust suppressant and determined the optimal ratio of the bacterial solution concentration OD600 = 1.5, urea and calcium chloride 0.8 $mol \cdot L^{-1}$. The anti-wind index of the microbial dust suppressant is 27.4 and the dust suppression efficiency is 79.1%. Zhu et al. (2020) obtained by co-cultivating two strains of urease-producing bacteria and found that the mixed bacteria of Streptococcus pastoris and Bacillus cereus were inoculated at a volume ratio of 1:1 at a continuous interval of 14 hours. The growth of mixed bacteria and urease activity was high at this rate. Microbial solidification dust suppression is a truly green dust suppression agent that is non-toxic, harmless, and easy to decompose, has excellent biocompatibility and has significant research application value. But the current research is mostly focused on the impact of microbial solution environment there is no report on the process and microscopic mechanism of coal dust mineralization.

According to Omane, Liu, and Pourrahimian (2018), at three different ambient temperatures (35˚C, 15˚C, and 19˚C), water and a variety of chemical surfactants (salt, chloride-free agents, polymers, and molasses) were tested for dust

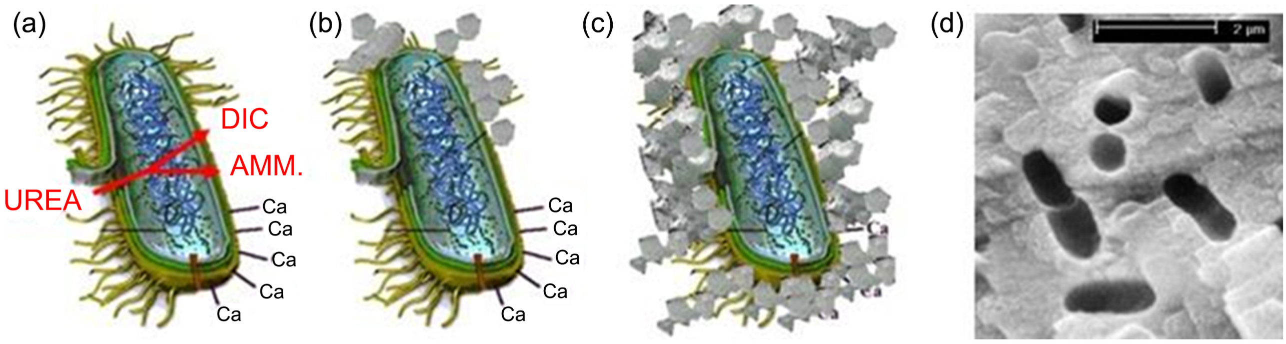
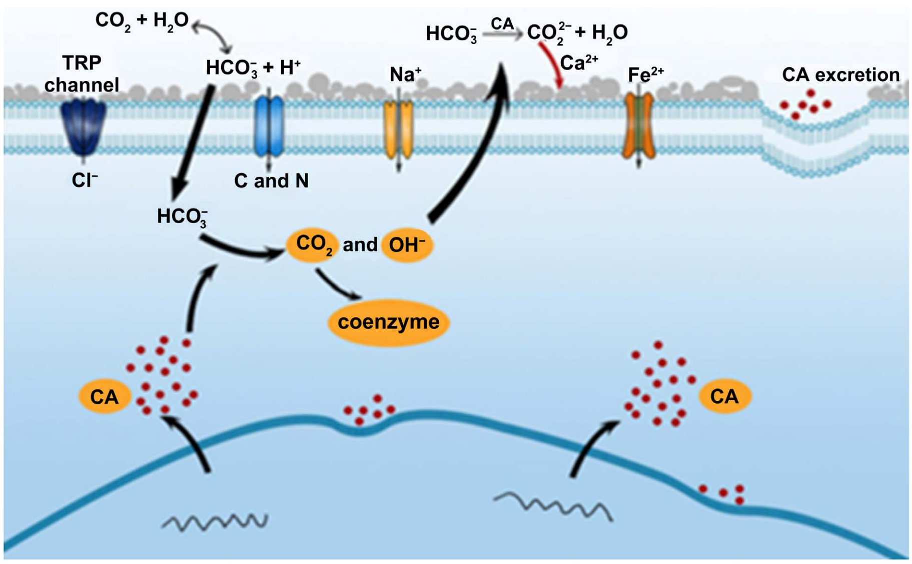
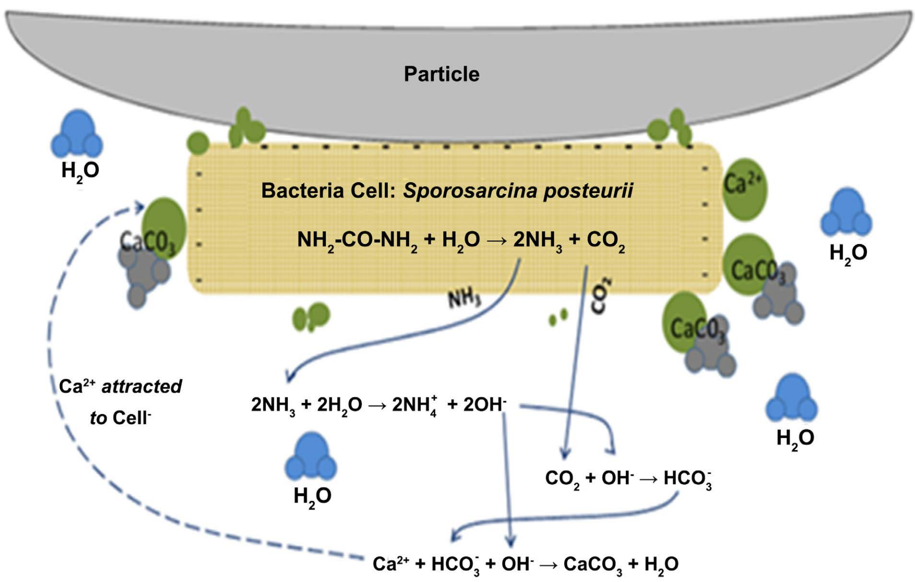


Figure 1. Schematic diagram of cementation mechanism (De Muynck, De Belie, & Verstraete, 2010).



(a)



(b)

Figure 2. (a) Carbonic anhydrase captures carbon mineralization and suppresses dust; (b) Urease hydrolyzes urea mineralization to suppress dust (Zhan & Qian, 2017).

retention efficiency. According to the findings, these chemical surfactants behaved differently when exposed to different temperatures. In terms of efficiency, he found that salt, chloride-free, polymer, and molasses solutions outperformed water.

According to the study, a foam performance test conducted by Guo, Ren, and Shi (2019) using a foaming agent in water reduces the contact angle with coal dust by 67 percent while raising the wettability rate by 30 times. The foam produced has a maximum apparent viscosity of 751 mPas when the expansion ratio is 30. By wetting and reacting to dust particles, this foam suppresses dust. A foam preparation device that automatically adds the foaming chemical by self-suction was installed to foaming equipment on a roadheader excavating a tunnel. Total and respirable dust suppression rates were 87.9 percent and 76.0 percent, respectively, 2.1 and 2.37 times greater than water spraying performances near the roadheader driver's position. In addition, when foam suppression was utilized, the driver's visibility rose from less than 0.5 m to 7.5 m, 1.8 times longer than when water spraying was used. Dust suppression might be used in power plants, quarries, and other dusty situations.

Furthermore, Zhou conducted a magnetic water dust reduction test to investigate surfactants' surface tension and contact angle under several magnetization condition parameters (Zhou, Qin, & Huang, 2021). The study found that a double diluted solution magnetized for 15 minutes at 750 Gs magnetic induction intensity had substantially lower surface tension than the same solution that had not been diluted or magnetized. This shows that magnetization mostly disrupts hydrogen link structures between water molecules, lowering solution cohesion and boosting solution wettability.

Hu et al. (2019) investigated the performance of an atomization device for coal dust control under various working situations. The experimental results showed that as the water pressure (Pw) increased, the particle sizes of the droplets reduced, the coverage radius increased, and the rate of rise slowed. Moreover, as the air pressure (Pa) increased, the radius of the covering expanded, and the particle sizes of the droplets decreased. This study looked at four different water-air pressure ranges to deal with the varying field conditions. Compared to a standard water curtain, the device's total and respirable dust suppression efficiency increased by 24.8 percent and 43 percent, respectively. In addition, the device was estimated to save roughly 25% water consumption compared to the water curtain approach. As a result, the new atomization device is anticipated to be an excellent replacement for existing water curtains in underground coal mines for dust suppression.

Wu et al. (2020) prepared a biological dust suppressant test by extracting urease from soybeans. The findings show that when the volume ratio of urease to $CaCl_2$-urea solution is 1:3 and the concentration of $CaCl_2$-urea solution is 0.6 mol/L, the precipitation ratio (PR) (83.83%) in coal dust is highest, and the mineralization product is $CaCO_3$. Furthermore, in a wind erosion-resistance test, the weight loss of coal dust is 2.56% when the angle between the airflow and the sample is 0, and the concentration of $CaCl_2$-urea is 0.6 mol/L. This implies that biological dust suppressant are non-toxic and less corrosive than chemical dust suppressant. As a result, biological dust suppressant appear to be a potential method for reducing coal dust.

3. Comparative Analysis of On-Site Application Effects

Tables 2-6 shows that foam dust suppression's comprehensive dust removal rate is about 75%, and the water consumption is 1 - 2 m^3/h. Water consumption can be reduced by 50% compared to other wet dust suppression methods. Foam dust suppression can cover dust without gaps. Source, prevent the spread of dust from the root cause; active magnetized water can effectively reduce the total dust concentration, while small-sized respirable dust is difficult to capture, so the effect of active magnetized water on the treatment of total dust is more obvious than that of breathing dust. The average dust removal efficiency is 81%; the super-generation atomization technology's operating cost is 0.016 to 0.031 dollar/t on average, and water consumption is exceedingly low. "Respirable dust" captures, the dust removal rate reaches 90%; the wind and fog double curtain is suitable for low gas tunneling face, and also has the best prevention and control effect against coal dust and rock dust, and can effectively remove the concentration of PM2.5 at the driver's place. The dust removal rate of respirable dust reaches more than 90%; the biological nano-film technology is suitable for working surfaces with large dust production, high dust concentration, and high dispersion in China. The dust removal efficiency is above 90%, and the highest can reach 99%.

Table 7 demonstrates that chemical dust suppression and foam dust suppression can quickly settle coal dust and have good dust removal efficiency, but the use of chemical reagents is corrosive and will pollute the underground environment. Although magnetized water technology can reduce the corrosion of equipment, it has extremely high requirements for water quality and is difficult to use widely. Double-screen technologies like ultrasonic atomization and wind fog have obvious effects on the treatment of respirable dust. Still, they are greatly affected by external conditions and are prone to secondary pollution. Biological nano-membrane technology has the highest dust suppression efficiency but costs a lot of money. Currently, no downhole application equipment is developed, and it is difficult to apply it to the mining face. As a new bonding type, microbial mine dust suppressant has good prospects for development and application. It can be truly green and environmentally friendly. However, the slow microbial mineralization process cannot be used for short-term dust suppression. In summary, the current mine dust prevention technology has advantages and disadvantages, and future research on the existing dust prevention technology needs further improvement and development.

4. Dust Prevention and Control Are Being Developed in the Following Directions

4.1. Prevention and Control of Respirable Dust

The prevention and control of respirable dust have become a major focus of

Table 7. Comparative analysis table of different dust removal technologies.

Dust removal Technology	Applicable place	Advantage	Disadvantage	Dust removal rate	Invest
Chemical dust suppressant	Mining face	Easy and Convenient	Corrosive, easy to cause pollution	80% - 90%	Small
Foam dust removal	Tunneling face	1) Combining the advantages of spray dust suppression and chemical dust suppression 2) Has good wettability, adhesion, and coverage	1) The foam is affected by downhole air currents 2) Chemical reagents corrode the nozzles, causing blockages	≥70	Small
Active magnetized water for dust decrease	Mining face	1) Lower the solution's surface tension 2) Suppress Ca^{2+} and Fe^{2+} plasma corrosion on downhole equipment and increase the equipment's service life	1) High requirements for water quality and suspended solids should not be greater than 150 mg/L 2) Long magnetization time	80% - 90%	Big
Wind and fog double curtain	Tunneling face	The best treatment effect on respirable dust	When the dust concentration is high, it affects the vision	≥90%	Small
Ultrasonic atomization	Mining face	1) The atomization effect is good; the particle size of the water mist is less than 10 μm 2) The water consumption is small, which is 1% of the water consumption of ordinary wet dust removal technology	1) Affected by low temperature, it is easy to freeze at the nozzle and block the nozzle 2) Affected by wind and current, water mist is formed and dispersed, which is easy to cause secondary pollution	≥80%	Small
Biomembrane	Coal preparation plant	1) Non-toxic and non-polluting to the human environment 2) Has an intelligent control system	High power and water consumption	≥90%	Big
Microbial dust suppression	Road, surface coal mine	Easily degradable, good biocompatibility	1) The process of microbial action is slow 2) Microbial activity depends on the environment	80%	Small

mine dust prevention in many countries, particularly respirable dust with a particle size of less than 5 μm. The reason why respirable dust is difficult to control is that most respirable dust is hydrophobic, which brings great difficulty to dust removal methods such as water injection and wet operation in underground coal seams. The research on dust prevention technology is far from enough, and it is essential to conduct more in-depth research on the joint dust prevention technology system of comprehensive coal mines. Table 8 summarizes the application of China's latest common dust prevention technology, combining two or more. The above dust removal technologies can achieve considerable control effects.

4.2. Hydrophobic Dust-Prevention

Presently, one of the most difficult aspects of dust reduction is preventing and

Table 8. Practical application of domestic joint dust-proof technology.

Coal mine	Place	Comprehensive dust-proof technology	Related parameters	Dust suppression effect			
				Dust concentration mg/m³		Dust removal rate	
				Total	Respirable	Total	Respirable
Zhangjiamao Coal Mine	Fully mechanized mining face	Coal seam water injection + ventilation and dust removal + return air tunnel combined water purification curtain	Water injection pressure 5 - 6 MPa, time 2 h	4.37	2.26	70.6%	69.7%
Shuangyashan mining area	Fully-mechanized mining face	High-pressure water injection + high-pressure spray	1) The water injection pressure is 18 MPa, the time is 60 h, and the drilling distance is 15 m.	98	30	94.8%	92.7%
Xinzhi Coal Mine	Fully mechanized excavation face	Wind and fog double curtain + dust suppressant spray	—	28.1	16.5	94.8%	93.9%
Donglin Coal Mine	Fully-mechanized mining face	Sectional sealing water injection + foam dust reduction + automatic spray dust reduction	1) The depth of 10 m water injection drilling hole is 1 m and 1.6 m from the top and bottom plate, respectively, and the water injection pressure is 12 MPa 2) Foam expansion ratio 70; foaming agent addition ratio 3‰	85	38.2	95.8%	94.8%

controlling hydrophobic dust. Coal dust is generally hydrophobic and difficult to moisten since the core of coal is aromatic and the surface contains many hydrophobic groups. However, Kilau and Pahlman (1987), the wetting ability of coal can be considerably improved by adding a modest number of monovalent cations and polyvalent anions to surfactants. Ni et al. (2019) studied that surfactants and inorganic salts were combined, and a novel form of NaCl-SDS compound solution was created to boost surfactant wettability. Currently, great progress has been achieved in the study of coal dust wettability. The study's findings create the conditions for coal seam water injection, spray dust removal, and other dust control technologies and stimulate the development of hydrophobic dust management technologies.

4.3. Prevention of Secondary Dust

Secondary dust refers to the fact that the static coal dust that has settled is affected by wind and diffuses into the air again. It is most common in the open-air stacking of coal and during transportation. The secondary dust is mostly particles with weak adhesion, which have the characteristics of suddenness, repetition, and disorganization. Once it occurs, it is challenging to get better control.

Table 9. Commonly used crust dust suppressant.

Classification	Element	Principle
Inorganic Dust Suppressant	$MgCl_2$ $CaCl_2$ $NaCl_2$	Hygroscopic agents can absorb the humidity in the air, maintain high humidity in the soil layer, increase surface tension, and prevent the evaporation of cohesive soil
	$NaSiO_3$	The binder increases the force of the bond between the particles and forms a covering layer on the soil particles to combine with it, making it easier to form a consolidation layer on the surface
Organic Dust Suppressant	Sodium Lignosulfonate Calcium lignosulfonate	The electrochemical method ionizes the water in the soil and Improves it through the effect of cation exchange High electrical conductivity, reducing soil deformability and permeability
	Enzyme	Biocatalysis or biotransformation uses enzymes to convert one compound into another. Reduce the affinity of clay particles to water and increase the density, bonding strength, and mechanical strength of the soil
	Polymer	Adhesive, the molecular form is a tightly combined network structure, and the polymer covers the surface of the particles to play a cohesive effect

Therefore, the secondary dust in coal mines is also a key problem that urgently needs to be solved. At present, the common treatment methods include watering and dust suppression and dust suppression with dust suppression agents. Bonded dust suppression agents can be divided into organic dust suppression and inorganic dust suppression, as shown in Table 9 for details. In recent years, composite polymer dust suppression agents have been continuously optimized. With the enhancement of the dust suppression effect, and has been widely used. In addition, emerging microbial dust suppression agents can be non-toxic and harmless based on ensuring the dust suppression effect and have gradually become the research field of dust control.

5. Conclusion

With the continuous improvement of the mining level, many innovative results have been achieved in the study on mine dust prevention and control technology. However, it is still difficult to meet the dust control standards in China. Therefore, mine dust prevention and control technology still has a lot of space for advancement. This work traces the latest research progress in dust control technology, including chemical dust suppressant, foam dust removal, ultrasonic atomization, magnetized water dust suppression, double curtains of wind and fog, biological nano-film, and emerging microbial suppressant in the field of dust. Furthermore, the benefits and disadvantages of various dust removal technologies are compared and assessed. Finally, the present three mine dust prevention and control directions are discussed, as well as the prospects for future development trends. Aiming at the above-mentioned future development direction of dust prevention and control, namely: the prevention and control of respirable dust, hydrophobic dust, and secondary dust, raises the following three perspectives:

1) The double curtain technology can achieve a good dust removal effect for the ultrasonic atomization of respiratory dust treatment. Still, dust removal treatment cannot be achieved in practical applications because of the different mining methods, technical levels, and underground conditions in China's mining areas. In order to solve this problem, we should study the mechanism of multi-source dust generation under different working conditions, construct a dynamic numerical model of different types of dust, especially the law of transport and settlement of respiratory dust, and further realize the control of dust according to the combine multiple dust prevention technologies based on numerical simulation.

2) Surfactants for the treatment of hydrophobic dust are still the focus of research. In the future, the relationship between the microphysical and chemical properties of coal dust and wettability needs to be studied further, and wetting agents should be continuously adjusted.

3) In view of the prevention and control of secondary dust in coalmines, microbial dust suppression is currently an emerging treatment method. It has achieved green environmental protection in a true sense and has good application prospects. However, the current application of this technology in coal dust prevention is less, so in the future, we will explore the micro-action between microorganisms and coal dust molecules based on microbial mineralization and cementation mechanism to achieve green prevention and control of coal dust.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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