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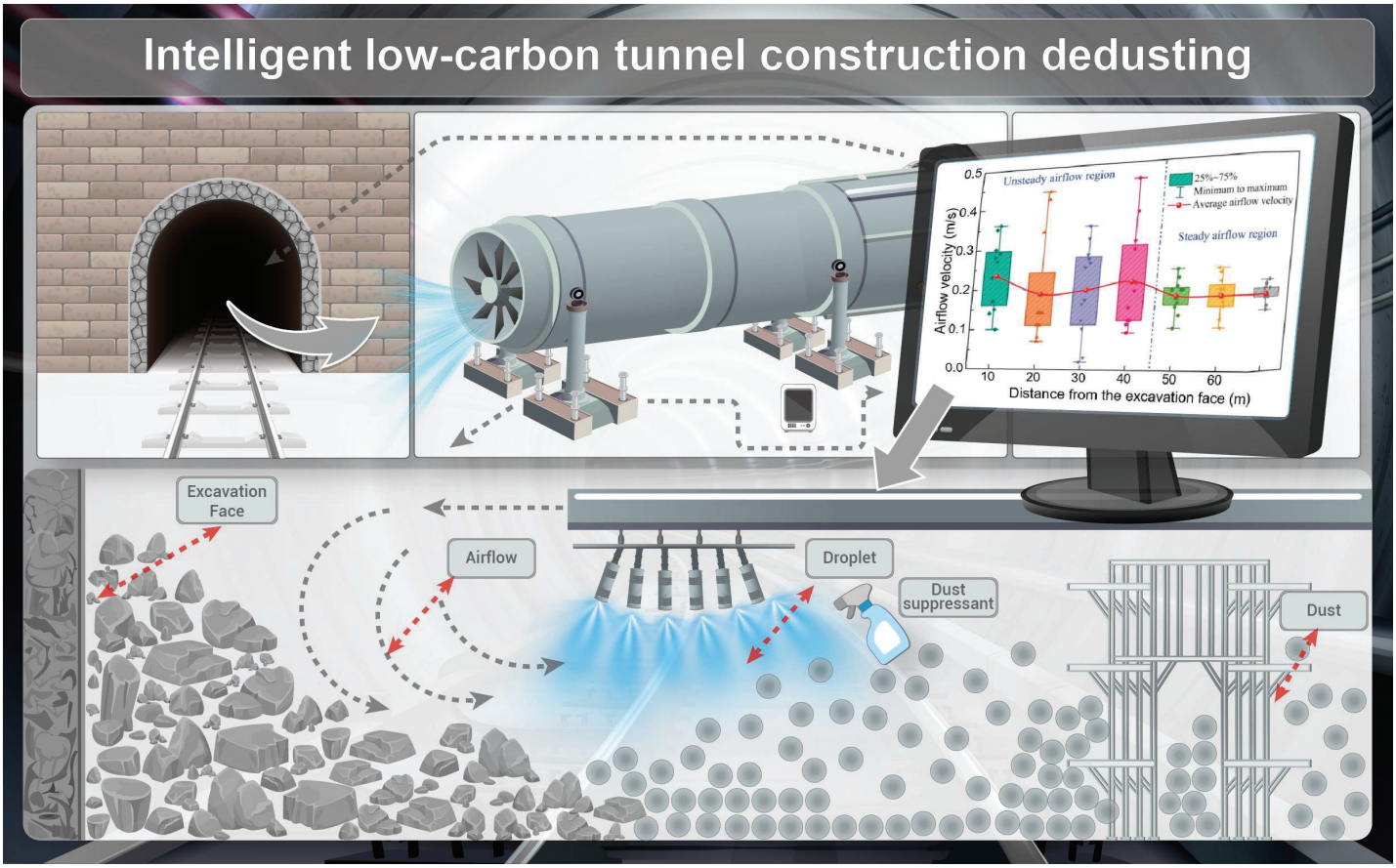
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- High-altitude, ultra-long and complex tunnels bring tough challenges for respirable dust control, with fine particles less than 10 μm easy to suspend and form local dust accumulation zones.
- This review compares tunnel dust removal methods: water spraying (~85%) and chemical dust suppressants (~94%); demand-controlled air supply cuts ventilation energy use by up to 64.6%.
- Research priorities include dust dispersion under coupled conditions, synergistic ventilation-dust control optimisation, and digital-twin intelligent air supply for low-carbon tunnel construction.

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Advances in Efficient and Low-Carbon Ventilation and Dust Removal in Tunnel Construction

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The increasing construction of high-altitude, ultra-long, and geometrically complex tunnels poses major challenges for controlling respirable dust while maintaining occupational safety, ventilation efficiency, and low energy consumption. Here, we systematically review recent advances in ventilation and high-efficiency dust-removal technologies for tunnel construction from three interconnected perspectives: ventilation and dust-removal performance, efficient dust-removal technologies, and intelligent low-carbon air-supply technologies. We identify key geometric and environmental constraints, including large-curvature spiral sections and V-shaped inclines, that alter airflow organisation and can create localised dust-accumulation zones. Fine particles (<10 μm) are particularly difficult to remove because they can remain suspended and be transported over long distances. Effective dust control generally requires the press-in ventilation duct outlet and exhaust inlet to be positioned within 10 to 70 m and approximately 5 m of the excavation face, respectively. Conventional dust-removal approaches, such as water spraying and wet grids, show reported removal efficiencies of approximately 85%, whereas chemical dust suppressants can achieve higher removal efficiencies, with median performance approaching 94% under the reviewed conditions. In addition, energy-efficient technologies, including air-cabin systems and demand-controlled air-supply strategies, can reduce ventilation energy consumption by approximately 20.7% and up to 64.6%, respectively. Finally, we identify key research priorities, including elucidating dust dispersion under coupled and complex operating conditions, optimising the synergistic performance of high-efficiency dust-control technologies and ventilation systems, and developing intelligent air-supply systems based on digital twins. These advances are expected to support safer, more energy-efficient, and low-carbon tunnel construction.

INTRODUCTION

With the rapid expansion of transportation infrastructure in China, tunnel engineering has become increasingly large-scale and complex, characterized by high-altitude construction,[1] ultra-long tunnels,[2] high geothermal temperatures,[3] and challenging geological conditions.[4] Tunnel construction processes, including drilling and blasting (Figure 1A) and fully mechanized tunneling (Figure 1B), generate substantial amounts of airborne dust particles[5] as well as hazardous gases such as CO and NO_2.[6] Exposure to these pollutants can cause severe occupational diseases, such as pneumoconiosis,[7] posing significant risks to personnel health and safety.[8] Moreover, extreme environments and complex tunnel geometries[9] can impede pollutant dispersion and removal, reducing the effectiveness of conventional diluted ventilation. Consequently, developing efficient ventilation and dust-removal technologies is essential to improve tunnel construction safety and efficiency while supporting energy conservation and low-carbon construction.[10]

Press-in ventilation is the most widely adopted ventilation strategy in tunnel construction.[11] As illustrated in Figure 2A, it employs axial-flow fans to deliver fresh air from outside the tunnel to the excavation face through press-in air ducts, thereby displacing dust-laden air and hazardous gases toward the tunnel outlet.[12] This process promotes air exchange while diluting and transporting airborne pollutants. Owing to its simple configuration, flexible duct installation, and long air-supply distance, press-in ventilation can rapidly improve the tunnel construction environment.[13] However, the interaction between the supply jet and the tunnel geometry often generates recirculation zones near the excavation face, leading to localized pollutant accumulation.[14]

Extraction ventilation relies on the negative-pressure region generated near the excavation face to remove dust and hazardous gases directly through extraction air ducts. However, its performance is highly sensitive to the inlet position of the extraction air duct,[17] and the effective suction range is inherently limited. Consequently, extraction ventilation is seldom used as a standalone strategy. Hybrid ventilation (Figure 2B) combines press-in and extraction ventilation in a "long press-in, short extraction" configuration,[15] thereby integrating the advantages of both systems. This arrangement can effectively suppress dust dispersion and improve dust-removal efficiency.[18]

In recent years, hybrid ventilation systems incorporating air curtains have attracted increasing attention.[19] In these systems, circular or lateral air-curtain devices are installed behind the excavation face in conjunction with the traditional hybrid ventilation layout. As illustrated in Figure 2C, a high-velocity radial airflow is generated by diverting a portion of the axial airflow under the effect of the air curtain,[16] forming a dynamic air barrier that restricts the downstream spread of dust-laden air.[20] Integrating air curtains with hybrid ventilation has been shown to significantly reduce dust pollution at the excavation face and improve the construction environment.[21]

To explore the performance of these ventilation and dust-removal technologies, extensive studies have been conducted worldwide, focusing on three aspects: airflow organization,[22] pollutant transport and dispersion,[23] and optimization of ventilation parameters.[24] For instance, the structural parame-

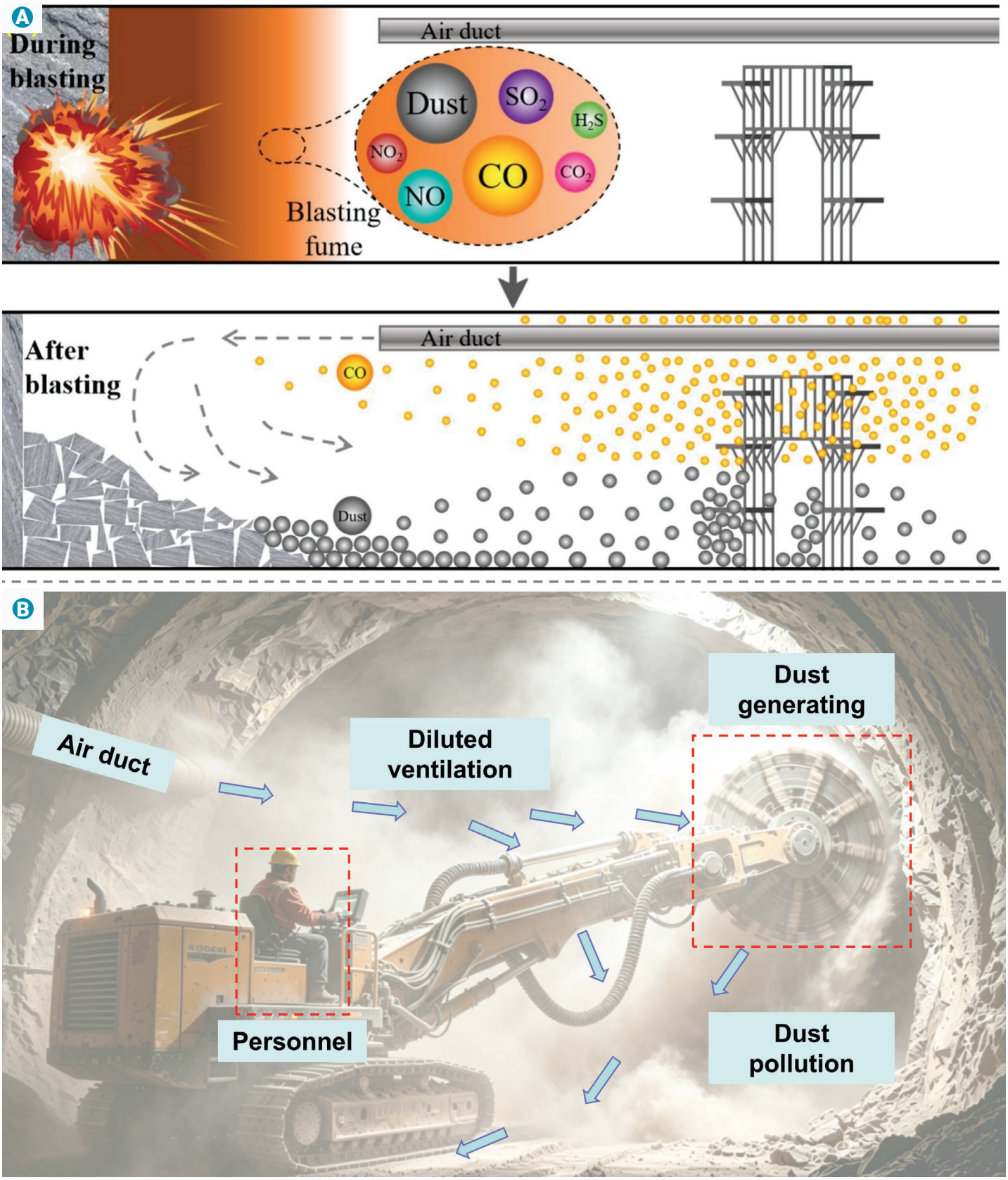


Figure 1. Schematic of ventilation and dust removal under different tunnel construction scenarios (A) Drilling and blasting (Reproduced with permission from Ref. 5, Copyright 2026 Elsevier); (B) Fully mechanized tunneling.

ters of air-curtain generation devices, such as the opening length and jet angle, have been optimized to produce a more uniform and stable air curtain, achieving dust-isolation efficiency of approximately 75%.[25] Despite the widespread use of these ventilation technologies in dust control during tunnel construction, the current progress is mainly focused on traditional plain straight tunnels and their static ventilation and dust-removal designs, while a systematic review comprehensively analyzing emerging topics such as ventilation and dust-control strategies for tunnels with special geometries

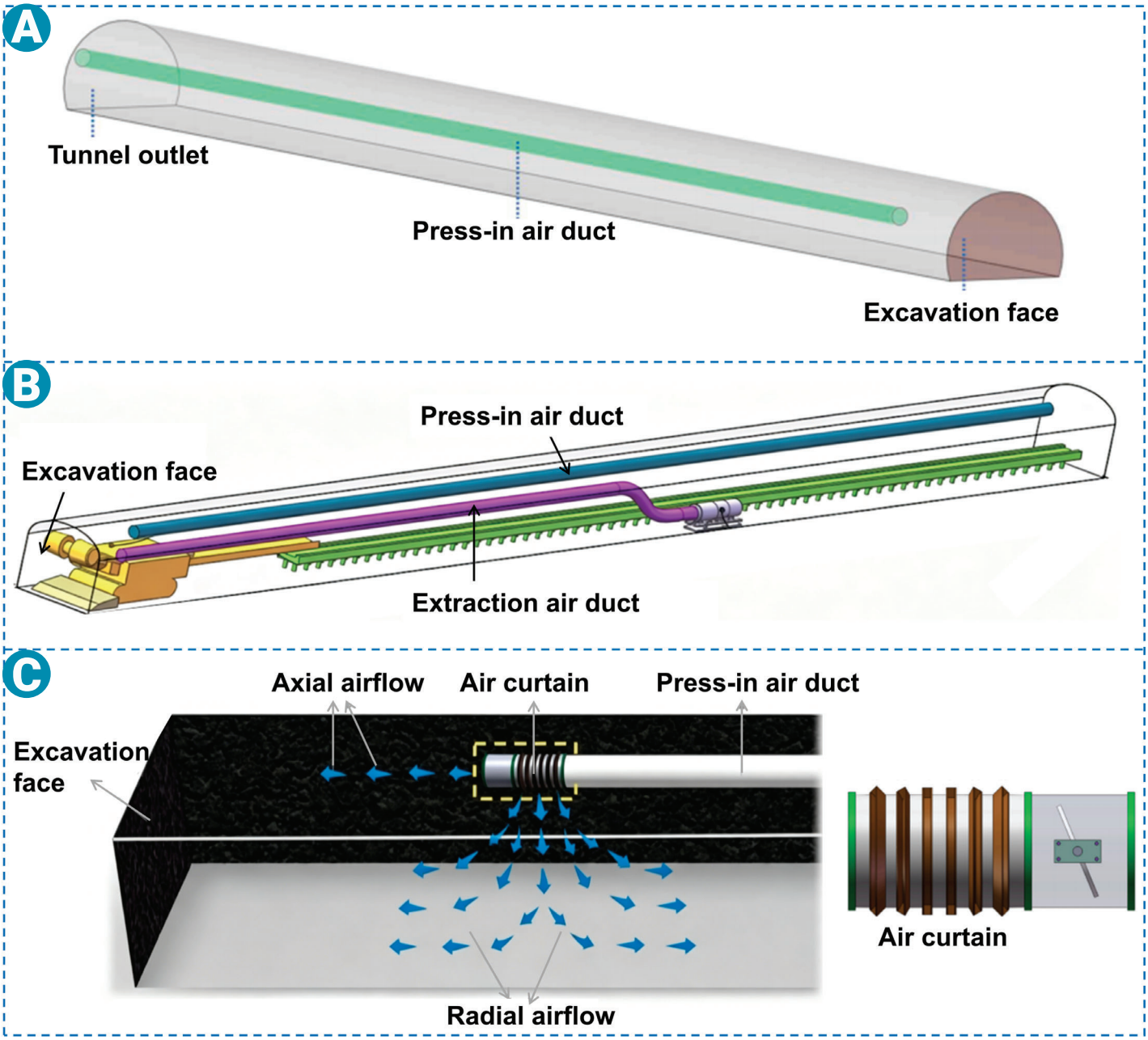


Figure 2. Schematic of different ventilation method for tunnel construction (A) Press-in ventilation (Reproduced with permission from Ref. 12, Copyright 2026 Elsevier.); (B) Hybrid ventilation (Reproduced with permission from Ref. 15, Copyright 2018 Elsevier.); (C) Hybrid ventilation system with air curtain (Reproduced with permission from Ref. 16, Copyright 2024 Elsevier.).

(i.e., spiral tunnels, inclined shafts), extreme environments (i.e., high altitudes), and intelligent low-carbon air-supply technologies is notably lacking.

To address this gap, this study conducts a comprehensive review of tunnel construction ventilation and dust-removal technologies based on a bibliometric analysis of 108 relevant publications. The review is divided into three interconnected themes: (1) ventilation and dust-removal performance during tunnel construction, (2) advanced duct-removal technologies, and (3) intelligent and low-carbon air-supply strategies. First, the airflow characteristics and dust-dispersion mechanisms within construction tunnels are examined, and the key factors influencing ventilation and dust-removal performance are discussed. Second, recent advances in efficient dust-removal technologies are summarized and analyzed. Finally, from a design and operational perspective, energy-saving air-supply technologies and their intelligent control strategies are analyzed. This review can lay the foundation for developing high-performance ventilation and dust-control technologies for tunnel construction and offer valuable guidance on green construction practices and achieving low-dust, low-carbon tunneling.

TUNNEL CONSTRUCTION VENTILATION AND DUST-REMOVAL PERFORMANCE

Ventilation energy consumption mechanisms

Construction ventilation, as the main means of pollutant control, focuses on effectively diluting and discharging pollutants,[26] and providing fresh air for the excavation face.[27,28] However, during actual tunnel construction, the ventilation system faces the challenge of high energy consumption.[29] Taking a 2.1 km construction tunnel as an example, when the air-supply volume was 2400 m^3/min, the fan power was 403.2 kW, and the cumulative fan energy consumption was 1306.92 MWh.[30]

To guide the energy-saving design of ventilation systems, it is necessary to further explore the composition of ventilation energy consumption. Ventilation energy consumption includes the energy of the air supplied to the excavation face (i.e., the kinetic energy of the supplied air), energy associated with air leakage from air ducts, and frictional and local resistance energy in air ducts and tunnels.

Air-supply energy. The air-supply volume at the excavation face is a key

parameter that affects the energy required for air supply, and it should meet the control requirements for construction pollutants. When the air-supply volume decreases, it not only reduces the air-supply energy at the excavation face but also correspondingly reduces air leakage and ventilation resistance in the air duct. For a 1 km ventilation system with a diameter of 1 m, when the air-supply volume decreased from 900 m^3/min to 420 m^3/min, the total ventilation resistance decreased from 4000 Pa to ~ 1700 Pa, a decrease of 57.5%, and the corresponding fan power consumption decreased from 97 kW to ~25 kW.[31] Considering that the excavation face advanced 4 m per day and the fan operated for 20 h per day, the total ventilation energy consumption corresponding to an air-supply volume of 900 m^3/min was up to 212.28 MWh.[31]

Moreover, for a 2.1 km ventilation system, when the air-supply volume at the excavation face increased from 1800 m^3/min to 2400 m^3/min, the fan power increased from 170.1 kW to 403.2 kW, and the corresponding fan energy consumption increased from 551.35 MWh to 1306.92 MWh.[30] In addition, the ratio of pollutant-control efficiency to ventilation energy consumption (0.4 decreased to 0.2) showed a decreasing trend as air-supply volume increased (950 m^3/min increased to 1,350 m^3/min),[32] indicating that increasing air-supply volume weakens the cost-effectiveness of the ventilation system.

Air-leakage energy. The air ducts may experience varying degrees of air leakage due to factors such as the connection method, the material used, and the air-supply volume.[30] Among them, the connection between the fan outlet and the air duct, as well as the air-duct joints,[33] are often high-risk areas for air leakage. In addition, upgrading the air-duct material grade can reduce air leakage. For a 1 km ventilation system, when the air-duct diameter was 1.4 m and the air-supply volume at the excavation face was 1500 m^3/min, the air-leakage volume was 45 m^3/min when using S-class air ducts, while the air-leakage volume of B-class air ducts was 234 m^3/min.[34]

Air leakage along air ducts requires higher fan power to maintain the required air-supply volume at the excavation face, increasing fan energy consumption. Using B-class air ducts rather than S-class air ducts nearly doubled fan energy consumption from 529.32 MWh to 1017.61 MWh.[34] These findings highlight that enhancing ventilation system maintenance and employing high-airtightness ducts are effective strategies for minimizing air leakage and reducing ventilation energy demand.

Frictional resistance. As airflow passes through solid walls, energy dissipates due to friction between the airstream, the ducts, and the tunnel surfaces. Consequently, the ventilation system must overcome the frictional resistance associated with both the supply airflow within the ducts and the exhaust airflow along the tunnels and duct walls.[35] The frictional resistance, P_f, can be calculated as Equation 1.[36]

$$P_f = f\frac{2\rho L Q^2}{\pi^2 D^5} \quad (1)$$

where, f is the frictional resistance coefficient; ρ is the air density; L is the ventilation length; D is the ventilation section size; Q is the air-supply volume.

As indicated by Equation 1, the frictional resistance depends primarily on the length and diameter of the air duct, as well as the air-supply volume. In long-distance tunnel construction, this frictional resistance becomes substantial and significantly increases fan energy consumption. Although enlarging the air-duct diameter can effectively reduce frictional losses, its application is constrained by spatial limitations within the tunnel cross-section and higher installation costs. Consequently, optimizing and reducing the air-supply volume at the excavation face generally offers greater potential to reduce overall energy consumption than modifying duct dimensions, particularly in long-distance ventilation systems.

Local resistance. As airflow passes through abrupt changes in cross-section, bends, splitters, and other flow disturbances, collisions, flow separation, vortices, and secondary flows are generated, resulting in additional energy loss.[37] The local resistance, P_l, can be calculated as Equation 2.[38]

$$P_l = \xi\frac{2\rho Q^2}{\pi^2 D^4} \quad (2)$$

where, ξ is the local resistance coefficient.

As indicated by Equation 2, the local resistance depends on the air-duct diameter, air-supply volume, and the local resistance coefficient. The local resistance coefficient is primarily determined by the geometric configuration of the ventilation system and tunnel, as well as the blockage ratio of the tunnel cross-section caused by construction equipment and other obstructions.[39] Consequently, local resistance can be reduced by optimizing the ventilation system layout, minimizing flow obstructions within the tunnel, and reducing the air-supply volume.

Airflow-dust transport and dispersion characteristics in tunnel construction

From the energy-consumption perspective discussed in previous section, the air-supply volume at the excavation face encompasses all four aspects above. Consequently, minimizing this parameter is the primary objective for improving the ventilation system's energy efficiency. Since the air-supply volume should satisfy construction dust control requirements, the objective shifts to developing efficient, energy-saving control technologies for construction dust. Understanding the transport and dispersion characteristics of construction dust provides the physical basis for developing effective dust-control strategies. Therefore, identifying the key factors that affect dust transport is important. The primary influencing factors are summarized below.

Airflow distribution structure. Due to the space constraint, the airflow distribution near the excavation face is highly complex.[40] As illustrated in Figure 3A, the high-speed air-supply airflow discharged from the air-duct outlet impinges on the excavation face and then generates a reverse flow under the press-in ventilation mode.[41] Due to entrainment effects, the reverse flow interacts with the incoming high-speed air-supply airflow, forming a complex airflow field.

Previous studies have indicated that the airflow field within the construction tunnel can generally be divided into several characteristic regions, including the vortex region near the excavation face, the airflow transition region, and the exhaust airflow region.[42] As illustrated in Figure 3B, the first two regions are referred to as unstable airflow regions due to the turbulent airflow caused by the vortex, while the latter region is referred to as a stable airflow region due to constant airflow velocity and a single flow direction.[5]

Among these regions, the vortex region represents a high-risk area for dust accumulation,[43] as the swirling airflow prolongs particle residence time and leads to localized high-concentration dust pollution.[44] As illustrated in Figure 3C, markers 1 through 21 denote the sequential spatiotemporal dispersion positions of an individual dust particle.[45] Driven by the localized vortex airflow, the particle remains trapped between the excavation face and the air-duct outlet, exhibiting multiple recirculating trajectories.

Dust particle diameter. The dispersion characteristics of dust particles with different particle diameters have significant differences.[46] As illustrated in Figure 3D, blasting dust with a diameter of 23.1-28.6 μm settles over time under the influence of gravity, resulting in a gradual decrease in mass percentage, while fine dust particles with a diameter of 1.1-12.1 μm are still exposed to the air, showing an upward trend in mass percentage.[5] Moreover, a study conducted 9 blasting tests in Chongqing metro tunnels and indicated that dust particles with a diameter of >30 μm had already settled 5 min after blasting. In contrast, 25-30 min after blasting, dust particles with a diameter of 15-30 μm further settled, and the particle diameter in the 30-50 m area from the excavation face decreased to <10 μm.[47] Generally, coarse particles (>30 μm) rapidly settle under gravity, while fine particles (<10 μm) can remain suspended for a long time and transport over long distances under the influence of airflow drag.

Altitude. In addition, although altitude has a relatively small impact on dust dispersion compared to the air-duct distance and air-supply volume, it cannot be ignored. Research indicated that the main particle diameter range of blasting dust in high-altitude tunnels was 1.1-28.6 μm, with an average particle diameter of 13.7 μm, which was significantly lower than that in low-altitude tunnels (20-40 μm).[5] This is because lower air density reduces resistance and accelerates the settling of coarse dust particles.

Tunnel geometric structure. Real-world construction tunnels rarely conform to ideal linear shapes, but frequently feature specialized structural alignments, such as spiral, inclined, or V-shaped, etc.[48] Due to their distinct spatial curvatures and longitudinal gradients, these special structures exhibit significant differences in airflow organization and dust dispersion patterns

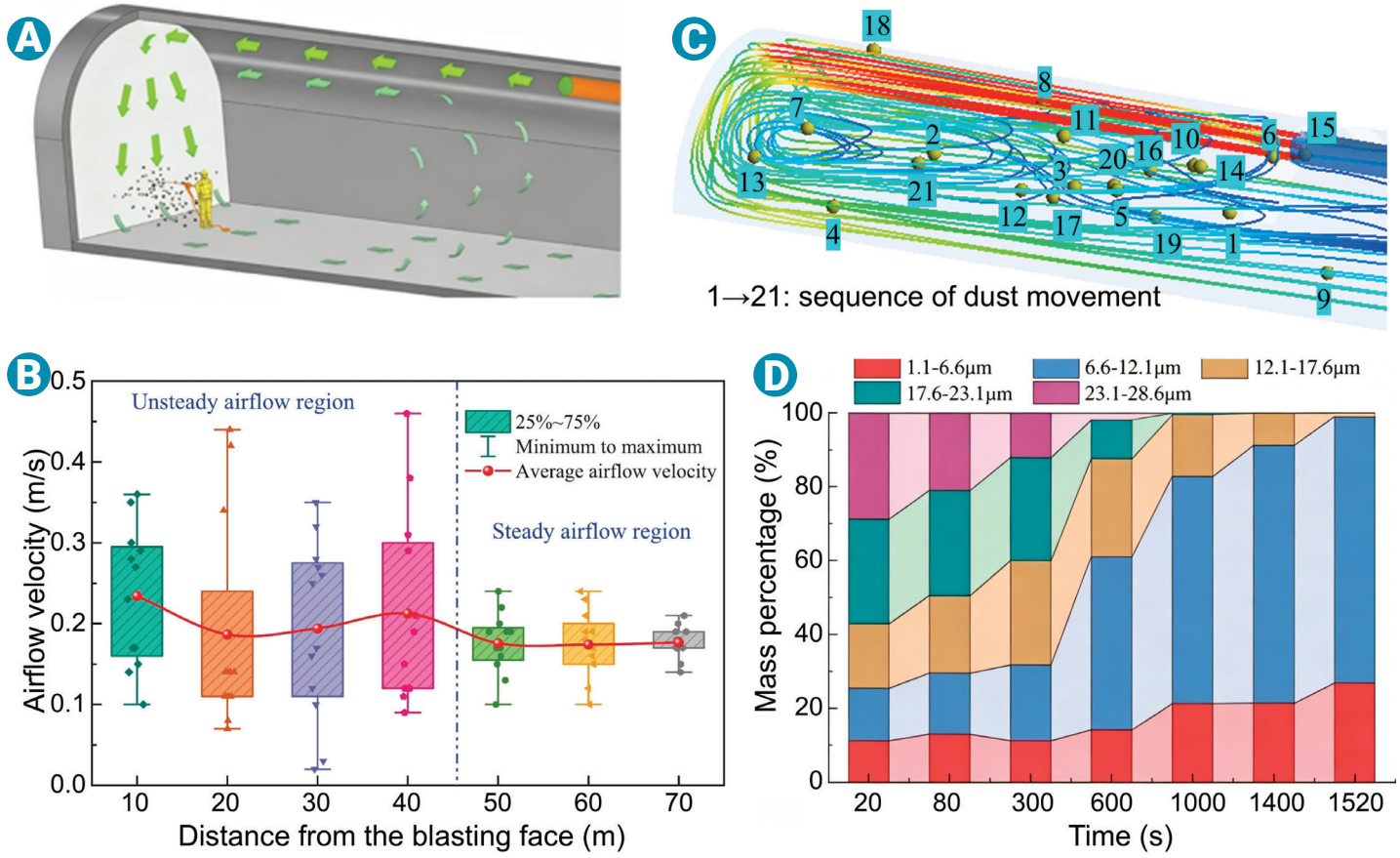


Figure 3. Schematic of airflow distribution and dust dispersion characteristics during tunnel construction (A) Airflow distribution near the excavation face;[41] (B) Airflow velocities at different distances from the excavation face (Reproduced with permission from Ref. 5, Copyright 2026 Elsevier); (C) Dispersion position of an individual dust particle over time near the excavation face (Reproduced with permission from Ref. 45, Copyright 2025 Tsinghua University Press); (D) Variation of mass percentage of blasting dust with different particle diameters over time (Reproduced with permission from Ref. 5, Copyright 2026 Elsevier).

within tunnels compared to straight tunnels.[49]

Specifically, for spiral construction tunnels, the curvature radius is the key factor affecting the dust distribution. Research has shown that dust distribution inside spiral tunnels can be divided into "heavily polluted areas" and "lightly polluted areas", and that the smaller the curvature radius, the more favorable it is for dust to be orderly discharged by the airflow, thereby shortening the time to reach safe concentrations.[50] As for the influence of longitudinal slope, research has found that in tunnels with positive slope (uphill), dust particles are more prone to secondary backflow, resulting in significantly higher weighted-average dust concentrations in local areas than in tunnels with negative slope (downhill).[51]

In addition, for V-shaped construction tunnels that include downhill, horizontal, and uphill sections, dust concentration along the tunnel may not show a monotonically decreasing trend as in straight tunnels, but rather exhibit a fluctuating decline pattern. This implies that local high-concentration pollution areas may also appear in the rear area far from the excavation face (such as at the beginning of the uphill section), posing an unconventional risk of dust accumulation.[52] Moreover, the included angle between the inclined shaft and construction section critically influences the airflow stability.[53] When airflow passes through the corner, inertial effects cause flow separation and vortex formation. This not only raises fan energy consumption but also disrupts the stable propagation of fresh air toward the excavation face, thereby weakening the dilution efficiency of pollutants in the near-face zone.

In conclusion, when designing ventilation and dust control for complex structured tunnels, it is essential to fully consider the impact of their geometric structure on airflow and dust dispersion. The relevant experience and conclusions provide theoretical guidance for optimizing the ventilation layout and dust-removal measures of such tunnels.

Tunnel construction ventilation optimization

Tunnel construction ventilation is a core method for improving the construction environment by diluting and discharging dust and harmful gases.[54] Efficient ventilation and dust removal can effectively reduce the demand for air-supply volume, thereby reducing ventilation energy consumption. Whereas the ventilation and dust-removal effect is not only determined by the selection of ventilation methods,[55] but also by the comprehensive control and constraints of specific ventilation parameters.[56] Consequently, it is urgent to systematically review the applicable scenarios and efficient dust-control parameters of various construction ventilation methods,[57] which can provide a reference for the optimization design of ventilation and dust-removal schemes in tunnel construction.

Up to now, many researchers have systematically explored optimal ventilation design parameters,[14] including air-duct position, ventilation volume, etc., through numerical simulation and orthogonal experimental methods. The technical parameters for construction ventilation are summarized in Table 1.

Air-duct position. Air-duct position is a key ventilation parameter, as airflow organization varies significantly with different air-duct positions. Optimizing the air-duct position can reduce the vortex zone and improve ventilation efficiency and pollution-control performance.[41] Among them, the distance from the outlet of the press-in air duct to the excavation face has attracted much attention, and there is an optimal value for this distance. If the distance is too close, the jet is blocked by the excavation face, forming strong eddies that are not conducive to discharging dust particles. While the distance is too far, the jet energy attenuates, making it difficult to effectively dilute the dust particles at the excavation face.

As shown in Table 1, under different construction ventilation methods, the distance between the outlet of the press-in air duct and the excavation face is usually between 10 and 70 m. In press-in ventilation, the air-duct outlets are usually located farther from the excavation face. This is because it is mainly used for drilling-and-blasting construction. In such construction modes, blasting operations can generate high-speed flying rocks. If the air-

Table 1. Summary of technical parameters for construction ventilation.

Construction ventilation method	Ventilation volume (m^3/min)	Air-duct distance from excavation face (m)	Dust concentration at the excavation face (mg/m^3)	Dust production rate (kg/s)	Refs.
Press-in ventilation	• press-in: 610	• press-in: 40	• 1700	• 3.648	[5]
	• press-in: 678	• press-in: 40	• 709.1	• 0.433	[58]
	• press-in: 924	• press-in: 69	• 180	• 0.0067	[59]
Hybrid ventilation	• press-in: 1,447.6, exhaust: 1,809.5	• press-in: 10, exhaust: 5	• 307.6	• 0.02	[60]
	• press-in: /, exhaust: 300	• press-in: 10, exhaust: 2	• 125.6	• /	[57]
	• press-in: 400, exhaust: 330	• press-in: 35, exhaust: 3	• ~9	• 0.002	[61]
Hybrid ventilation with air curtains	• press-in: 60, exhaust: 400, air curtain: 540	• press-in: 10, exhaust: 4, air curtain: 30	• 52.68	• 0.02	[16]
	• press-in: 300, exhaust: 400, air curtain: 240-270	• press-in: 10, exhaust: 3, air curtain: 20-30	• 79.8	• 0.02	[19]
	• press-in: 32, exhaust: 312, air curtain: 288	• press-in: 10, exhaust: 2, air curtain: 20	• 83	• 0.0028	[62]

duct outlets are placed too close to the excavation face, it is likely to cause damage. Moreover, to achieve the dust-removal effect of negative pressure, the exhaust inlet of the hybrid ventilation system and the hybrid ventilation system with air curtains are usually located within 5 m of the excavation face.

Ventilation volume. Ventilation volume is another crucial ventilation parameter. For press-in ventilation, increasing the air-supply volume can significantly enhance the ability to dilute and remove dust particles, but it will also greatly increase the ventilation energy consumption.[30] Related research has indicated that during the construction of highway tunnels in high-altitude areas, when the air-supply velocity increases from 6 m/s to 14 m/s, the dust concentration within a range of 60 m near the excavation face can be reduced below the safety threshold.[63] However, excessively high air-supply velocities can cause dust particles smaller than 30 μm to suspend again near the secondary lining trolley, thereby reducing the dust-removal effect. This indicates that an optimal air-supply volume can meet the requirements of dust discharge, secondary dust control, and energy consumption reduction.[64] In addition, hybrid ventilation systems and their coupled air curtains also require matching the press-in and exhaust air volumes with the air-curtain volume.

EFFICIENT CONSTRUCTION DUST REMOVAL TECHNOLOGY

Relying solely on ventilation for dust control is of limited effectiveness in long-distance and high-intensity construction, and it also consumes a large amount of energy. Consequently, integrating ventilation with other efficient dust-removal technologies has become the mainstream trend, including spray, wet grid, and local purification devices, as well as chemical dust suppressants.

Among them, spray technology (Figure 4A) focuses on depositing dust particles exposed to the air by atomizing droplets, with a wider effective dust-removal range.[13] However, wet grid and local purification technology (Figure 4B) focuses on guiding dust-laden airflow into the purification device (such as a dust removal box) through the collection inlet and uses measures such as filter units or wet string grids to capture dust particles and purify airflow. In contrast, the effective range of dust removal is limited.[65] Chemical dust suppressant (Figure 4C) emphasizes the application of self-developed chemical reagents to enhance the wetting ability of liquid media in contact with dust particles, thereby effectively improving the consolidation effect on dust particles.[66]

The key technical parameters of various dust-removal technologies are summarized in Table 2. Furthermore, the dust-removal efficiency of these dust-removal technologies is compared and analyzed. As illustrated in Figure 4D, spray technology demonstrates relatively stable dust-removal performance, indicating that dust-removal efficiency varies little under different working conditions, with a median of 84.06%. In contrast, the dust-removal performance of wet grid and local purification technology, as well as chemical dust suppressant technology, varies significantly under different working conditions, but their upper limits of dust-removal efficiency are higher, with medians of 86.2% and 93.89%, respectively.

Spray technology

Spray technology is one of the most widely used efficient dust-removal technologies.[82] As illustrated in Figure 5A, the core equipment of spray technology is the nozzle.[70] Through atomization, the nozzle breaks the liquid medium into tiny droplets, and the dust suppression mechanism relies primarily on inertial impaction, interception, and gravitational sedimentation as droplets capture airborne particulate matter. However, effective capture depends heavily on droplet dynamics. As depicted in Figure 5B, when a significant size mismatch exists between droplets and dust particles, the dust particles tend to follow the surrounding air streamlines and bypass collision with the droplets.[83]

Consequently, achieving optimal dust suppression performance requires establishing an appropriate droplet field characterized by suitable droplet diameter, velocity, and spatial concentration. These characteristics are intrinsically linked to operational parameters, including spray pressure, nozzle orifice size, and nozzle geometry. To address this, extensive research has focused on optimizing these engineering parameters to maximize dust capture efficiency.

For the construction of a cantilever roadheader, when a fine solid conical nozzle with an aperture of 1.6 mm, a spray pressure of 8 MPa, and a nozzle number of 11 was selected, the proportion of high-concentration droplets formed reached 77.36%.[69] As illustrated in Figure 5C, after the application of spray technology, the dust concentration at different distances from the excavation face has substantially decreased, and the dust-removal efficiency at the driver's position has reached 81.48%.[69]

For drilling and blasting construction of metro tunnels, dust particle diameter differed significantly at different locations from the excavation face, and a zoning spray strategy was required.[68] It was determined that the wide-angle solid conical nozzle with an aperture of 1.9 mm had a dust-removal efficiency of 73.64% for large particle dust, while the fine nozzle with an aperture of 1.2 mm had a higher removal efficiency for respirable dust.[68]

In response to the challenge of dust control in high-altitude tunnels (with 90.09% of the dust diameter being in the range of 0.1-0.7 μm), an intelligent "Highland Lung" dry-fog dust-suppression system (droplet diameter <10 μm) was developed.[13] Field measurements showed that the submicron dust-removal efficiency within 250 m from the excavation face reached 81.8%-88.6%. In addition to nozzle aperture and spray pressure, wind speed is also a key factor affecting dust-removal efficiency.[67]

From nozzle selection and parameter optimization to field application, the above research covers a variety of complex working conditions such as cantilever roadheader construction, drilling and blasting construction, and plateau tunnel, fully verifying the widespread application and remarkable effect of spray dust-removal technology in different engineering scenarios, and providing solid technical support for dust control in tunnel construction.

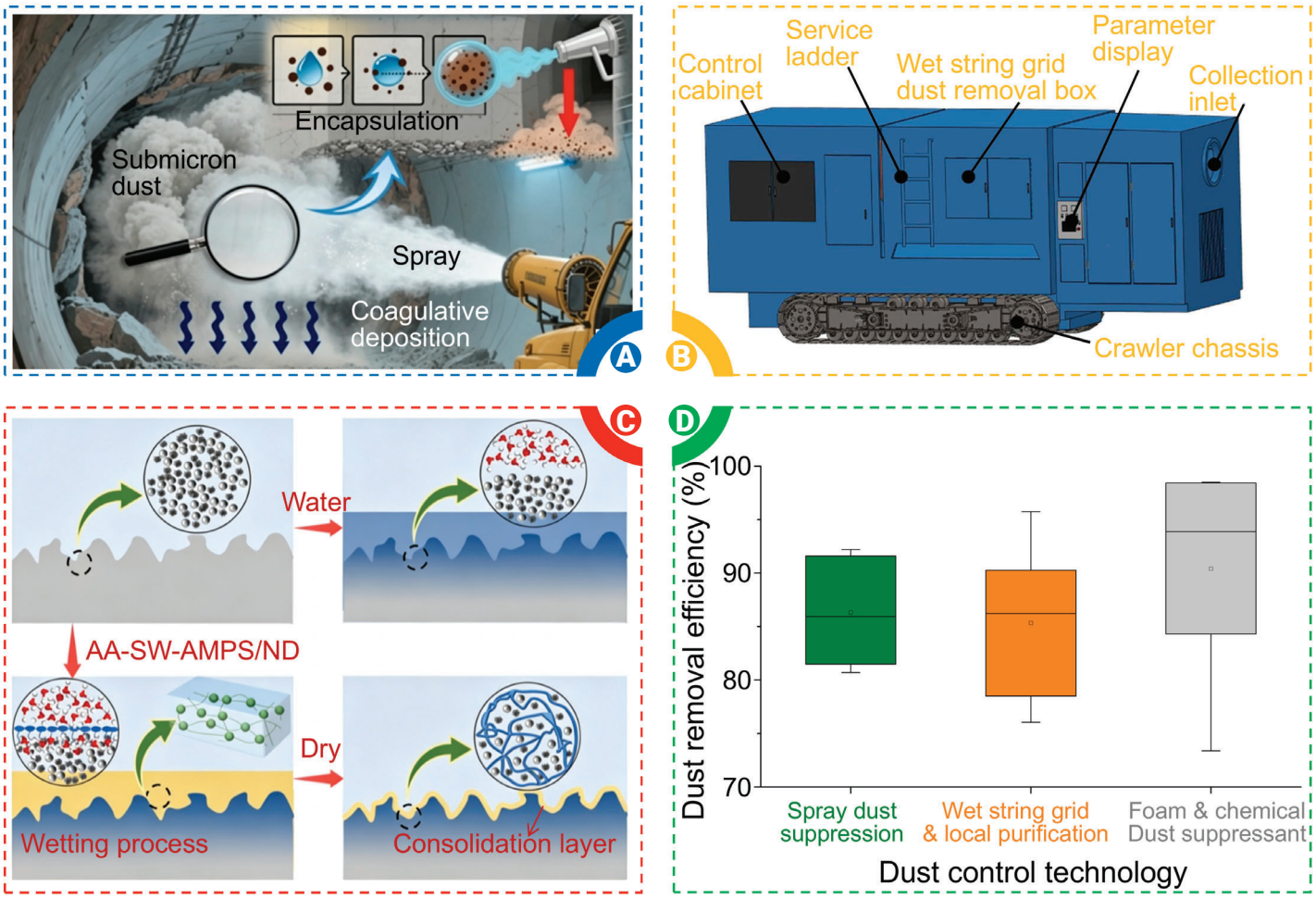


Figure 4. Schematic of efficient dust-removal technology (A) Spray technology (Reproduced with permission from Ref. 13, Copyright 2026 Elsevier); (B) Wet grid and local purification technology (Reproduced with permission from Ref. 65, Copyright 2025 Institution of Chemical Engineers); (C) Chemical dust suppressant technology (Reproduced with permission from Ref. 66, Copyright 2023 Elsevier); (D) Comparison of dust-removal efficiency of different technologies.

Wet grid and local purification technology

Researchers have developed various mobile or fixed local purification devices to address the local high-concentration dust pollution that traditional ventilation systems struggle to handle.[84] These devices fall into two main categories: mobile dust-removal vehicles based on wet filtration, and track-mounted or bracket-mounted purification systems that combine jet flow and vacuum suction for a synergistic effect.

The wet grid (Figure 6A) serves as the core component of mobile dust collector vehicles, using permeable, wetted filter media or grid structures coated with surface water films to remove particles.[76] As illustrated in Figure 6B, atomized droplets are used to wet or form a water film on the wet grid or filter media. As dusty airflow passes through the wet grid, dust particles contact the water film on its surface and are captured.[73] Subsequently, the cleaned moist airflow passes through demisting components, such as W-shaped baffle eliminators, to remove excess droplets.

Filtration velocity is a key factor affecting dust-removal efficiency and filtration resistance.[86] Figure 6C illustrates that dust-removal efficiency tends to be positively correlated with filtration velocity; that is, increasing filtration velocity increases the relative velocity between dust and droplets, which can improve dust-removal efficiency to a certain extent.[85] However, Figure 6D illustrates that increasing the filtration velocity significantly increases the filtration resistance.[85] When the filtration velocity increased from 2.5 m/s to 3.0 m/s, the filtration resistance increased by 47.3%-53.9%.[85]

To address the issue of high filtration resistance of wet grid dust-removal vehicles, the dust collection port structure was optimized to a parabolic shape,[65] achieving a 91.04% reduction in the pressure difference between the inlet and outlet. On this basis, a jet-assisted dust collection port was further proposed, where the dust-removal efficiency at 10 m behind the vehicle achieved 95.74% when the jet velocity reached 20 m/s.[65] Furthermore, a wet grid dust-removal vehicle was developed,[73] which coupled the exhaust outlet of the vehicle's diesel engine radiator with the suction of the axial-flow fan to form a dust-control zone on the excavation face. When the axial-flow fan frequency was 30 Hz and the filtration velocity was 3.34 m/s, the dust-removal efficiency was about 78.49%.[73]

For bracket-mounted purification systems, a wet dust catcher installed on the hydraulic support was developed to address severe dust dispersion during coal cutting and frame movement in the fully mechanized mining face.[76] It was found that when using a 2.4 mm X-shaped guide core with a wide-angle solid-cone nozzle and a spray pressure of 6 MPa, a high-quality water curtain could be formed in the cross-section, and the total dust-removal efficiency at the coal cutter position reached 86.20%. Moreover, because the dust concentration near the cutting head of the roadheader was up to 2,000 mg/m^3 and was mainly concentrated in the range of 3.5~13 m behind the roadheader, a five-stage external spray system was designed,[74] where the dust-removal efficiency reached 76.04%.

The above research indicates that whether it is the fully mechanized excavation in a tunnel or the mining face in a coal mine, the wet grid and local purification technology can effectively compensate for the shortcomings of traditional ventilation in near-source control and fine-dust removal, and significantly alleviate the high dust pollution at the excavation face.

Chemical dust suppressant technology

Dust particles are generally spherical, with rough surfaces and strong hydrophobicity. Contact angle is commonly used to characterize the wettability of dust particles. As illustrated in Figure 7A, a contact angle of 90° is the critical criterion for determining the wettability of dust particles.[87] When the

Table 2. Summary of technical parameters for efficient dust-removal technology.

Dust control technology	Core equipment/medium	Key parameters	Application scenario	Dust-removal efficiency	Refs.
Spray technology	• pressure cyclone atomization nozzle, press-in air duct	• nozzle aperture: 0.5 mm, spray pressure: 8 MPa, air-supply velocity: 10 m/s	• simulation experiment platform	• 85.2%	[67]
	• wide–angle solid conical nozzle, press-in air duct	• nozzle aperture: 1.9 mm, spray pressure: 8 MPa, spray angle: 30°, nozzle flow rate: 10.1 L/min	• nozzle: 20 m from excavation face, air-duct: 10 m from excavation face	• 80.7%	[68]
	• fine solid conical nozzle, press-in air duct	• nozzle aperture: 1.6 mm, spray pressure: 8 MPa, air-supply velocity: 9.61m/s	• nozzle: 1.2 m from excavation face, air duct: 10 m from excavation face	• 81.48%	[69]
	• internal mixing air-atomizing nozzle	• water-supply pressure: 0.5 MPa, air-supply pressure:0.4 MPa, mixing chamber length: 6 mm	• transfer point of fully mechanized excavation face	• 92.19%	[70]
	• supersonic coaxial aerodynamic atomizer	• nozzle aperture: 1.2 mm, air-supply pressure: 0.5MPa, nozzle flow rate: 0.0666 L/min	• simulation experiment platform	• 91.59%	[71]
	• fan-shaped atomization nozzle	• nozzle aperture: 0.28 mm, spray pressure: 4 MPa	• simulation experiment platform	• 86.64%	[72]
Wet grid and local purification technology	• wet string grid dust-removal vehicle, press-in air duct	• nozzle aperture: 2.0 mm, spray pressure: 0.6 MPa, air-supply volume: 1,824 m^3/min	• dust-removal vehicle: ~20 m from excavation face, air duct: 20 m from excavation face	• 78.49%, 95.74%	[65,73]
	• multistage atomization spray system, press-in air duct	• spray pressure: 4 MPa, nozzle flow rate: 9 L/min, air-supply volume: 285 m^3/min	• spray system: 3, 4, 10 m from excavation face, air duct: 10 m from excavation face	• 76.04%	[74]
	• wet-dry dual-purpose dust reduction device	• nozzle aperture: 2.4 mm round-orifice with X-shaped core, spray pressure: 7 MPa	• return airway of a fully mechanized excavation face	• 90.25%	[75]
	• wet dust catcher	• nozzle aperture: 2.4 mm X-type swirl core, spray pressure: 6 MPa	• hydraulic support of a fully mechanized mining face	• 86.2%	[76]
Chemical dust suppressant technology	• composite dust and toxic gas suppressant	• 0.0497% alpha-olefin sulfonate, 0.100% glucose, 0.115% isopropanolamine, 0.109% urea	• simulation experiment platform	• 84.3%	[77]
	• soy protein isolate-based gel foam	• 0.2% xanthan gum, 0.4% soy protein isolate, 0.15% transglutaminase, 1.0% dodecyl dimethyl amine oxide	• simulation experiment platform	• 98.42%	[78]
	• discrete foam composite	• 5% alpha-olefin sulfonate, 4% sodium dodecyl sulfate, 1% sodium tripolyphosphate, 2% cocamide diethanolamide, 0.6% sodium lignosulfonate	• simulation experiment platform	• 73.38%	[79]
	• cross-linked network dust suppression foam	• 0.5 % γ-polyglutamic acid, 1.0 % polyvinyl alcohol, 0.3 % ethylene glycol diglycyl ether, 1.0 % sodium dodecylbenzene sulfonate	• simulation experiment platform	• 98.5%	[80]
	• sawdust-based super absorbent dust suppressant	• acrylic acid, sawdust, 2-acrylamide-2-methylpropanesulfonic acid, ceric ammonium nitrate, N, N-methylene-bisacrylamide, moisturizer, dodecyl polyglucoside	• fully mechanized face	• 90.07%	[66]
	• sesbania gum-based dust suppression foam sol	• sesbania gum, 88% polyvinyl alcohol, 95% sodium trimetaphosphate, 6% hydrogen peroxide, 90% sodium dodecyl benzene sulfate, 90% octdecyl glucoside, 90% sodium fatty alcohol polyoxyethylene ether sulfate, 90% fatty alcohol polyoxyethylene ether	• outdoor spraying experiment of foam dust suppressant	• 97.7%	[81]

contact angle is less than 90°, dust particles are easily wetted by droplets, which improves dust-removal efficiency. However, the contact angle of droplets with dust particles is generally greater than 90°, indicating that they are difficult to wet effectively.[88]

As illustrated in Figure 7B, adding dust suppressants to pure water enhances the wetting of dust particles through physical or chemical reactions, thereby achieving bonding and filling of dust particles, forming a hard shell, and improving the dust-suppression effect.[80] Consequently, scholars have focused on developing high-performance chemical dust suppressants 89, aiming to enhance wettability, increase adhesion, and prolong dust-suppression duration to improve dust-removal performance.

In terms of chemical dust suppressants, researchers have developed multifunctional formulations that combine wetting, solidification, and toxicity-reduction functions through grafting copolymerization, compounding optimization, and natural material modification.[90,91] Recently, researchers developed a composite dust suppressant to fill the gap for chemical reagents that can simultaneously suppress dust and toxic gases.[77] Its removal efficiency for total dust and respirable dust was 84.3% and 70.4%, respectively, and its removal efficiency for CO and NO_2 reached 40.0% and 90.5%, respectively. In addition, a degradable, high-water-absorbency dust suppressant made from pine sawdust was prepared.[66] After applying this dust suppressant, the average dust-removal efficiency for total dust and respirable dust reached 90.07% and 85.43%, respectively, achieving high-value utilization of waste biomass resources.

Similarly, a polymer dust-suppression foam with a dual-enhanced network structure, prepared by glycosylation and transglutaminase cross-linking modification of soybean protein isolate, achieved a removal efficiency of up to 98.42% for PM10.[78] Furthermore, γ-polyglutamic acid and polyvinyl alco-

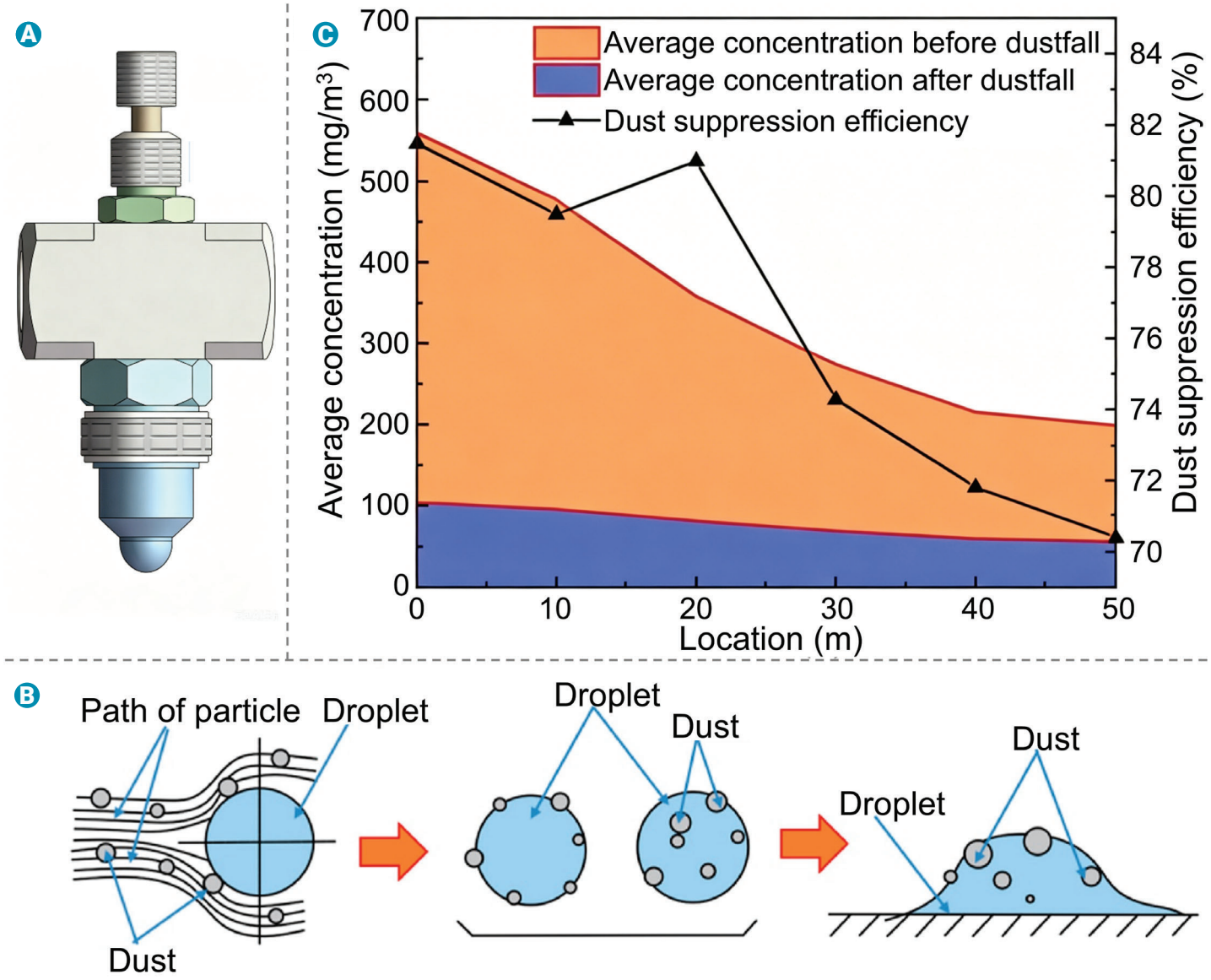


Figure 5. Spray dust suppression (A) Nozzle (Reproduced with permission from Ref. 70, Copyright 2026 Elsevier); (B) Interaction mechanism between droplets and dust particles (Reproduced with permission from Ref. 83, Copyright 2025 Elsevier); (C) Dust concentration at different distances from the excavation face and its spray dust-removal efficiency (Reproduced with permission from Ref. 69, Copyright 2023 Elsevier).

hol cross-linked with glycidyl ether of ethylene glycol were utilized to construct a dust-suppression foam with a three-dimensional network structure, where the removal efficiency of PM2.5 and PM10 reached 97.68% and 98.76%, respectively.[80] The uniformity and stability of the foam were superior to those of traditional surfactant systems.

In conclusion, chemical dust suppressants can significantly improve the wetting and consolidation capacity of hydrophobic dust by optimizing material composition and microstructure, providing a feasible technical path for efficient, long-term dust suppression in tunnels and underground engineering.

INTELLIGENT LOW-CARBON AIR-SUPPLY TECHNOLOGY

The air-supply system is one of the main sources of energy consumption in tunnel construction, demonstrating enormous energy-saving potential.[30] The previous chapter summarized how to efficiently control dust pollution at the excavation face from the perspective of end technologies, while this chapter summarizes how to achieve intelligent, low-carbon operation of air-supply systems from the perspective of system regulation, including energy-saving air-supply technology and intelligent air-supply control technology.

Energy-saving air-supply technology

As long-distance construction tunnels become more common, air-supply systems are becoming increasingly complex, and frictional and local resistance cannot be ignored. Consequently, the energy-saving air-supply technology deserves in-depth analysis. Current research on this topic mainly focuses on two aspects: new air-supply technology and maintenance management of the air-supply system.

Air-cabin air-supply technology. To address the air-supply challenges in the multi-workface concurrent construction of ultra-long tunnels, a new air-cabin air-supply system was proposed.[92] The principle is to install sealed air cabins within the tunnel to replace part of the air ducts, thereby increasing the air-supply cross-section and effectively overcoming the high ventilation resistance of a single air duct. Compared with the air-duct mode, the frictional resistance of the air-cabin air-supply system can be reduced by 47.04%, and the ventilation energy consumption can be decreased by 20.7%.[93]

Subsequently, parameters such as the length of the air cabin or partition and the layout of the fans were optimized, achieving a 13.3% improvement in ventilation efficiency.[94,95] Compared with the arched-partition air cabin, the total pressure difference of the full-section air cabin was 36% larger, and the ventilation efficiency was 14% higher.[96] Furthermore, for the scenario of full-section air supply and exhaust in tunnels, the spacing between jet fans has a significant impact on the pollutant dispersion and the energy consumption of fans, where the annual energy savings achieved 950.4-1900.8 MWh under a

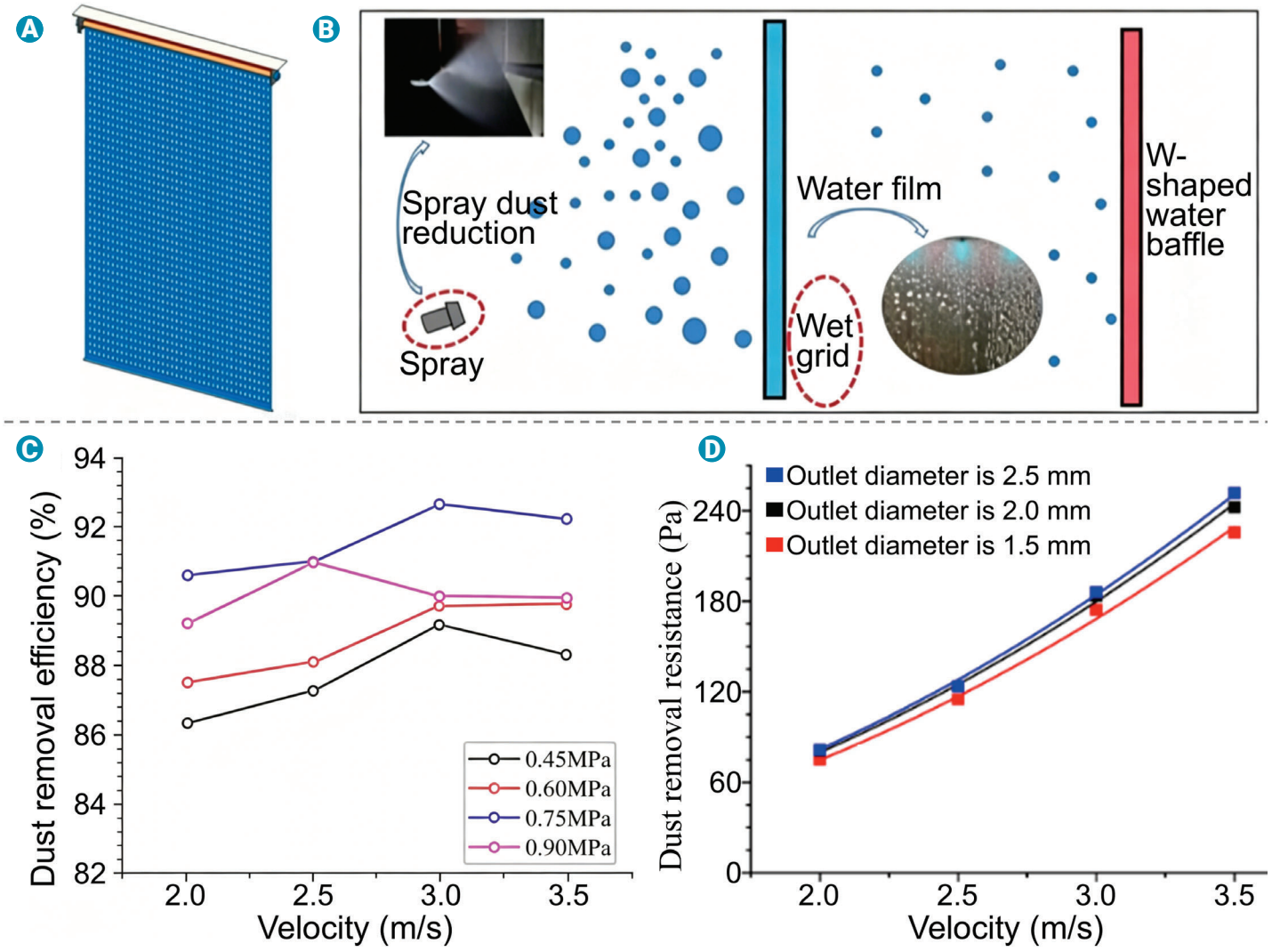


Figure 6. Wet grid technology (A) Wet grid (Reproduced with permission from Ref. 76, Copyright 2024 Elsevier); (B) Dust-removal mechanism of wet grid;[73] (C) Dust-removal efficiency under different filtration velocities (Reproduced with permission from Ref. 85, Copyright 2021 Elsevier); (D) Filtration resistance under different filtration velocities (Reproduced with permission from Ref. 85, Copyright 2021 Elsevier).

600 m spacing between jet fans.[97]

Dual-tunnel complementary air-supply technology. In addition, the dual-tunnel complementary air-supply technology was proposed for long-distance construction tunnels. This technology uses cross-passageways between the two parallel tunnels to transfer surplus fresh air from the tunnel with lower air demand to the tunnel with higher air demand, achieving air-volume complementarity. This reduces total fan energy consumption and demonstrates significant potential for energy conservation. Recently, a study examined the feasibility and parameter influence of dual-tunnel complementary air supply using bidirectional four-, six-, and eight-lane tunnels as the research objects.[98] The results showed that the bidirectional six-lane tunnel met the complementary air-supply characteristics and could transfer surplus airflow from the small air-demand tunnel to the large air-demand tunnel, thereby reducing fan energy consumption on the large air-demand side.

Maintenance management of the air-supply system. Moreover, efficient installation and maintenance of fans and air ducts are key technologies for ensuring the actual performance of the air-supply system. For tunnel construction using the drilling-blasting method, installation and maintenance techniques for air ducts, such as pre-installed straps or pre-drilled holes for air-duct adapters, can effectively prevent air leakage at connection points or air-duct rupture due to excessive wind pressure.

In conclusion, future research and development of tunnel construction energy-saving air-supply technologies should focus on structural optimization of air cabins, dynamic matching of dual-tunnel complementary air supply, and standardization of air-duct installation and maintenance processes. This will maximize energy conservation and reduce consumption while ensuring construction safety and a safe working environment, promoting sustainable development.

Intelligent air-supply control technology

Because the demand for air-supply volume at the excavation face varies dynamically with construction dust intensity, real-time adaptive intelligent control technology for the air-supply system is particularly significant. With the development of Internet of Things (IoT),[99] Artificial Intelligence (AI),[100] and big data technologies, air supply in tunnel construction is gradually shifting from the traditional constant air-volume mode to an intelligent, low-carbon direction, aiming to achieve on-demand air supply, precise control, and energy consumption optimization.

Environmental parameter identification and prediction. The core element of intelligent air-supply control lies in accurately acquiring and predicting environmental parameters at construction site.[101] To address this, researchers have focused on issues such as sparse sensor layouts, incomplete monitoring data, and the difficulty of accurately predicting pollutant concentrations at construction sites. A dimensionality reduction reconstruction method combining principal component analysis and Gaussian process regression was proposed.[102] By optimizing the placement of only five sensors, the global dust-concentration field can be reconstructed with high accuracy, with a calculation time of merely 0.28% of traditional CFD (Computational Fluid Dynamics) simulations.

Furthermore, an improved Kolmogorov-Arnold Network-iTransformer

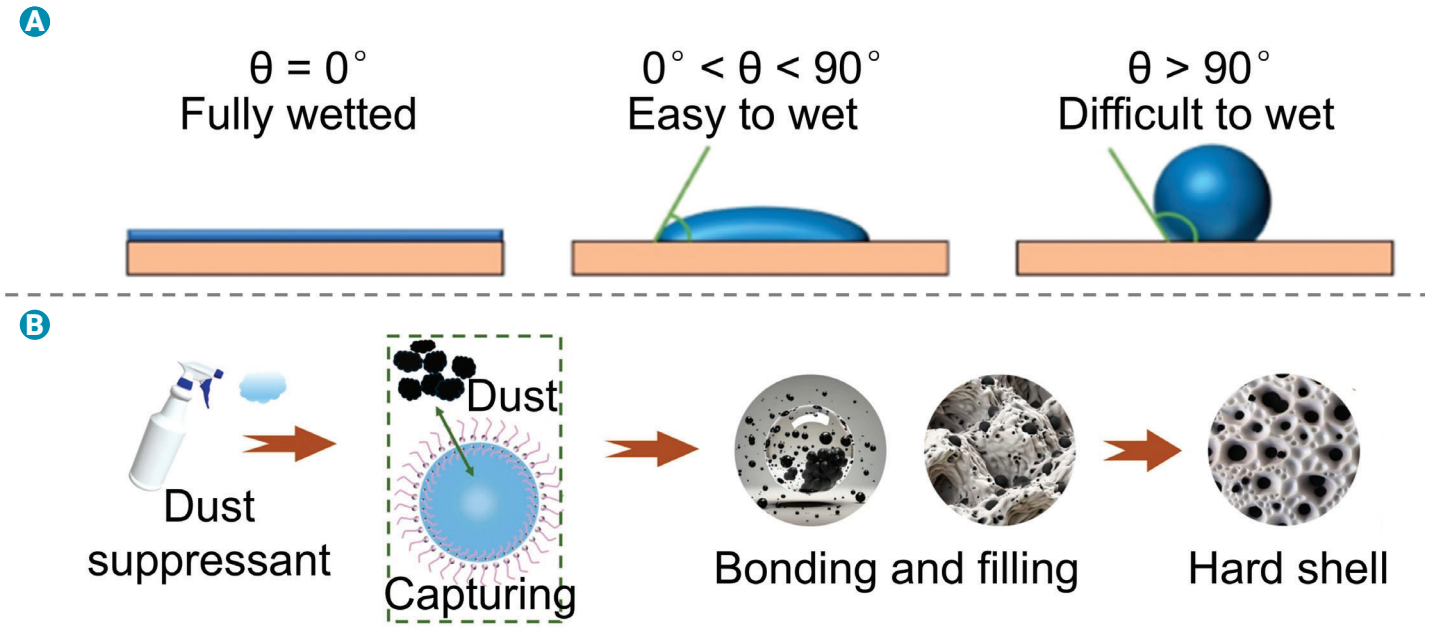


Figure 7. Dust suppressant technology (A) Relationship between contact angle and wettability (Reproduced with permission from Ref. 87, Copyright 2024 Elsevier); (B) The mechanism of dust suppressants (Reproduced with permission from Ref. 80, Copyright 2025 Elsevier).

model was proposed to intelligently predict the pollutant concentration.[103] By introducing the learnable kernel function of the Kolmogorov-Arnold Network and a graph attention mechanism to encode the spatial topological relationship of sensors, the mean square error in single-step gas concentration prediction was low, and the determination coefficient reached 0.916. In addition, a STA-CNN-ResBiLSTM hybrid model was constructed,[104] integrating the spatio-temporal attention mechanism and the residual bidirectional long short-term memory network. The root mean square error of the predicted pollutant concentration during the tunnel construction period was reduced by 23.1% compared to the baseline model.

Air-supply system control strategy. The second core element of intelligent air-supply control lies in formulating intelligent, low-carbon control strategies for the air-supply system based on perception and prediction information. One study combined CFD simulation with PID (Proportion Integration Differentiation) control to achieve dynamic closed-loop regulation of air-supply volume, effectively overcoming the sparse data and low control accuracy of traditional monitoring systems.[105] Based on the BP neural network, the deep Q-network reinforcement learning algorithm was employed to construct a high-fidelity simulation environment and achieved adaptive-optimization control of the mine-ventilation window angle, significantly enhancing the regulation stability of gas and dust concentration.[106]

In addition, based on the double-layer bidirectional long short-term memory algorithm model, the pollutant concentration was dynamically predicted, and the required air-supply volume was dynamically adjusted accordingly. This not only ensured the pollutant-removal efficiency but also reduced the fan energy consumption by 64.6%.[107] Moreover, a ventilation intelligent frequency control system based on a radial basis function neural network was developed, which directly established the nonlinear mapping between fan operating frequency and multiple environmental parameters, including gas concentrations, tunnel length, and temperature. Field application in the Huayingshan tunnel demonstrated a 42% reduction in electricity consumption compared to manual control, with estimated total savings of approximately 1,426 MWh.[108]

In summary, current research on intelligent air-supply control focuses on two major aspects: "environmental parameter identification and prediction" and "air-supply system control strategies", covering the entire technical chain from construction-site data acquisition, concentration prediction, to control decisions and energy-efficiency optimization. This has jointly promoted the development of tunnel construction air-supply technology toward intelligence, refinement, and low-carbonization, laying a solid theoretical and technical foundation for building an integrated "perception-prediction-decision-control" intelligent air-supply system.

SUMMARY AND PERSPECTIVES

This study systematically reviews recent advances in ventilation and dust removal in tunnel construction, focusing on three interconnected themes: ventilation and dust-removal performance, efficient dust-removal technologies, and intelligent, low-carbon air-supply strategies. Based on the preceding literature analysis, the following primary conclusions are drawn:

(1) Dust dispersion and Tunnel geometry: Dust dispersion during tunnel construction exhibits significant particle-size sorting and strong dependence on tunnel geometry and airflow organization. Coarse particles (>30 μm) tend to settle under gravity, while fine particles (<10 μm) can remain suspended for prolonged periods and be transported over greater distances. In spiral tunnels, a smaller curvature radius is more conducive to organized dust transport and discharge, while in V-shaped tunnels, the dust may exhibit a fluctuating decline rather than the monotonic decrease typically observed in straight tunnels, with localized high-concentration zones potentially forming near the beginning of uphill sections. The ventilation and dust-removal performance is governed by the coordination of ventilation methods, air-duct layout, and air supply volume. Notably, hybrid ventilation systems equipped with air curtains can enhance dust confinement and removal near the excavation face. Operationally, the reported effective distance between thepress-in air-duct outlet and the excavation face typically ranges from 10 to 70 m, whereas the exhaust inlet should be maintained within 5 m of the face.

(2) Efficiency of suppression technologies: The application of spray systems, wet-grid purification, and chemical dust suppressants can enhance the capture of fine dust, effectively improving overall dust-control performance during tunnel construction. These technologies are particularly valuable where ventilation alone is insufficient, such as long-distance or high-intensity construction environments. The dust-removal efficiencies of spray and wet-grid purification technologies are comparable, with reported median values of approximately 85%, whereas chemical dust suppressants show higher median removal performance, approaching 94% under the reviewed conditions. However, their performance varies substantially with formulation, application method, and operating conditions, indicating that direct comparison across studies should be interpreted cautiously.

(3) Energy optimization and intelligent control: Energy-efficient air-supply systems and intelligent control strategies provide substantial potential to improve ventilation efficiency while reducing energy use and associated carbon emissions. Air-supply technologies such as air-cabin ventilation and dual-tunnel complementary ventilation can reduce ventilation resistance, and

with air-cabin systems reporting ventilation energy savings of approximately 20.7%. Furthermore, the integration of intelligent algorithms for dynamic airflow regulation facilitates a transition from constant-rate to on-demand, precision air supply. Demand-responsive control strategies have achieved fan-energy reductions of up to 64.6% in the reviewed studies, highlighting the potential of integrated sensing, prediction, and adaptive control for low-carbon tunnel construction.

Despite these advances, several critical research gaps remain and should be addressed to support the development of safer, more efficient, and lower-carbon tunnel-construction environments:

(1) Complex multi-scenario modeling: Future research should investigate dust dispersion characteristics and optimize ventilation parameters across complex, multi-variable and coupled environments, including spiral alignments, large longitudinal slopes, V-shaped tunnels, inclined shafts, and high-altitude conditions. Greater emphasis should be placed on the interactions among geometry, altitude, thermal conditions, construction equipment, dust-generation intensity, and time-varying ventilation conditions rather than examining these factors in isolation.

(2) Coupled control strategies: Further investigation is required to develop coupled dust-control strategies that integrate main ventilation systems with auxiliary technologies, such as spray systems and local purification devices, to establish multilevel, synergistic control frameworks. Future studies should optimize these technologies jointly rather than independently, with the objective of simultaneously minimizing dust exposure, airflow demand, and ventilation energy consumption.

(3) Economic synthesis of chemical suppressants: The widespread industrial application of chemical dust suppressants is currently hindered by complex formulations, preparation requirements, and potential application costs. Developing efficient, economically viable preparation methods that balance high dust-control performance with material and application costs is essential. Future work should also evaluate long-term stability, environmental compatibility, reusability or biodegradability where relevant, and performance under realistic tunnel conditions to facilitate field-scale adoption.

(4) Digital twins and predictive algorithms: There is a significant demand for high-precision data acquisition frameworks and real-time predictive algorithms for pollutant monitoring at the excavation face. Future research should integrate distributed sensing, rapid pollutant-field reconstruction, predictive models, and closed-loop ventilation control within digital-twin frameworks. Such systems could enable real-time prediction of pollutant dispersion, adaptive air-supply regulation, and coordinated dust-removal control, providing a pathway toward fully integrated "perception–prediction–decision–control" systems for smart tunnel construction

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The authors declare no competing interests.

DATA AND CODE AVAILABILITY

No primary research results, software or code have been included, and no new data were generated or analyzed as part of this review.