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Invited review

Recent progress of coal seam water injection technology for dust prevention: A comprehensive review

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Abstract:
Coal seam water injection constitutes a fundamental measure for ensuring safe and efficient coal mine production, preventing pneumoconiosis hazards, and protecting the environment. However, systematic reviews integrating its dust reduction theories and technologies remain scarce. This paper reviews the foundational theories and technological advancements in coal seam water injection for dust control, revealing the regulatory mechanisms of dust reduction through coal's seepage-wetting behavior from dual perspectives of the internal structural features of coal and the evolving stress-water pressure environment. Additionally, it evaluates the technologies for modifying coal's physical properties and technologies for injected fluids modification. Finally, it identifies the challenges faced by coal seam water injection technology and proposes future research directions. Our review found that pore-fracture network connectivity governs water transport pathways, while dynamic equilibrium between interfacial tension and chemical group interactions determines wetting efficiency at the microscopic level. Macroscopically, hydro-mechanical coupling effects induce multi-stage fracture network evolution through stress redistribution, forming multi-level interconnected topological structures that significantly enhance wetting homogeneity. From a technological perspective, this study establishes a geology-adaptive technical framework based on coal seam characteristics and physicochemical parameter compatibility. The review promotes the transition of water injection technologies from experience-driven "extensive pressurization" to data-driven "precision wetting," providing a theoretical foundation for developing safe, green, intelligent, and source-controlled dust reduction technologies.

1. Introduction

Coal, as an essential component of the global energy structure, provides substantial energy support for industrial production (Lv et al., 2025). According to data from the International Energy Agency (2024), as shown in Fig. S1, global coal production reached 9,096 million tons in 2023, with China contributing approximately 51.8% of the total output. Correspondingly, global coal consumption amounted to 164.03 exajoules, of which China accounted for 56.2%, these statistics highlight coal's critical role as a stabilizer for China's energy security. However, high-intensity coal mining has significantly increased hazards including coal dust, gas-outbursts, and fires, with coal dust being particularly prominent, posing threats

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to both the safe and clean production of enterprises and the health and lives of miners (Castranova and Vallyathan, 2000; Wang et al., 2020c). Under conditions of oxygen availability, accumulated dust concentrations, and ignition sources, coal dust explosions pose severe risks due to their catastrophic destructive potential (Jiang et al., 2023). Historically, 16 of 18 major coal mining disasters with fatalities exceeding 300 were attributed to coal dust or dust-gas explosions, causing massive casualties and economic losses (Zhu et al., 2018; Li et al., 2023). Furthermore, chronic exposure to high concentrations of coal dust increases miners' risk of developing pulmonary fibrosis and scarring, significantly elevating the incidence of pneumoconiosis (Huang et al., 2019). In response, global initiatives such as the WHO/ILO Global Programme for Silicosis Elimination (1995) and China's pneumoconiosis prevention legislation (2002) have been implemented. Notably, the U.S. Department of Labor's Mine Safety and Health Administration reduced permissible dust exposure limits from 2.0 to 1.5 mg/m^3 in 2016, marking a 25% reduction. These developments underscore the urgent need for technological measures to mitigate coal dust's adverse effects, ensuring safe coal production, protecting miners' health, and preventing environmental degradation.

Dust control in coal mines is a critical issue in safe production and occupational health that urgently needs to be addressed (Yuan, 2020; Zhou et al., 2023b). Current research on dust prevention and control demonstrates multiple trends (Fig. S2), categorizing existing technologies into three main approaches. First, spray dust suppression technology utilizes atomized solutions to capture dust particles through mechanisms including inertial collision, interception, diffusion, gravity, and electrostatic forces (Wang et al., 2017a; Han et al., 2024). Second, ventilation dust control systems employ three operational modes: Pressurized systems that inject clean air to dilute dust concentrations, exhaust systems that remove dust-laden air through negative pressure, and mixed systems that combine both approaches for enhanced efficiency (Ren et al., 2014; Geng et al., 2017). Third, physicochemical dust suppression methods, such as the use of wetting agents (Xu et al., 2019), magnetized water (Wang et al., 2018b), and foam suppression (Guo et al., 2019), work by enhancing water's ability to wet dust and altering the surface properties of coal dust particles, thereby effectively reducing dust levels (Wu et al., 2020). While these methods significantly improve underground working conditions, they primarily address dust dispersion rather than preventing dust generation at the source during coal cutting and crushing operations.

Coal Seam Water Injection (CSWI) effectively reduces dust at the source and prevents coal and gas outbursts, rock bursts, and spontaneous combustion of coal seams. (Wang et al., 2024). The technology's efficacy arises from multi-mechanism synergies: Pressurized water injection into target coal seams facilitates moisture penetration through the pore-fracture network, enhancing coal's binding properties and reducing dust dispersibility. This modification of coal's mechanical properties transforms the breakage mode from brittle fracturing to plastic deformation during cutting operations, thereby minimizing secondary dust generation and achieving source control. Additionally, water transforms the coal-gas system into a three-phase (coal-gas-water) state, mitigating outburst risks (Lin et al., 2023b). Moreover, increased water content enhances coal plasticity while reducing elasticity and strength, redistributing mining-induced stresses to lower rock burst probability (Yu et al., 2013). Furthermore, elevated thermal capacity and conductivity in water-saturated coal inhibit temperature rise and spontaneous combustion (Lu et al., 2017).Therefore, these integrated mechanisms validate CSWI's significant role in hazard prevention, occupational health protection, and sustainable mining.

The theories and technologies of CSWI have evolved from empirical practices to systematic scientific explorations, achieving certain progress and achievements. However, comprehensive reviews that summarize the current research status and challenges in dust reduction via CSWI remain scarce. This review systematically examines the fundamental dust reduction mechanisms associated with CSWI, discusses dust reduction technologies based on coal physical property modification and injected fluid modification, and identifies existing challenges and future directions for CSWI development. The paper provides theoretical and technical foundations for addressing coal mine dust pollution, safeguarding miners' occupational health, and improving mining safety and operational efficiency, offering critical insights into sustainable coal resource utilization.

2. Basic theoretical research on CSWI for dust prevention

Coal constitutes a complex material comprised by organic matter, mineral components and porosity. Coal's pore-fracture networks govern dual fluid behaviors: Seepage and wetting. Stress variations from overburden pressure dynamically alter pore-fracture geometry, reshaping flow pathways and amplifying stress-sensitive seepage-wetting interactions (Ge et al., 2023; Sun et al., 2024). Therefore, understanding these structural dynamic changes and stress-response mechanisms is essential for advancing CSWI theory and optimizing dust prevention in mining at the source.

2.1 Coal internal structural features

2.1.1 Fine characterization of pore-fracture structure and seepage properties

Theoretical research on CSWI for dust prevention hinges on elucidating dynamic pore-fracture evolution impacts on seepage characteristics (Cheng et al., 2018). Hodot classified the pore structure of coal into four categories based on its mechanical properties and permeability characteristics: Micropores (< 10 nm), transition pores (10$\sim$100 nm), mesopores (100$\sim$1,000 nm), macropores ($> 1,000$ nm) (Hu et al., 2023). The current characterization techniques for pore and fracture structures mainly include: (1) Microscopic observation, (2) radiographic detection, and (3) fluid intrusion techniques (Zhou et al., 2018). As illustrates in Fig. 1, the Low-Field Nuclear Magnetic Resonance (LF-NMR) technique measures the relaxation time of ^{1}H-containing fluids in coal under an external magnetic field, generates a T_2 distribution curve, and converts it to obtain pore size information of fluid-containing

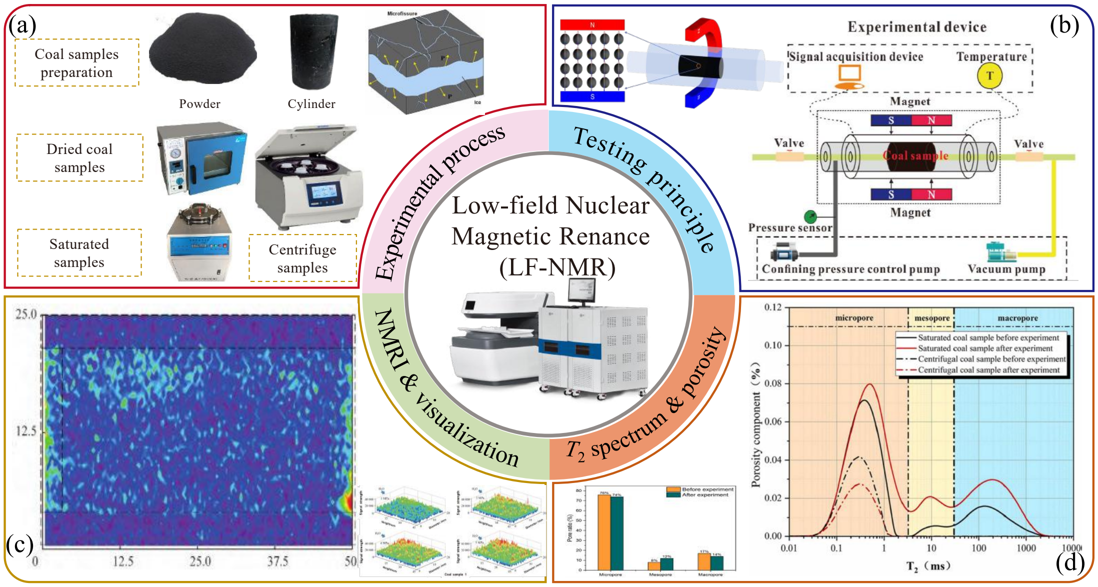


Fig. 1. Detailed characterization process of coal pore structure using LF-NMR technology: (a) Experimental procedures and equipment, (b) testing principles, (c) nuclear magnetic resonance imaging and visualization and (d) T_2 spectrum and porosity (Zhou et al., 2021; Wang et al., 2024).

pores, achieving rapid and non-destructive testing (Guo et al., 2020; Rudszuck et al., 2021).

Theoretical advances in describing water transport mechanisms combine NMR with innovative modeling approaches. Liu et al. (2020) established a model incorporating fractal theory into the Kozeny-Carman (K-C) equation, accounting for the fractal dimension of pore tortuosity.

$$K=\frac{\phi\lambda^2}{32\tau_{\text{av}}} \tag{1}$$

where K is the permeability, mD; ϕ is the porosity of the porous medium, dimensionless; λ is the pore diameter, nm; τ_{av} is the tortuosity, which characterizes the degree of bending in the direction of the streamline, dimensionless. Permeability modeling considering tortuosity fractal dimension is:

$$K=\frac{\phi}{32\tau_{\text{av}}}\times\exp\left(-\frac{2}{D_T}\ln\frac{4L_0}{S_rD_T}\right) \tag{2}$$

where D_T is the tortuosity fractal dimension that describes the degree of curvature of the streamline, dimensionless; L_0 is the length of capillary tube, cm; S_r is specific surface area the pore, cm^2. This model quantitatively depicts the migration of water and changes in permeability during water injection, highlighting the significant influence of pore structure on water migration.

LF-NMR technology effectively quantifies seepage characteristics evolution in coal. Zhou et al. (2021) identified mesopores, macropores, and micro-fractures as dominant permeable pathways (contributing to over 99% of the permeability), while micropores are hindered by the Jamin effect and capillary forces. Li et al. (2022) further confirmed that as saturation pressure increases, the pore-fracture structure in coal begins to expand and interconnect, significantly enhancing the efficiency of water transport. Yang et al. (2023) established NMR-water content correlations, distinguishing free water migration (pores/fractures) from matrix absorption under constant pressure, with three infiltration stages: Inflow, transportation, and adsorption. Mu et al. (2024) confirmed permeability-pore volume synchronicity, underscoring dynamic pore-fracture evolution as the permeability drivers. Although LF-NMR technology enables the characterization of coal pore attributes, including pore typology, size distribution, connectivity, and moisture content distribution, its ability to directly assess permeability remains indirect. Furthermore, the technique struggles to differentiate macroscopic fractures and fails to accurately characterize the complexity of pore-fracture networks, thus limiting a comprehensive understanding of their connectivity and seepage behavior.

The seepage in coal is mainly controlled by fracture structure, and studying its geometric size, shape, distribution, and connectivity is key to understanding seepage mechanisms. (Fig. 2(a)) (Lan et al., 2018). X-ray Micro Computed Tomography (Micro-CT) technology, with its high resolution and non-destructive advantages, provides technical support for the quantitative characterization of coal's pore-fracture parameters and the study of its seepage characteristics. (Fig. 2(b)) (Mostaghimi et al., 2017; Wang et al., 2019b, 2025; Zhang et al., 2024c). Wang et al. (2020b) and Liu et al. (2021a) used CT scanning to show that pore connectivity, which positively correlates with permeability, is crucial for seepage. Connected fractures mainly form the main seepage channels, reducing energy loss and spreading towards smaller pores, as shown in Fig. 2(c). In contrast, due to their lack of connectivity, isolated fractures and dead-end pores fail to significantly contribute to the overall water migration, exhibiting a dynamic behavior characterized by "initial increase, followed by decrease, and stabilization" in their seepage velocity (Wang et al., 2020a).

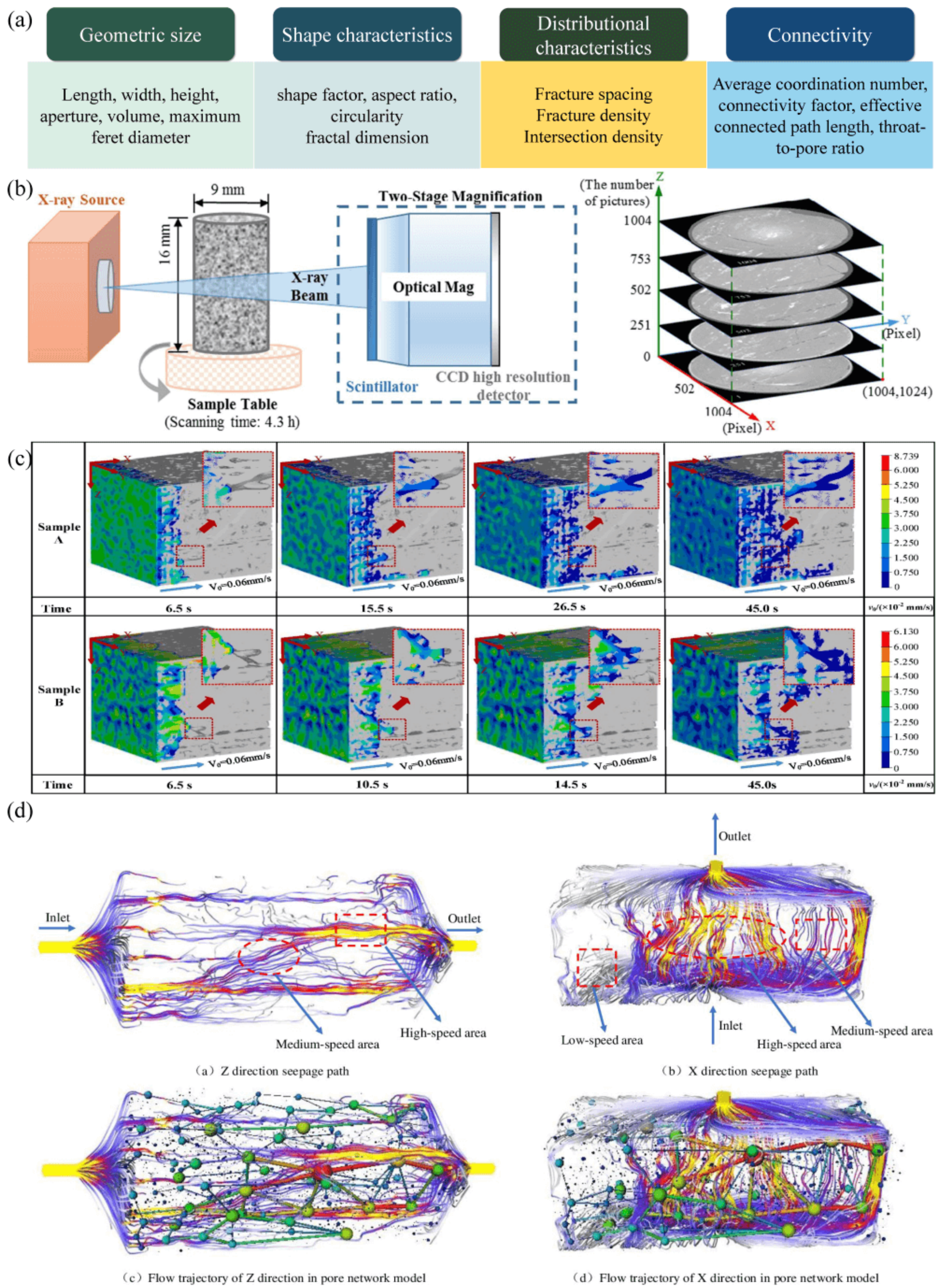


Fig. 2. Application of X-ray Micro-CT technology in analyzing coal fracture connectivity: (a) Basic fracture parameters, (b) Micro-CT scanning experiment and three-dimensional reconstruction process (Wang et al., 2019b), (c) seepage process of dead-end pores over time (Wang et al., 2020a) and (d) seepage trajectory and yellow high-speed flow region (Jing et al., 2021).

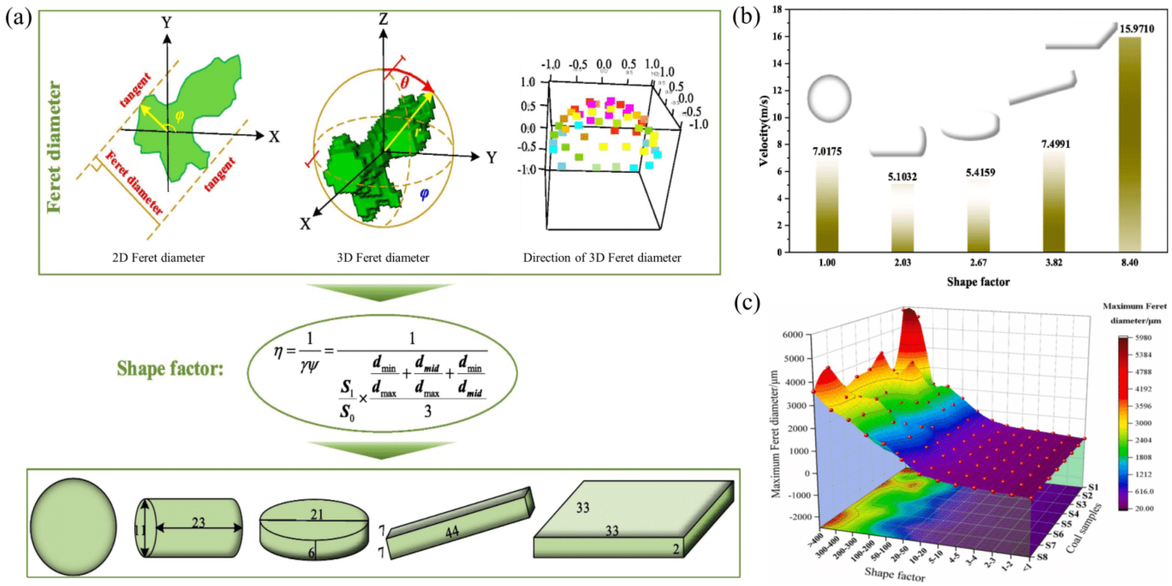


Fig. 3. The impact of fracture morphology on seepage velocity: (a) Calculation of shape factor and different fracture with shape factor (Chen et al., 2023), (b) average seepage velocities in fractures of different shapes and (c) relationship between shape factor and maximum Feret diameter (Wang et al., 2022a).

These studies demonstrate that enhanced permeability arises when isolated pores interconnect under uniform pressure, forming new pathways. As shown in Fig. 2(d), Jing et al. (2021) further revealed the zonal characteristics of seepage velocity, noting that high-speed seepage regions are mainly concentrated in the well-connected throat channels. Moreover, as the coordination number increases, fracture connectivity and overall seepage capacity progressively improve. These studies comprehensively demonstrate the decisive influence of fracture connectivity on the seepage properties of coal.

The diverse shapes of coal fractures (e.g., spherical, tubular, slot, slit, and flat) result in different contributions to seepage (Wang et al., 2020d), the shape factor quantifies fracture geometry using the Feret diameter-the distance between parallel tangents along fracture orientation at a given angle (Fig. 3(a)):

$$\eta = \frac{1}{\gamma\varphi} \tag{3}$$

$$\gamma\varphi = \frac{S_1 \times \left(\dfrac{d_{\min}}{d_{\max}} + \dfrac{d_{mid}}{d_{\max}} + \dfrac{d_{\min}}{d_{mid}}\right)}{3S_0} \tag{4}$$

where η is the shape factor of the fracture, dimensionless; γ is the abnormity index, dimensionless; φ is the degree of true sphericity, dimensionless; S_0 is the surface area of the fracture, μm^2; S_1 is the surface area of the spherical fracture with the same volume, μm^2; $d_{\max}$ and $d_{\min}$ are the maximum and minimum Feret diameters, μm; d_{mid} is the intermediate Feret diameter lying in a plane orthogonal to the maximum Feret diameter, μm.

Wang et al. (2022a) and Chen et al. (2023) revealed that fractures with shape factors exceeding 2 (e.g., slit and flat fractures) serve as dominant seepage pathways. Larger shape factors widen flow channels, linearly enhancing velocity, with flat fractures exhibiting an average flow velocity of 15.97 m/s (Fig. 3(b)). Furthermore, these high-shape-factor fractures amplify fluid transport efficiency in interconnected fracture networks through velocity superposition effects. In contrast, spherical and tubular fractures exhibit lower water infiltration speeds due to their simpler shapes. As the shape factor increases, both the maximum Feret diameter and coordination number of fractures rapidly grow, indicating improved connectivity (Fig. 3(c)). These findings demonstrate that the fracture shape factor not only quantifies the complexity of fracture geometry but also significantly influences pore structure parameters, thereby enhancing the connectivity of the fracture network and increasing coal permeability.

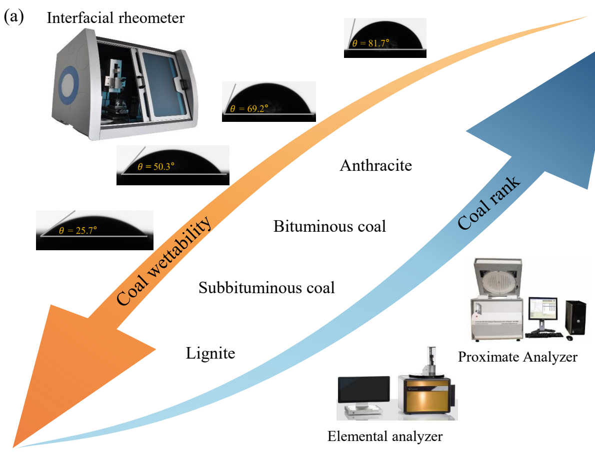
2.1.2 Chemical structural characteristics of coal and wetting mechanism

In the process of CSWI, water is not completely absorbed by the coal seam after the pressure-driven seepage stage, and then it is transferred to the natural seepage stage, also called the slow capillary wetting process (Jiang et al., 2024). The capillary force drives water into coal micropores via capillary action, achieving uniform coal wetting. Capillary pressure equation governing water migration in micropores during wetting stage:

$$P_c = \frac{2\gamma\cos\theta}{r_p} \tag{5}$$

where P_c represents the capillary pressure, MPa; γ denotes the interfacial tension, mN/m; θ is the contact angle, °; r_p signifies the effective radius of micropores, μm. This Young-Laplace-based formulation quantifies the spontaneous water wetting driven by capillary forces in low-permeability media, where the pressure differential across curved liquid-gas interfaces dominates fluid redistribution at the pore scale (Ma

(a)



(b) Proximate analysis and ultimate analysis of four coal rank from related literature

Coal rank	Proximate analysis (w/%)			
	M_{ad}	A_{ad}	V_{daf}	FC_{ad}
Lignite	17.16	13.19	57.39	30.64
Subbituminous coal	5.88	21.18	42.81	57.9
Bituminous coal	1.55	5.69	27.53	62.29
Anthracite	1.70	4.03	8.50	86.32

	Ultimate analysis (w_{daf}/%)				
	C	O	H	N	S
Lignite	72.88	15.02	8.66	2.36	1.05
Subbituminous coal	74.91	17.57	5.65	1.50	0.37
Bituminous coal	87.34	4.80	5.71	1.56	0.59
Anthracite	91.79	2.31	3.81	1.43	0.66

(c)

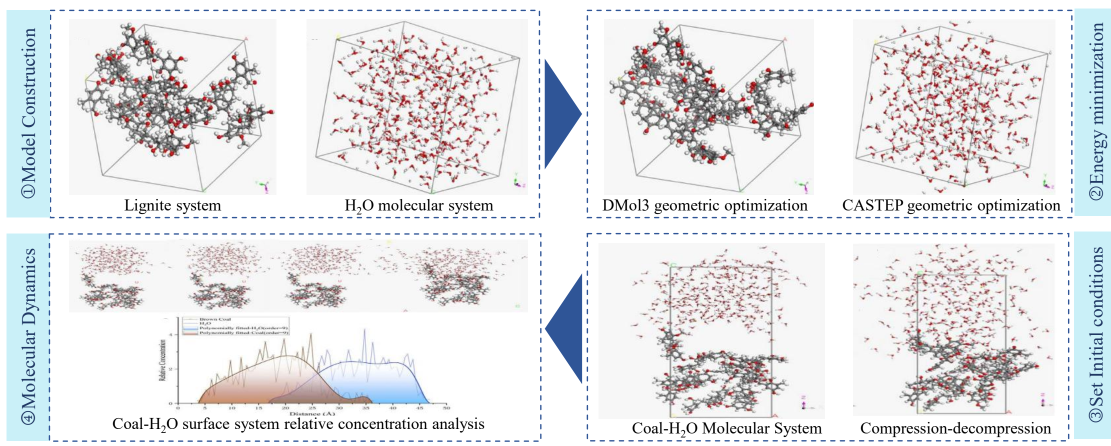


Fig. 4. Wettability and molecular dynamics characterization of coal dust surfaces: (a) Classification of coal ranks and comparison of wettability, (b) proximate and ultimate analysis of four coal ranks (Zhao et al., 2011; Cheng et al., 2016; Wang et al., 2021b) and (c) interaction between coal surface and water molecules (Zhang et al., 2021a).

et al., 2022).

Coal rank (degree of metamorphism) critically governs coal-water interactions (O'Keefe et al., 2013). Coal is classified by ASTM D388 as lignite, subbituminous, bituminous, and anthracite (Fig. 4(a)). Higher-rank coals exhibit decreased volatile matter (V_{daf}) and increased fixed carbon (FC_{ad}) and carbon content, directly modulating wettability (Fig. 4(b)) (Yi et al., 2017). This stems from metamorphism-driven chemical restructuring: Oxygen-containing groups ($-$OH and $-$COOH) that enhance hydrophilicity via hydrogen bonding degrade with rank elevation, shifting dominance to hydrophobic aliphatic/aromatic hydrocarbons (Zhao et al., 2011; Savitskyi, 2015; Semenova and Patrakov, 2017). Contact angle measurements validate this trend-low-rank coals (e.g., lignite, $\theta < 60°$) show strong water affinity due to abundant hydrophilic groups, contrasting with high-rank coals (e.g., anthracite, $\theta > 100°$) (Mahoney et al., 2015; Li and Li, 2016). Quantitatively, hydroxyl ($-$OH) content decreases from 38.4% in lignite to 13.0% in anthracite, and the increase in contact angles (47.05° to 72.88°) correlates with this decline, confirming the coal rank-functional group-wettability linkage (Cheng et al., 2016; Wang et al., 2017b).

Molecular dynamics simulations reveal coal-water interactions through interfacial adsorption and diffusion mechanisms (Badar et al., 2022). Zhang et al. (2021a) found that, through concentration profile analysis of lignite-water systems (Fig. 4(c)), water molecules exhibited a Z-axis distribution spanning 17 to 48 Å (1.7-4.8 nm) in the small-scale system, with their overlap regions with coal molecules occupying 56.25% of the coal's Z-axis length, driven by hydrogen bonds and van der Waals forces. Crucially, the interplay between chemical adsorption and physical pore structure regulates overall wettability. Zhou et al. (2024) demonstrated that coal wetting increases total pore volume (2%) and average pore diameter (26.71%), with water diffusion stabilizing at 0.41 cm^2/s. Initial wetting stages showed a 15% hydrogen bond increase and maximum pore expansion (23.42 to 32.60 Å), demonstrating a physicochemical synergy: Pore connectivity enhances water transport (van der Waals-driven) , while oxygen-containing groups (e.g., carboxyl) strengthen interfacial adhesion via hydrogen bonds. These findings resolve coal wetting mechanisms and lay the foundation for optimizing modification techniques (detailed in Section 3.2).

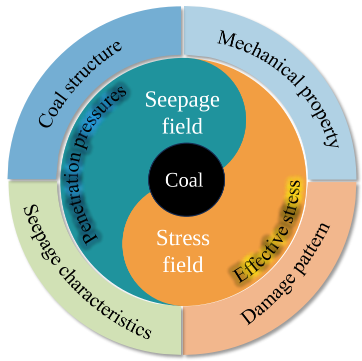


Fig. 5. Hydro-mechanical coupling effect of coal.

2.2 Water injection pressure and changes in the stress conditions

2.2.1 Influence mechanism of pore water pressure on the permeability characteristics of coal

Pore water pressure critically modulates coal permeability through pore geometry adjustments (Horn et al., 2023). As shown in Fig. S3(a), low-pressure injection preferentially enlarges macropores ($10^2 \sim 10^5$ nm) due to reduced flow resistance, while minimally affecting smaller pores ($2\sim 10^2$ nm) (Wang et al., 2018c). Elevated pressure enhances pore connectivity and porosity, Zhou et al. (2020) further elucidated that the distribution of pressurized water is dynamically optimized through pore structure reorganization: On the one hand, the enhanced pore connectivity reduces flow resistance in micropores; on the other hand, the fluid mobility in macropores is significantly improved. This dual mechanism synergistically enhances the overall seepage efficiency of the coal seam.

Water injection pressure can expand the primary fractures and regulate the seepage characteristics of coal seams. Based on Micro-CT scanning and numerical simulations (Fig. S3(b)), Mao et al. (2022) elucidated increasing water pressure gradients drive heterogeneous propagation of coal fractures. This induces geometric alterations in primary fractures and secondary fractures, promoting their progressive interconnection and topological reorganization. Enhanced connectivity increases flow pathway complexity, with primary fractures showing minimal velocity attenuation, while secondary fractures exhibit flow rates dependent on developmental maturity. Under constant water injection conditions, pore water pressure exerts dual effects on the transformation of the seepage field. As shown in Fig. S3(c), Yan et al. (2020) demonstrated that this transformation simultaneously modifies the pore-fracture network and drives wetting radius evolution via water redistribution, governed by three-stage wetting dynamic: (1) Rapid initial imbibition establishing preferential flow channels, (2) transitional phase with flow path competition leading to decelerated expansion, and (3) eventual stabilization through capillary action and pressure equilibrium. These dual effects underscore pressurized water's control over coal permeability enhancement and internal wetting optimization through coupled structural-fluid interactions.

2.2.2 Hydro-mechanical coupling and seepage-wetting interaction

The hydro-mechanical coupling effect—the interaction between coal's seepage and stress fields—induces stress redistribution near injection boreholes, driving pore-fracture damage that enhances permeability and modifies seepage-wetting dynamics through hydraulic-driven structural reorganization (Fig. 5) (Li et al., 2020a).

As illustrated in Fig. 6(a), Liu et al. (2018) established a fractal permeability model, revealing that permeability correlates with confining and pore water pressures: Increased pore water pressure enhances permeability, while higher confining pressure reduces it by altering effective stress and compressing coal pores, particularly those exceed 0.27 μm. High-pressure water injection's hydro-mechanical coupling minimally impacts the coal meso-structure due to capillary forces (Yang et al., 2020a, 2020b; Liu et al., 2022b). Furthermore, the coupled cyclic loading/unloading of confining pressure and water pressure can replicate the complex stress conditions experienced by coal seams during mining processes. Yu et al. (2024b) demonstrated that cyclic loading/unloading of confining pressure induces progressive pore enlargement across distinct phases, with its damaging effects on coal pore structure being significantly greater than those caused by water pressure variations (Figs. 6(b) and 6(c)). This confirms that confining pressure is the dominant factor in coal seam permeability evolution, suppressing water pressure effects under high geo-stress. In low-permeability coal seams, increased water injection pressure leverages hydraulic-confining pressure interactions to enhance pore-fracture network propagation, developing seepage pathways and optimizing CSWI efficiency through improved seepage-wetting dynamics.

In unmined coal seams, water injection disrupts original stress equilibrium, triggering stress-seepage redistribution. Cao et al. (2017) observed in deep-hole injection zones (Fig. 7(a)), that coal within unloading-damaged areas exhibits progressive declines in seepage boundary expansion and injection flow rates over time, with permeability and wetting degree diminishing along drilling depths due to hydro-mechanical coupling. As shown in Fig. 7(b), Liu et al. (2022a) further delineated stress-seepage evolution near boreholes into four phases: Unfilled, injection-cracking, fracture expansion, and injection termination. Yu et al. (2021) quantified micro-seepage dynamics via Fluent simulations, categorizing CSWI into three stages: Elastic deformation (minimal pore changes, reduced seepage parameters), plastic deformation (fracture propagation, permeability enhancement) (Fig. 7(c)), and post-peak deformation (macroscopic fracturing, surged seepage). These findings elucidate hydro-mechanical coupling effects on coal seepage and wetting properties.

3. CSWI dust prevention technology

To maximize water injection dust prevention effectiveness, researchers focus on two key areas (Xie et al., 2022): Coal property modification technology, enhancing water permeability by altering coal's physical characteristics, and injected fluid modification technology, improving coal dust wetting

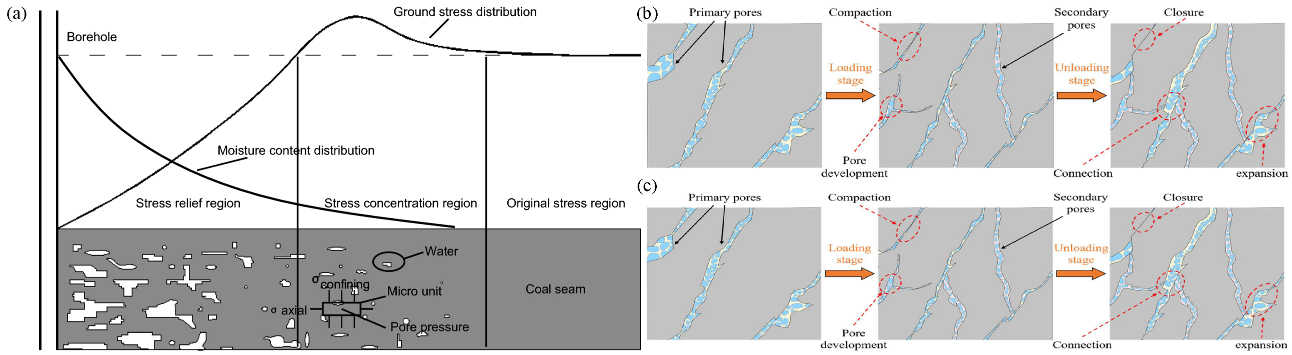


Fig. 6. Hydro-mechanical coupling effects and their impact on coal structure and seepage characteristics: (a) Seepage characteristics of coal around water injection boreholes (Liu et al., 2018), (b) the mechanism of confining pressure cycling on coal pore structure under constant water pressure and (c) the mechanism of water pressure cycling on coal pore structure under constant confining pressure (Yu et al., 2024b).

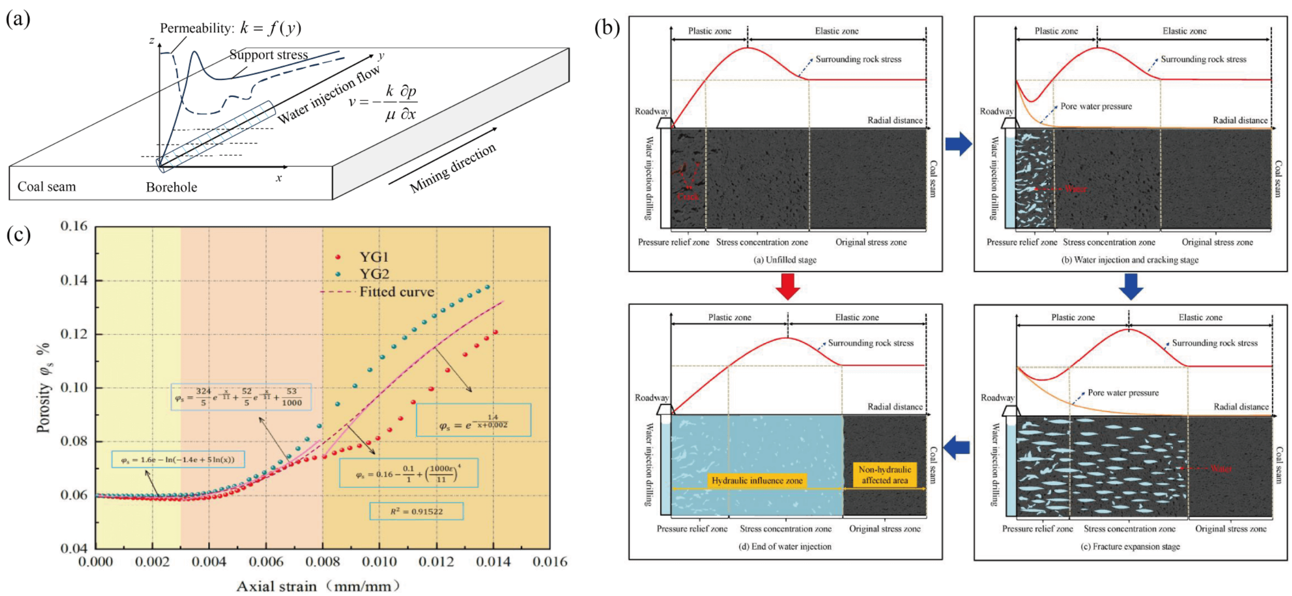


Fig. 7. Comprehensive analysis of stress, seepage, and pore structure changes during CSWI process: (a) Stress and permeability distribution and water flow state of deep-water injection (Cao et al., 2017), (b) the dynamic evolution law of the stress-seepage field during the whole water injection process (Liu et al., 2022a) and (c) porosity change curve of coal sample during the stress-strain process (Yu et al., 2021).

through chemical adjustments. These advancements optimize dust control efficiency and support safe, efficient coal mining.

3.1 Coal physical property modification technology

3.1.1 Conventional CSWI methods

Currently, conventional water injection methods are classified based on water injection pressure, borehole placement, and water supply dynamics (Wang et al., 2015), as shown in Fig. 8(a). Water injection pressures are categorized into low-pressure (< 3 MPa), medium-pressure (3∼10 MPa), and high-pressure (> 10 MPa). Borehole placements are divided into shallow, deep, and long borehole injection, and based on water supply dynamics, methods are classified into hydrostatic and dynamic water injection (Li et al., 2021a; Wang and Wang, 2021).

Shallow borehole water injection is applicable to thin coal seams with a thickness of less than 1.3 m, which are characterized by complex geological structures and unstable occurrence (Zhou et al., 2019). As depicted in Fig. 8(b), boreholes are arranged on the mining face, matching the water injection length with the progress of the coal mining cycle, requiring relatively low water pressure (< 3 MPa). As shown in Fig. 8(c), deep-hole water injection is designed for coal seams subjected to high in-situ stress, where the coal has underdeveloped fractures and poor permeability. Higher water pressure (> 3 MPa) is required to overcome the resistance posed by the in-situ stress, thereby ensuring effective water penetration into the coal seam. Long borehole water injection

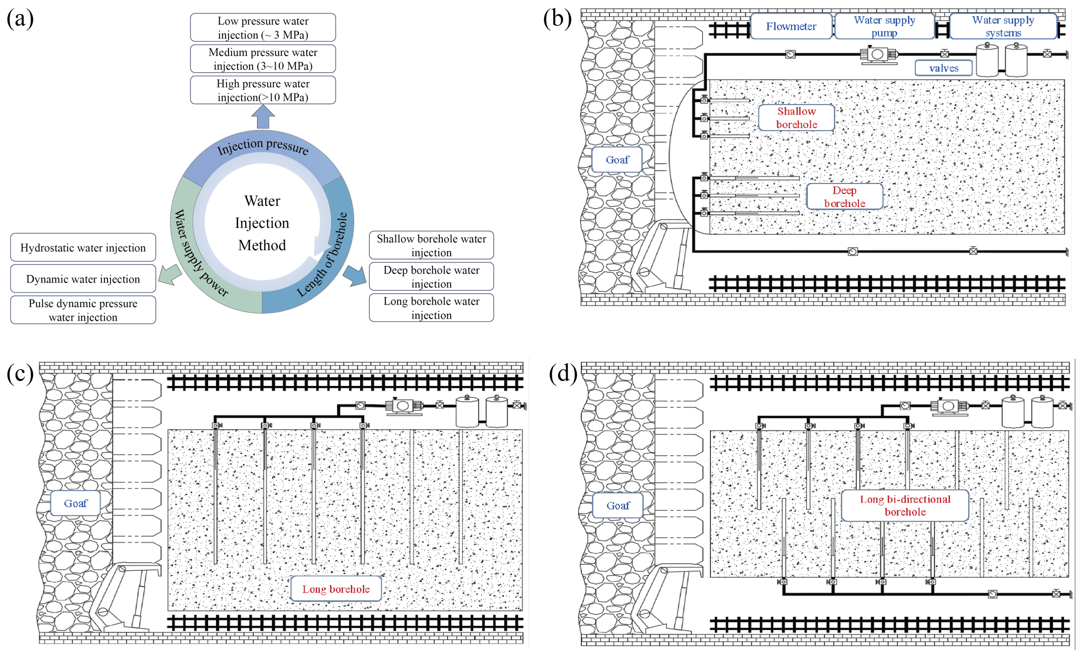


Fig. 8. CSWI systems: (a) Conventional water injection methods and classifications, (b) shallow and deep borehole water injection, (c) long borehole water injection and (d) long bi-directional borehole water injection.

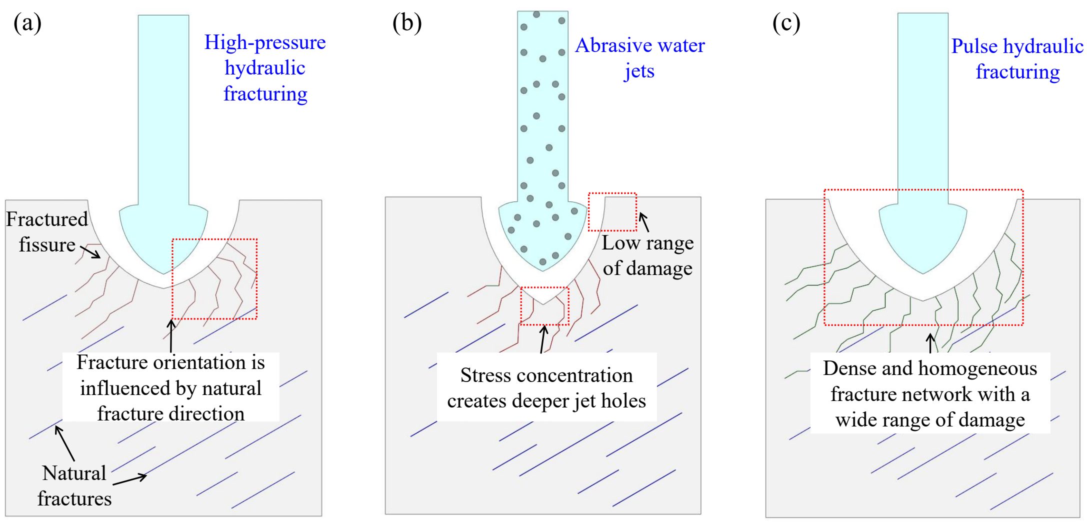


Fig. 9. Hydraulic fracturing technology to improve permeability of coal seams: (a) High-pressure hydraulic fracturing, (b) abrasive water jets technology and (c) pulse hydraulic fracturing technology.

is utilized in thick coal seams with a thickness of over 3.5 m, where the roof and floor rocks are relatively stable and have well-developed fractures. It is primarily located in the return airways of the advanced working face, with boreholes placed in fracture development zones, as illustrated in Fig. 8(d), using upward, downward, or bi-directional boreholes to utilize gravity and capillary action fully (Hu et al., 2016). Fan-shaped borehole arrangements are employed for thick coal seams with poor top and bottom permeability to achieve thorough wetting. Water supply dynamics are divided into hydrostatic (<3 MPa), where water is slowly permeated using the static water pressure from the surface to underground, suitable for coal seams with strong water permeability but limited by small pressure flow and long periods, potentially affecting regular production (Nguyen et al., 2019). Dynamic water injection (>10 MPa) employs high-pressure pumps suitable for coal seams with poor water permeability. However, excessive pressure may lead to water leakage from adjacent boreholes or galleries, thereby reducing the effectiveness of the water injection (Chen, 2019). Zhou et al. (2017) demonstrated that combined high/low-pressure water injection reduces total and respirable dust by 52.96% and 53.84%, respectively. Thus, selecting appropriate technology requires consideration of coal seam geology, equipment capabilities, and operator skills to

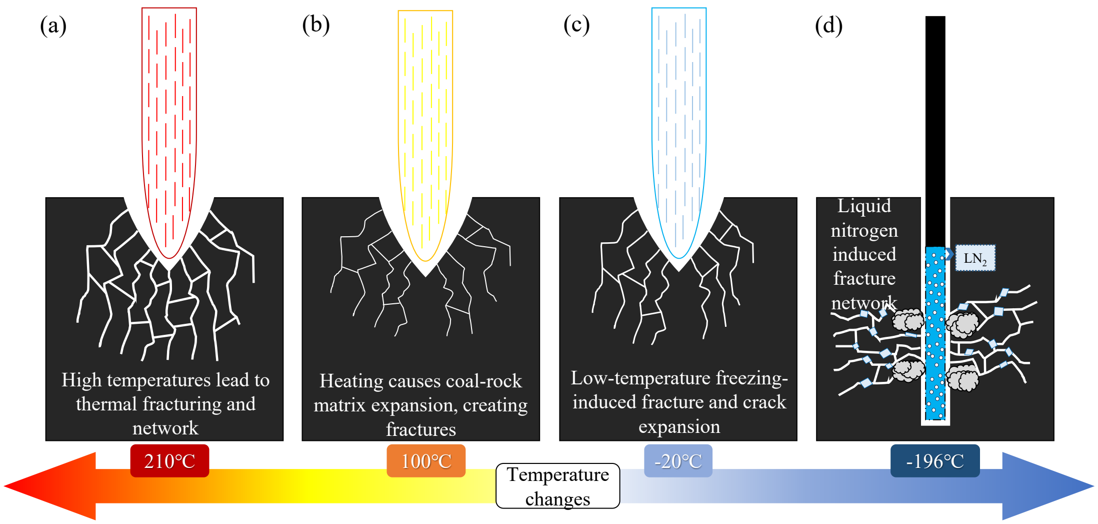


Fig. 10. The formation process of fracture networks in coal under different temperature changes: (a) High-temperature induced coal rock fracture networks, (b) expansion of the coal matrix due to heating, (c) fracture expansion in coal induced by cryogenic freezing and (d) L-N_2 cryogenic-phase transition fracturing of coal.

ensure safety and production efficiency.

3.1.2 High-pressure fluid fracturing technology

High-pressure fluid fracturing technology plays a crucial role as a key method for enhancing the permeability of coal seam (Zhang et al., 2024a). As illustrated in Fig. 9(a), hydraulic fracturing employs continuous high-pressure water to redistribute stress, fracturing coal rocks and forming complex networks, suitable for thick seams with low natural fracture density and high horizontal stress differences (Yu et al., 2022). Fracture propagation aligns with maximum principal stress direction, inversely correlating with horizontal stress difference: Lower differences promote uniform micro-fracture connectivity (Fang et al., 2023). Natural fractures critically influence hydraulic fracture propagation: Bedding-plane fractures cluster along a single orientation, while joint fractures disperse multi-directionally (Jia et al., 2023). These factors collectively determine the efficacy of hydraulic fracturing and improvements in coal seam permeability. Han (2019) applied hydraulic fracturing in field construction and found that the influence range of high-pressure fracturing was 15-20 m, the coal seam moisture content increased by 2.1%-5.0%, and the total dust concentration decreased by approximately 25%. Traditional mechanical cutting results in large chunks of coal collapsing with instantaneous impact forces, leading to the release of a significant amount of primary dust. Abrasive water jets technology, as depicted in Fig. 9(b), utilizes a solid-liquid slurry (e.g., water mixed with abrasive particles) to fracture brittle coal via axial compression and shear failure, suppressing dust through water encapsulation. Suitable for thin-to-medium seams (0.5-3 m, medium-low hardness coal seam), its limitations include localized damage and slow coal-breaking rates (Lu et al., 2013; Wang et al., 2018a). Pulsating hydraulic fracturing generates fatigue-driven fracture networks through periodic pressure pulses, inducing alternating “compression-expansion” at fracture tips (Fig. 9(c)) (Li et al., 2014; Zhai et al., 2015) , while high-frequency pulsation scours mineral crystals to enhance permeability (Chen et al., 2020). Its efficacy relies on frequency modulation: Low-frequency pulses reduce initial fracturing pressure by coal softening, whereas high-frequency pulses elevate pore pressure for rapid fracture initiation (Li et al., 2013; Yu et al., 2024a). Cheng et al. (2012) developed a pulsating water injection technology with a permeation agent, optimizing the process parameters to increase the single injection volume by six times compared to traditional methods, achieving an average dust reduction rate of 32.9% for total dust and 33.8% for respirable dust, thereby significantly improving the effectiveness of CSWI in wetting and dust prevention. However, pulsating hydraulic fracturing faces challenges in pulse frequency optimization, improper frequency settings can lead to suboptimal fracturing and hinder the formation of an ideal fracture network, posing adaptability issues in regions with complex coal seam fracture distributions.

3.1.3 High-temperature shock fracturing and cold-shock fracturing technology

Numerous studies have demonstrated that the influence of temperature on the modification of coal seam permeability is significant (Lin et al., 2023a). Techniques such as high-temperature shock fracturing and cold-shock fracturing take advantage of temperature changes to induce thermal stress differences within coal, thereby giving rise to pores and micro-fractures that can enhance permeability (Cao et al., 2024). As illustrated in Figs. 10(a) and 10(b), the expansion of the coal rock matrix and the generation of fractures are triggered by heating. Under high-temperature conditions, thermo-hydro-mechanical coupling drives a transition in coal fragmentation from “hydro-wedge” to “hydro-thermal fracture” modes, intensifying dynamic damage and directly inducing thermal failure fractures within coal. Furthermore, cyclic thermal shock can effectively connect relatively independent fracture struc-

Table 1. Types of surfactants and their representative substances.

Category	Surfactant	Molecular formula	Charge characterization of head functional groups	Mechanism of action
Cationic	DTAB	$C_{15}H_{34}BrN$	Positively charged	Electrostatic adsorption to neutralize negative charges
Anionic	SDS	$C_{12}H_{25}NaO_4S$	Negatively charged	Hydrophobic chain adsorption
Nonionic	NPEO-12	$C_{15}H_{24}O_{13}(C_2H_4O)_{12}$	No net charge	Hydrogen bonding and van der Waals force adsorption
Amphoteric	CAB-35	$C_{19}H_{38}N_2O_3$	Coexistence of positive and negative charges	Adaptive charge balance

tures and generate micro-fractures, and then the pore groups rupture and expand, forming an intertwined fracture network (Yang et al., 2018). Cold-shock fracturing technology uses extremely cold liquids like liquid nitrogen (L-N_2) to freeze coal, altering its pore structure and thus increasing permeation space (Wang et al., 2019a). As shown in Figs. 10(c) and 10(d), the extreme cold of L-N_2 (-196 °C) and the expansion from phase change under atmospheric pressure (expansion by 696 times) generate thermal stresses and stress concentrations promoting coal rock matrix fracture extension and expansion. Similar to thermal shock cycles, multiple L-N_2 freezing cycles significantly increase the width, density, and connectivity of coal fractures with each iteration, and the expansive force from the vaporization phase change of L-N_2 further promotes secondary fracture propagation, achieving secondary fracturing through freezing and phase change (Su et al., 2020). The core value of the technology lies in providing theoretical feasibility for the permeability enhancement modification of low-permeability coal seams. However, non-uniform temperature control/distribution induces localized fracturing and non-uniform fracture propagation with unpredictable patterns. Constrained by coal seam geological complexity, cost, and safety constraints, these techniques are confined to laboratory research, with no reported field applications of CSWI.

3.2 Injection fluid modification technology

3.2.1 Surfactant

Surfactants are compounds capable of reducing the surface tension of water and enhancing its wettability on coal (Zhang et al., 2023). As depicted in Table 1, they can be classified into four types, namely cationic, anionic, nonionic, and amphoteric. Different types of surfactants play distinct roles in different stages of CSWI. Cationic surfactants (such as dodecyl trimethyl ammonium bromide, DTAB) exhibit relatively strong adsorption effects during the wetting and adsorption stages and have better water solubility than anionic surfactants, making them particularly suitable for negatively charged coal surfaces (Wang et al., 2021a, 2022b; Wei et al., 2022). Anionic surfactants, like Sodium Diethylhexyl Sulfosuccinate (SDS), gradually enhance during the permeation process (Wang et al., 2022d). Nonionic surfactants improve wettability through polar interactions, Lyu et al. (2018) found that the ethoxy groups in nonionic surfactants (such as nonylphenol ethoxylate with 12 ethylene oxide groups, NPEO-12) interact polarly with the hydrophilic sites on coal, controlling coal-water adsorption. This interaction strengthens the bond between coal surfaces and water, enhancing wettability. Amphoteric surfactants (such as Cocoamidopropyl Betaine, CAB-35) possess multi-stage wetting mechanisms and are suitable for various coal types (Wang et al., 2019c; Yang et al., 2022). Yuan et al. (2020), Niu et al. (2021) and Liu et al. (2021b, 2021c) demonstrated that hydrogen bonding drives coal molecule adsorption and wetting. Surfactants enhance coal dust hydrophilicity by forming surface adsorption layers, promoting water molecule interactions and improving wetting properties. These studies reveal that surfactant mechanisms in CSWI are significantly influenced by molecular structure and hydrophilic group types. Wang et al. (2023) experimentally determined the optimal wetting concentration of octylphenol polyoxyethylene ether (TX-100) and SDS, and field tests at different water injection locations in Taoyuan coal mine demonstrated that a 1 wt.% composite solution of TX-100 and DSS improved the dust reduction efficiency for total dust and respirable dust by 39.14% and 23.71% compared to ordinary water, confirming that the use of surfactants significantly enhances the wetting effect of coal seams.

3.2.2 Synthetic wetting agents

Recent advances in synthetic wetting agents, achieved through chemical grafting and molecular modification, enable materials with superior permeability and wettability. These materials effectively reduce coal surface tension while demonstrating robust thermal/shear stability and moisture absorption capabilities (Sun et al., 2021). As shown in Fig. S4(a), Ma et al. (2021) synthesized a novel water injection additive with a star-shaped structure through modified β-cyclodextrin, effectively binding with the hydrophilic sites on coal surfaces. Zhou et al. (2023a) utilized modified carboxymethyl cellulose and linear micelles, as illustrated in Fig. S4(b), to create a multilayer composite network structure of humidifiers through electrostatic interactions. The modification of carboxymethyl cellulose enhances its hydrophilicity and stability. At the same time, the multilayer network structure formed by linear micelles through electrostatic interactions further strengthens the adsorption capacity of the wetting agent on coal surfaces.

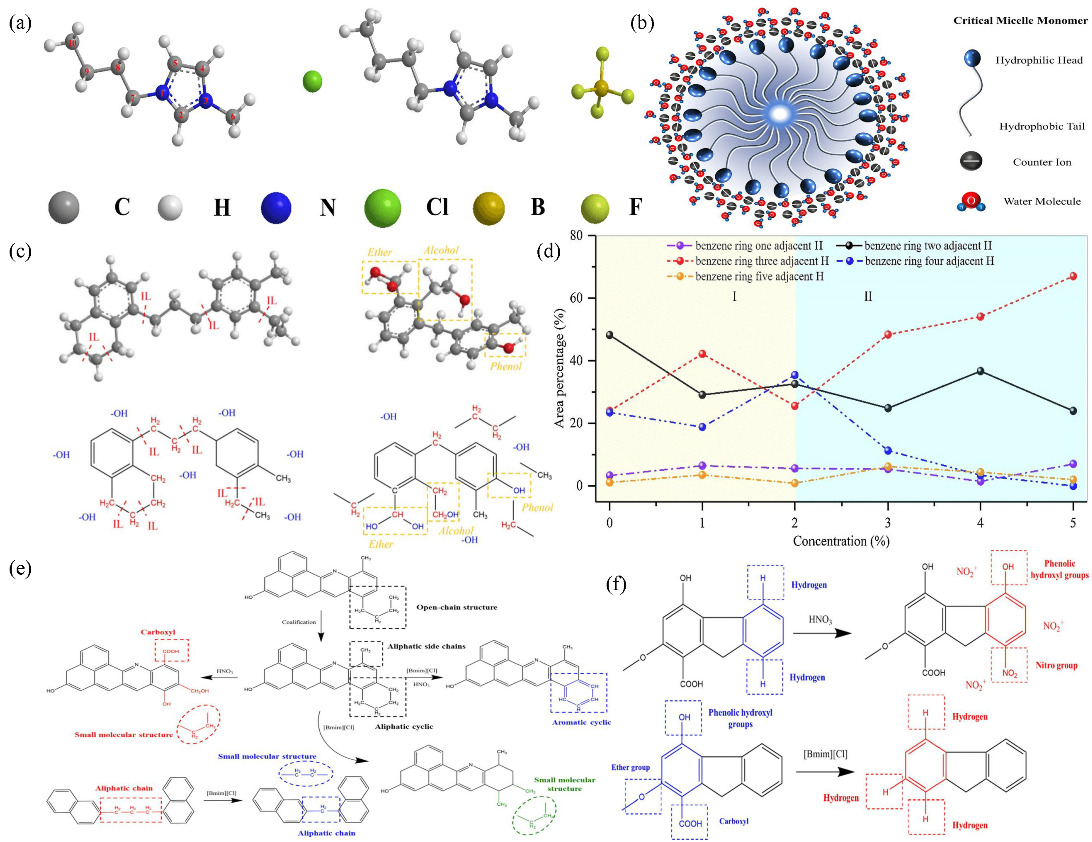


Fig. 11. Interactions between ionic liquids and their aqueous solutions with coal: (a) 1-butyl-3-methylimidazolium chloride ([Bmim][Cl]) and 1-butyl-3-methylimidazolium tetrafluoroborate ([Bmim][BF_4]), (b) formation of critical micelle concentration in ionic liquid solutions (Wang et al., 2022f), (c) ionic liquids disrupting the alkyl side chains of coal, (d) changes in the aromatic structures of coal with varying concentrations of ionic liquids (Li et al., 2020b), (e) changes in the aliphatic structures of coal due to the synergistic effects of [Bmim][Cl] and HNO_3 and (f) changes in the aromatic structures of coal due to the synergistic effects of [Bmim][Cl] and HNO_3 (Li et al., 2021b).

Zhang et al. (2022a) synthesized a novel highly permeable and moisture-retaining additive ((Sodium Alginate-Acrylamide-Caprolactam)/Dodecyldimethyl Betaine Solution, SACB) by modifying sodium alginate through free radical polymerization and graft copolymerization theory. As simulated in Fig. S4(c), the hydrophilic groups in its molecular structure enhance coal wettability via hydrogen bonding, achieving a diffusion coefficient of 1.37×10^{-4} cm^2/s. In the field application of CSWI at Qiwu coal mine, SACB demonstrated a significant improvement in dust reduction efficiency, increasing the average total dust reduction rate from 56.30% to approximately 80.95% and the average respirable dust reduction rate from 54.8% to 77.69%, compared to traditional surfactants. New wetting agents enhance coal surface interactions through molecular incorporation of hydrophilic groups, thereby improving permeability and moisture diffusion capabilities. These agents demonstrate robust stability under high-temperature/high-shear conditions, enabling effective performance in complex CSWI scenarios.

3.2.3 Ionic liquids

Ionic liquids, composed of organic cations and inorganic anions, are characterized by their distinctive physicochemical properties, such as low volatility, high thermal stability, excellent solubility, and adjustable molecular structures. Furthermore, the low surface tension and significant surfactant properties of their aqueous solutions effectively alter coal surfaces' chemical structure and porosity, offering a new technical pathway to enhance water injection effects in coal seams (Xi et al., 2020). Ni et al. (2019), Li et al. (2020b), and Wang et al. (2022f) demonstrated that 1-butyl-3-methylimidazolium chloride ([Bmim][Cl]) and 1-butyl-3-methylimidazolium tetrafluoroborate ([Bmim][BF_4]) (Fig. 11(a)), exhibit significant surface activity in aqueous solutions, with their critical micelle concentration determined through ^{1}H NMR and conductivity experiments (Fig. 11(b)), and further investigated the modification mechanisms of coal surface functional groups and aromatic structure content by aqueous solutions of ionic liquids at varying concentrations, elucidating the impact of concentration changes on coal microstructure and wettability behavior (Figs. 11(c) and 11(d)). In improving coal pore characteristics, ionic liquid treatments significantly increase coal's total pore volume and surface area, particularly by increasing mesopore volume and reducing the proportion of micropores. This treatment also enhances the roughness and structural complexity of the coal surface, providing more sites for water molecule adsorption and thereby boosting the adsorptive capacity of the aqueous solution (Wang et al., 2022e). Additionally, Li et al. (2021b) found that the synergistic action of oxidative acids with the [Bmim][Cl] could decompose some active functional groups, causing the detachment of aliphatic structures from coal and significantly increasing its aromaticity, which delays the oxidation process and demonstrates a beneficial synergistic effect in modifying coal surfaces and controlling oxidation reactions (Figs. 11(e) and 11(f)). These findings provide theoretical support and practical rationale for optimizing CSWI techniques by regulating the concentration and composition of ionic liquids. However, current research on ionic liquids predominantly focuses on microscopic mechanisms and static experiments, presenting challenges for their field application in CSWI. For instance, the relatively high cost of ionic liquids limits their widespread adoption, and their environmental impact and biodegradability remain insufficiently studied. Consequently, the environmental safety and sustainability of ionic liquids urgently require further evaluation to ensure their long-term efficacy and safety in practical applications.

3.2.4 Nanofluids

Nanofluids, formed by dispersing nanoparticles (e.g., SiO_2) in base fluids, enhance coal wettability in CSWI through reduced surface tension (Zhao et al., 2024). However, the abundant unsaturated bonds on the nano-silica surface readily led to aggregation, causing poor dispersion and affecting wetting effectiveness (Zou et al., 2022). To address this issue, as depicted in Fig. S5(a), Wang et al. (2022c) performed surface modification of silica nanoparticles with dichlorodimethylsilane to improve their dispersion in solutions. They introduced SDS to prepare nanoparticle-surfactant nanofluids, achieving an interface tension as low as 15.79 mN/m (Fig. S5(b)). Zhang et al. (2024b) demonstrated the synergistic effects of Alpha-Olefin Sulfonate (AOS) modified SiO_2 nanofluids, where the addition of AOS not only enhanced the adsorption layer thickness of water molecules but also extended the diffusion range of water molecules, thereby further improving the wetting performance of the nanofluids (Fig. S5(c)). This research provides a critical theoretical basis and experimental support for applying surfactant-modified nanoparticles to enhance wetting properties. It is noteworthy that the stability of nanofluids is greatly influenced by concentration. Zhang et al. (2022b) found that 0.5 wt% SiO_2 nanofluid exhibited the best wetting stability, while higher concentrations, although increasing water adsorption, decreased stability. As the concentration increases, SiO_2 nanofluids form a coffee ring structure (Fig. S5(d)), creating a circular deposition on the coal surface, which increases the contact area between the nanofluid and coal, enhancing the adsorption of water molecules. However, this structure also disrupts the fluid uniform distribution, affecting its long-term wetting effectiveness (Zou et al., 2023). Moreover, different concentrations of SiO_2 nanofluids can alter the micro-mechanical properties of coal. Zou et al. (2024) found that SiO_2 nanofluids can reduce coal's hardness and elastic modulus. By enhancing its water absorption, the plasticity of coal is strengthened, and its brittleness is weakened. When subjected to shearing forces during the cutting process, coal is more likely to undergo plastic deformation rather than fracture into fine dust particles, effectively reducing the dust generated during mining. Evidently, nanofluids exhibit significant potential for application in CSWI for dust reduction. Despite their potential, challenges persist in long-term stability due to agglomeration at high concentrations and incomplete understanding of nanofluid-coal interactions at microscales, hindering field-scale deployment.

4. Conclusion and prospects

CSWI constitutes a crucial measure for ensuring safe and green production in coal mines, preventing the hazards of pneumoconiosis, and safeguarding the environment. This paper first systematically summarizes the progress of the basic theoretical research on dust prevention. Subsequently, it explores the technologies for modifying the physical properties of coal and injection fluid modification. It undertakes an in-depth analysis of the potential and effects of these technologies in improving permeability, enhancing wettability, and thereby achieving dust prevention. Based on the literature reviewed, the following conclusions are drawn:

1) From a microscopic perspective, the seepage-wetting behavior within coal is governed by the coupled effects of pore-fracture networks and chemical properties. Advanced characterization techniques (LF-NMR and Micro-CT) have enabled precise delineation of pore structures, revealing that connectivity between pores and fractures predominantly dictates fluid transport pathways - where macropores and mesopores enhance matrix connectivity while micropores exhibit limited participation due to Jamin effects and capillary resistance. Furthermore, coal rank evolution directly modulates chemical composition and wettability. Molecular dynamics simulations demonstrate that the wetting process fundamentally represents a dynamic equilibrium between interfacial tension and chemical group interactions. Hydrophilic functional groups drive directional water molecule adsorption and diffusion through hydrogen bonding mechanisms, providing critical microscopic insights for optimizing water injection strategies.
2) From a macroscopic perspective, the hydro-mechanical coupling effect dynamically regulates stress distribution and fracture network evolution in coal seams, governing the stage-specific characteristics of the seepage-wetting process. During the initial low-pressure water injection phase, subtle adjustments in pore structure dominate, with moisture primarily distributed along pre-existing pores. As injection pressure increases in the mid-phase, irreversible expansion of newly formed fractures occurs, accelerating the interconnection of primary-secondary fracture systems. This leads to a surge in permeability efficiency, expansion of the wetting radius, and rapid moisture diffusion into deeper coal seams. In the late injection stage, the formation of a complex multilevel interconnected fracture network topology enables significant homogenization of moisture distribution through pore

pressure equilibration. Ultimately, this achieves comprehensive coal wetting and dust reduction, providing a theoretical foundation for optimizing engineering parameters.

3) The application of different injection technologies varies significantly depending on the geological conditions of different coal seams. Conventional CSWI technologies serves as a foundational method but requires integration with coal modification techniques to improve efficiency. High-pressure fluid fracturing technology is suitable for thick coal seams with low natural fracture density and significant horizontal stress differences, yet it necessitates precise pressure threshold control to prevent adjacent roadway leakage and faces technical limitations such as low abrasive recovery rates and frequency control inaccuracies. Existing fluid modification technologies, including surfactants, synthetic wetting agents, ionic liquids, and nanofluids, enhance wetting efficiency by altering the physicochemical properties of fluids and their interaction modes with coal matrices. However, surfactants and synthetic wetting agents exhibit toxicity and resistance to degradation, posing risks to groundwater safety, while also encountering bottlenecks such as complex synthesis processes and high application costs. Advanced techniques such as high-temperature shock fracturing, cold-shock fracturing technology, ionic liquids, and nanofluids remain confined to laboratory research, requiring further evaluation for industrial-scale CSWI applications.
4) From a theoretical perspective, it is imperative to integrate multi-scale research methodologies by combining advanced macroscopic-mesoscopic-microscopic characterization techniques to systematically elucidate the evolutionary patterns of pore-fracture structures and key influencing factors of seepage behavior under diverse geological conditions. The establishment of quantitative correlations between coal rank indices and wettability parameters should be achieved through in-situ spectroscopic analysis. Multi-physics coupled numerical simulations must be implemented to quantify dynamic water migration pathways within coal fracture networks under realistic reservoir pressures. Technologically, breakthroughs are required in engineering multi-technology synergies to create homogeneous fracture networks. This entails developing intelligent water injection control systems enabling adaptive parameter optimization and real-time wetting front monitoring. Concurrently, eco-friendly bio-based wettability modifiers with controlled degradability should be designed to accelerate wetting and enhance dust suppression efficiency. Such innovations will drive the paradigm shift from extensive pressurization to precision wetting strategies, advancing CSWI from isolated technological upgrades toward integrated system solutions, thereby providing scientific foundations for safe and sustainable mining practices.

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Supplementary file

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Conflict of interest

The authors declare no competing interest.

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