Techniques for Suppressing Mineral Dust Aerosol from Raw Material Stockpiles and Open Pit Mines: A Review

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ABSTRACT

About 50% of the global aerosol is mineral dust, part of which originates from industrial stockpiles. Mineral dust aerosol adversely affects the environment, public health, occupational safety, and productivity. The propensity of mineral aggregates to emit dust depends on particle size distribution, specific gravity, moisture content, storage conditions, and abrasion forces. In conventional stockpiles, the tendency to produce mineral dust is higher in coal and coke than in other material aggregates such as limestone, gypsum, iron ore, magnetite, and bauxite. Industries with notable mineral dust production capture and suppress dust using dry and wet techniques to curb nuisance and attain air quality regulations. Wet techniques are more versatile than dry methods for large stockpiles requiring constant loading and offloading. Chemical agents, including organic biopolymers, chemical surfactants, and inorganic, have higher dust suppression efficiency than plain water due to higher hygroscopicity and agglomeration potentials. So far, hybrids of biopolymers and chemical surfactants have the highest dust suppression efficiencies (up to 99%). Nevertheless, there is skepticism about adopting hybrid surfactants due to insufficient knowledge of environmental impacts and hazards to human health.

Keywords: Mineral dust aerosol, Dry techniques, Wetting techniques, Surfactants, Suppression efficiency

1 INTRODUCTION

About 1–5 billion tons of global aerosol is mineral dust (Lian et al., 2022). This represents 50% of the total global dust emissions. Significant proportions originate from industrial mineral stockpiles during material handling activities such as loading, offloading, separation, comminution, and aeolian cycles on exposed material piles, where threshold friction velocities for the predominant portion of mineral dust measuring < 30 µm are 6–7 m s⁻¹ (Sweeney, 2020). Since it is a high-priority emission source, adopting primary (proactive) and secondary (active) methods for dust suppression is essential to prevent health hazards, meet safety standards, and reduce nuisance (Anlimah et al., 2023). Typical mineral aggregates include coal, coke, limestone, ferrite ores, non-ferrite metal ores, bauxite, phosphate, gypsum, lithium, zinc, and potash (Mutuku et al., 2021). They are commonly
applied in coal-fired power plants (Kim and Sohn, 2016), and ferrite (Tang et al., 2016) and non-ferrite (Wong et al., 2012) smelting industries. Their dust emission potential depends on the scale and length of operation and activities in the stockpile and properties of the mineral aggregates.

Inhalation of coal mineral dust aerosol causes pneumoconiosis (Borowski et al., 2020) and induces acute inflammation and apoptosis in the liver and spleen (Della Guardia and Shin, 2022). Exposure to silica dust causes fibrosis and cancer (Li et al., 2021). Furthermore, mineral dust aerosols adsorb and promote the transport of harmful substances, including potentially toxic elements (PTEs), persistent organic pollutants (POPs), and biological pathogens (Lü et al., 2019). Increased mineral dust aerosols correlate positively with cardiovascular and respiratory complications, including recent association with COVID-19 (Broomandi et al., 2022). Besides adverse health effects, mineral dust causes other adverse effects, including nuisance and explosions. Nuisance dust reduces environmental amenities, damages machinery, and diminishes visibility. Explosive dust belongs to two categories: organic dust, whose threshold concentration for an explosion is 500 g m⁻³ (Cheng et al., 2022), and metal dust, whose threshold for deflagration is 1500 g m⁻³ (Guo et al., 2022). Consequently, the Occupational Safety and Health Administration (OSHA) particulate matter (PM) permissible exposure limit (PEL) is 50 µg m⁻³ for an 8-hour shift (Li et al., 2020a), and the recommended exposure limit (REL) for PM is 1 mg m⁻³. A summary of the adverse effects of mineral dust is provided in Table 1, where respiratory difficulties, allergic reactions, skin damage, and inflammation response are the most common.

Economic losses due to mineral dust emissions are complex and multifaceted with specific costs for healthcare, productivity losses, environmental implications, crop damage, aesthetics, infrastructure, and tourism. The healthcare burden of diseases is perhaps the most significant cost (Entwistle et al., 2019). A detailed economic impact assessment is unique to industries and region for instance, in Eastern Mongolia the total local cost of a dust storm on 26–27th of May 2008 was $ 0.46 Million (Jugder et al., 2011). In the red dawn dust storm on the 23rd of September 2009 in New South Wales, Australia, the cost was $219 million (Tozer and Leys, 2013).

The most important phenomenon for mineral dust transportation is geophysical resuspension involving wind action due to deflation, saltation, and disintegration (Ishizuka et al., 2008). It occurs when the uplift force on mineral dust exceeds binding capacity due to gravitational. The particle size distribution for mineral dust aerosols indicates that particles with diameters > 30 µm make a more significant proportion and usually deposit 100 m within the emission source (Martuzevicius et al., 2011). Particles of sizes ranging from 10–30 µm deposit 200–500 m from the emission source, while particles < 10 µm remain airborne for long and might undergo long-range transportation (Jänhäll, 2015). Therefore, dust suppression devices should be within 100 m of the emission source, to increase their impact.

Adopting dust suppression techniques at all stages of mineral aggregate disintegration is essential to combat the adverse effects of amplified mineral dust emissions. This is achieved by

<table>
<thead>
<tr>
<th>Dust Impacts</th>
<th>Classification of Adverse Effects</th>
<th>Evaluation/Quantification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental</td>
<td>Nuisance</td>
<td>Color contrast between deposited dust and surrounding</td>
</tr>
<tr>
<td></td>
<td>Influence to ecology</td>
<td>Ambient air concentration, particle-size distribution, deposition and chemistry</td>
</tr>
<tr>
<td></td>
<td>Influence to agriculture</td>
<td></td>
</tr>
<tr>
<td>Human Health</td>
<td>Damage to the respiratory system</td>
<td>Concentrations in comparison to OSHA, PEL, and REL</td>
</tr>
<tr>
<td></td>
<td>Allergic reactions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Damage to the skin</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Irritation and inflammatory response</td>
<td></td>
</tr>
<tr>
<td>Safety and Prouductivity</td>
<td>Visibility in work place</td>
<td>Opacity</td>
</tr>
<tr>
<td></td>
<td>Explosions</td>
<td>Concentration of combustible dust</td>
</tr>
<tr>
<td></td>
<td>Minimize productivity</td>
<td>Worker’s output and labor supply</td>
</tr>
<tr>
<td></td>
<td>Product damage</td>
<td>LCA, product quality</td>
</tr>
</tbody>
</table>
Fig. 1. VOSViewer map presenting term co-occurrence map for literature in fugitive dust suppression found using keywords: Particulate matter, dust; capture, and suppression.

primary and secondary dust suppression methods that apply dry and wet techniques. Wetting techniques for dust suppression are more popular due to their efficiency, versatility, and cost-effectiveness (Xu et al., 2018). Previous reviews on dust suppression have focused on road and street dust, indoor PM (Anlimah et al., 2023), and dust emissions from mining activities (Petavratzi et al., 2005). This paper reviews the current status of dust suppression for mineral dust released from aggregate mineral stockpiles, which remains primarily overlooked, as indicated by the less literature on suppression and wettability in Fig. 1, despite the significant contribution of stockpiles to the global mineral dust budget. It highlights essential perspectives on dust suppression techniques for mineral aggregate stockpiles and current techniques that will affect future trends.

2 METHODS

2.1 Literature Search

A systematic and exhaustive search was performed on the Web of Science and Google Scholar using the following search terms, mineral dust, aerosol, capture, and suppression. Herein, journal papers published between 2000 and 2022 in the databases were included with no restrictions regarding spatial coverage.

2.2 Criteria for Selecting Journal Articles

The screening process applied the title, abstract, and full text based on the number of times
the search words were repeated in the texts. This investigation used a union of at least two search words to identify the papers included in this review. Studies that investigated dust suppression in underground mines were excluded. Before inclusion, the full manuscripts were assessed to ensure they primarily focused on suppressing mineral dust aerosol.

2.3 Data Extraction, Analysis, and Presentation

To summarize the properties of mineral dust aerosol from typical raw material stockpiles, the following information was extracted from the journal papers, including raw material, dust composition, particle size range, specific gravity, and dust impacts. To understand the performance of different wetting mechanisms, the data extracted from journal papers included location, particle size, the chemical composition of the wetting agent, spraying mechanism, consolidation layer strength, and suppression efficiency. Data analysis focused on the raw material aggregates with the highest propensity for dust suppression and the dust suppressants with the highest efficiencies.

3 ESSENTIAL FACTORS IN MINERAL DUST AEROSOL CONTROL

Stockpiles are either elevated conic (height to base ratio > 2) (Cong et al., 2012) or flat-topped (height-to-base ratio ≤ 2) (Turpin and Harion, 2009), as presented in Fig. 2. This affects the surface area open to external environmental factors and consequently influences the concentration of dust emitted. Specifically, flat-topped stockpiles emitted 13%–60% less mineral dust aerosols than conical stockpiles (Cong et al., 2012). This is mostly due to the higher angle of repose attained by flat-topped than the elevated conic stockpiles (Beakawi Al-Hashemi and Baghabra Al-Amoudi, 2018). In practice, industrial raw material storage sites have multiple stockpiles and their arrangement is critical because the topography modifies the near-field uptake force of the wind through changes in mean flow.

Fig. 2. Schematics indicating (a) an elevated conic and (b) a flat-topped stockpile.
Other parameters determining the concentration of dust emitted include properties of the environment surrounding the stockpiles, such as temperature and wind speed; surface conditions (Lee et al., 2022a), such as exposure to sunlight, UV, and ground-level ozone; and surface loadings (Figgis et al., 2018). The intrinsic and extrinsic properties of the mineral aggregates, such as material hardness, specific gravities, particle size distribution, shape, moisture content, and size of weathered or oxidized surfaces, also affect the concentration of dust emitted from stockpiles. Typical mineral aggregates and properties of their respective dust are presented in Table 2. The specific gravities are inversely proportional to their propensity for dust emission, whereby coal and coke dust have the highest propensity for dust formation. Lastly, handling activities, such as the drop from height, affect the properties of mineral dust aerosol released.

Overall, mineral dust is less complex than dust emissions from chemical processes such as combustion, granulation, and precipitation. The average density for mineral dust particles is 2.65 g cm^{-3}, and the mineral dust aerosol with diameters > 30 µm deposits on the surface soon after suspension unless its original resuspension altitude is high (Adebiyi et al., 2023). Naturally, stockpiles are limited reservoirs, implying that suspendable dust is depleted exponentially without direct abrasion forces. However, continuous disturbance of stockpiles creates unlimited reservoirs that emit mineral dust aerosols whenever the aerodynamic forces exceed the threshold suspension level (Yen et al., 2023).

Understanding the fundamental separation forces is critical in evaluating the propensity of raw material aggregates to form dust during transportation, handling, or processing (Petavratzi et al., 2005). Experimentally, estimations are determined using surface loadings and dustiness indices. Surface loadings are determined by vacuuming specific areas on stockpiles and calculating the mass of dust emissions per unit area. The dustiness index is assessed by the concentration of dust emitted from a unit mass of the mineral aggregates. In the laboratory, dustiness is evaluated through a single drop test, fluidization test, or rotating drum test (Chakravarty et al., 2019).

Several factors determine the choice of dust suppression technique, including the clearance and degradation mechanisms, the volume of parent material, the layout of the material storage site, prevailing parameters, the relative fractions of erodible (< 2 mm) to non-erodible (> 2 mm) particles, the potential impact of the dust, and dust suppression effectiveness (Xie et al., 2022). Methods for assessing dust suppression include wind tunnel tests and direct shear tests of the cemented crust layer (Song et al., 2020; Sun et al., 2021), consolidation layer strength and permeability (Zhou et al., 2023a), surface tension and contact angle (Liang et al., 2022), water retention, dust fixation efficiency and anti-wind erosion (Hu et al., 2020), and wind reduction ratio (Duan et al., 2023). In an investigation by Yen et al. (2023), dust fixation efficiencies were monitored for 1 hour, averaging 80% for a conventional sprinkler and 87% for a fog cannon.

### Table 2. Properties of mineral dust emissions from typical raw material stockpiles.

<table>
<thead>
<tr>
<th>Raw Material</th>
<th>Dust Composition</th>
<th>PM Size (µm)</th>
<th>Environmental Effects</th>
<th>Health Effects</th>
<th>Specific Gravity</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal, coke</td>
<td>C, other minerals</td>
<td>1–100</td>
<td>Flammable, explosive</td>
<td>CWP, COPD</td>
<td>1.3–1.5</td>
<td>(Azam and Mishra, 2019)</td>
</tr>
<tr>
<td>Limestone</td>
<td>CaCO_{3}</td>
<td>1–100</td>
<td>–</td>
<td>Highly toxic, Silicosis, cancer</td>
<td>2.2–2.8</td>
<td>(Karaşahin and Terzi, 2007)</td>
</tr>
<tr>
<td>Gypsum</td>
<td>CaSO_{4}</td>
<td>1–100</td>
<td>–</td>
<td>Not highly toxic, COPD</td>
<td>2.2–2.4</td>
<td>(Abdul-Wahab et al., 2005)</td>
</tr>
<tr>
<td>Iron ore</td>
<td>FeO, Fe_{2}O_{3}</td>
<td>1–100</td>
<td>soil and water contaminant, impacts terrestrial life, nuisance</td>
<td>Abrasive, Pneumoconiosis</td>
<td>3.4–4.7</td>
<td>(Upadhyay et al., 2010)</td>
</tr>
<tr>
<td>Magnetite</td>
<td>FeO, Fe_{2}O_{3}</td>
<td>1–100</td>
<td>–</td>
<td>–</td>
<td>4.64</td>
<td>(Sivríkaya and Arol, 2013)</td>
</tr>
<tr>
<td>Bauxite (aluminium)</td>
<td>SiO_{2}, FeO(OH), Al_{2}O_{3}, trace elements</td>
<td>1–100</td>
<td>–</td>
<td>–</td>
<td>3.2–3.7</td>
<td>(Gore et al., 2016)</td>
</tr>
</tbody>
</table>

CWP represents Coal Workers' Pneumoconiosis.
COPD represents Chronic obstructive pulmonary disease.
4 SUPPRESSION TECHNIQUES FOR MINERAL DUST AEROSOL FROM INDUSTRIAL STOCKPILES

This review covers 81 papers whose common most fundamental insight is evaluating the performance of dust suppression systems. Criteria for selecting the papers here include those published since 2000 and there was no scope in terms of spatial locations and dust suppression techniques.

Dust suppression applies primary and secondary approaches, where wet and dry techniques are adopted (Liu et al., 2021). Primary methods are proactive and suppress the dust at the source using covers and wind collection systems such as bag filters or cyclones (Noble et al., 2017). On the other hand, secondary methods are active and collect the already emitted dust using electrostatic precipitators (ESP), barriers/screens, and ventilation systems to control airflow and remove dust (Shi et al., 2022). Dry techniques exclude fluids in their dust suppression mechanisms, while wet approaches apply moisture to suspended dust, weighing it down and causing deposition. Herein, dry and wet techniques for dust suppression are discussed, focusing more on the latter due to their popularity and versatility.

4.1 Dry Approaches for Suppressing Dust

Dry approaches apply chutes, collectors, screens, covers, bag houses, and cyclones to contain dust from mineral aggregates (Chen et al., 2018). They are commonly used in material-handling machinery like loaders and conveyors. Several factors determine the choice between wet and dry dust suppression mechanisms, including water scarcity and the effect of moisture content on the mineral handling processes. Ventilation through cyclones is one of the most common dry dust suppression techniques.

There are two forms of ventilation systems applied for mineral dust control. The first approach involves dilution, while the second approach involves displacement, where dust is confined to the source and put downwind of the region where it is unlikely to result in human exposure (Wang et al., 2017). The involute, tangential and spiral cyclone dust collectors presented in Fig. 3(a), are among the most widely adopted ones, with the former having the highest dust suppression efficiencies among the three as seen in Fig. 3(b) (Wu et al., 2023). Covers effectively suppress dust in construction and industrial raw material storage sites. However, they are impractical for large stockpiles requiring constant loading and offloading.

4.2 Wetting Techniques for Suppressing Dust

Wetting techniques use plain water, as seen in Fig. 4, chemical solutions, and foams to form adhesive forces, including van der Waals, electrostatic forces, and surface tension of adsorbed liquid films to increase the minimum energy needed to entrain the particles (Gao et al., 2023). Depending on the size of the droplets applied for dust suppression and the physical state of the liquid used, mechanical systems for dust suppression are categorized into atomized water sprays seen in Fig. 5(a), electrostatically charged fogs, high-pressure sprays, and foams. Overall, supersonic siphon sprays have higher dust suppression efficiencies than ultrasonic dust suppression, as seen in Fig. 5(b). Secondary methods of fugitive dust suppression aggregate suspended particles and weigh them down, causing successful dust suppression (Faschingleitner and Hoflinger, 2011). They also reduce primary dust emission by agglomerating dust particles through capillary action, increasing their aerodynamic diameters and thus reducing their propensity for suspension (Lee et al., 2019b). The aggregation of tiny dust particles forms larger particles, increasing surface roughness and decreasing wind speeds at the surface of the stockpiles. This leads to higher shear resistance of solid particles, which reduces their tendency to saltation.

The wetting techniques’ efficiencies are determined by the type of material, properties of the PM, the form of the wetting technique, and prevailing weather conditions. They are more commonly applied to suppress coal dust than other mineral aggregates due to their low cost, convenient operation, and practicability, as presented in Table 3 (Wang et al., 2019). Successful collisions between water droplets and dust are higher for mist systems than conventional sprinklers, hence their higher dust suppression efficiencies (Lee et al., 2022b). The efficiency of air and water spraying
techniques on dust suppression efficiencies was 93% compared to plain water, whose efficiency was 42% (Prostański, 2013). In addition to adhesive forces that bind dust particles, some surfactants apply droplets with electrostatic charges to suppress PM with surface charges. Strong winds limit the spans of dust suppression plans by changing the trajectories of spray droplets. In addition, hot and dry environments cause excessive evaporation, limiting dust suppression efficiencies. Therefore, structural optimization and optimal operation conditions for the pressure nozzles are critical for ensuring adequate coverage of stockpiles (Huang et al., 2021).

Surface wetness is critical for dust suppression in construction sites, where for moisture content of 1%, 2%, and 3%, peak dust concentration relative to dry conditions is reduced by 37%, 40%, and 65%, respectively (Zhang et al., 2022). Chutes are mainly applied during handling processes such as crushing and screening, creating a curtain of atomized droplets around a specified area to contain dust. The overall dust suppression efficiencies of spraying techniques range between 51%–100%, where the efficiencies vary with the particle size distribution of the PM, wetting agent, and spraying mechanism. During mineral dust suppression, wetting techniques introduce difficulties in handling raw materials, whereby wet fine dust sticks on conveyor belts and high moisture content lower the heating value of coal (Lee et al., 2022b). According to investigations conducted in Taiwan and China, the suppression efficiencies of coal mineral dust with plain water as the wetting agent range from 71%–88%, as seen in Table 3 (Zhang et al., 2019; Yen et al., 2021; Lee et al., 2022b). For iron ore, the suppression efficiencies using plain water range from 73%–76%,
and dry fog range from 51%–90%, depending on the particle size distribution as summarized in Table 3 (Saurabh et al., 2022; Lee et al., 2022b).

Because of the mentioned drawbacks of water as an ineffective binder, it is necessary to adopt chemical wetting agents to improve dust suppression efficiencies. Chemical agents applied for dust suppression are classified into humectants, hygroscopic, agglomerates, and surfactants. Humectants retain moisture; like aloe vera, hygroscopic agents absorb moisture from the surrounding ambient air, and agglomerates attract smaller particles together (Jia et al., 2021). Calcium magnesium acetate is a typical agglomeration agent with hygroscopic properties that bind fine dust particles together to prevent suspension (Volkov et al., 2023). Surfactants reduce the surface tension of wetting agents, facilitating penetration in deep voids within the aggregate matrices, where they suppress dust through wetting, surface coating, and agglomeration (Tang et al., 2016). The evolution of chemical agents applied as surfactants is provided in Fig. 6(a). Key drawbacks for most of these wetting agents include inadequate dust suppression efficiency, lack of compliance with sanitary and hygienic requirements, complex preparation methods, corrosive effects on equipment, high cost, insufficient knowledge of their impacts on humans, and low biodegradability (Tang et al., 2016; Zhou et al., 2023a). Furthermore, the wettability of hydrophobic dust particles such as coal, silica, and graphite is problematic, so nonionic and ionic surfactants have been adopted (Shi et al., 2021). Chemical wetting agents are classified into three classes based on their chemical properties: organic dust suppressants, biopolymers combined with chemical agents, and inorganic dust suppressants, as seen in Fig. 6(b).

4.2.1 Organic wetting agents

Plain water as a wetting agent has the drawback of quick drying and therefore requires frequent application for acceptable performance (Lee et al., 2019b). Naturally available biopolymers, including lignosulfonates, starch, xanthan, guar, and chitosan, are compatible with water and are used to prolong the moisture retention capability in water (Dang et al., 2017; Lee et al., 2019b; Chang et al., 2021). Their most significant advantage is biodegradability. Furthermore, they are compatible with water since their viscosity at room temperatures is comparable to liquid water at 1 mPa s at 20°C (Lee et al., 2019b).
Lignosulfonates are a mixture of lignin from woody biomass and sulfite compounds such as CaSO₃, NaSO₃, or MgSO₃ (Liu et al., 2018a). It is a byproduct of the sulfite pulping process. It suppresses fugitive dust through hygroscopicity and agglomeration. Starch is also a popular hydrophilic biopolymer that suppresses dust through hygroscopicity and agglomeration (Hu et al., 2020). A polymer suppressant formed by combining starch with acrylic acid and acrylamide reduced water loss by 87% compared to pure water for a wind speed of 15 m s⁻¹, temperature of −12–50°C and a duration of 3 hours (Lai et al., 2011). Oxidized corn starch-gelatin-based suppressant (OCS-gel) had 68% and 79% suppression efficiencies for PM₂.₅ and PM₁₀, respectively (Dang et al., 2017). This suppressant has a higher tolerance for a wide range of pH and salinity than the earlier polymer dust suppressant. Guar gum contains D-mannose chains attached to D-galactose in its chemical structure, making it a potential soil stabilizer that prevents dust emission through the primary mechanism (Zhang et al., 2018). Chitosan is a biopolymer obtained from chitin that agglomerates with dust particles and forms a protective layer for underneath dust particles against wind erosion. An ammonium salt obtained using chitosan N-(2-hydroxyl) propyl-3trimethyl...
<table>
<thead>
<tr>
<th>Type of dust</th>
<th>Location</th>
<th>PM Size</th>
<th>Wetting agent</th>
<th>Spraying mechanism</th>
<th>Consolidation layer strength (kPa)</th>
<th>Wind speed (m s⁻¹)</th>
<th>Suppression efficiency (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>coal</td>
<td>China</td>
<td>-</td>
<td>Cellulose + polyvinyl alcohol + polyacrylamide</td>
<td>-</td>
<td>42.3 KPa higher than pure water</td>
<td>10</td>
<td>&gt; 90</td>
<td>(Zhou et al., 2023a)</td>
</tr>
<tr>
<td></td>
<td>Taiwan</td>
<td>TSP, PM₁₀, PM₂.₅</td>
<td>water</td>
<td>Mist generator</td>
<td>-</td>
<td>1.6–10.7</td>
<td>77–81</td>
<td>(Lee et al., 2022b)</td>
</tr>
<tr>
<td></td>
<td>China</td>
<td>water</td>
<td>Down bend shape chute</td>
<td></td>
<td></td>
<td>77</td>
<td></td>
<td>(Zhang et al., 2019)</td>
</tr>
<tr>
<td></td>
<td>Arizona, USA</td>
<td>Corn straw/SCMC/additives (65:20:15 [m/m])</td>
<td></td>
<td>200 KPa</td>
<td>14</td>
<td>99</td>
<td></td>
<td>(Liang et al., 2021)</td>
</tr>
<tr>
<td></td>
<td>1–3 mm</td>
<td>AA/SD/2-AA-2-2MPA/CAN/mMBA</td>
<td></td>
<td></td>
<td>3.4–10.7</td>
<td>90.1</td>
<td></td>
<td>(Zhou et al., 2023b)</td>
</tr>
<tr>
<td></td>
<td>20.8 μm</td>
<td>0.05% SCMC</td>
<td></td>
<td></td>
<td>15</td>
<td>95.9</td>
<td></td>
<td>(Borowski et al., 2020)</td>
</tr>
<tr>
<td></td>
<td>20.8 μm</td>
<td>0.1% SCMC</td>
<td></td>
<td></td>
<td>15</td>
<td>99.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20.8 μm</td>
<td>0.2% SCMC</td>
<td></td>
<td></td>
<td>15</td>
<td>98.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20.8 μm</td>
<td>0.4% SCMC</td>
<td></td>
<td></td>
<td>15</td>
<td>96.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>2% SCMC</td>
<td></td>
<td></td>
<td>15</td>
<td>88</td>
<td></td>
<td>(Li et al., 2020b)</td>
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<tr>
<td></td>
<td>PM₁₀</td>
<td>Humic substances + ASQ + CMC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Volikov et al., 2023)</td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>Humic substances + ASQ + CMC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20.8 μm</td>
<td>Water + surfactant</td>
<td>Atomizing techniques</td>
<td></td>
<td>10</td>
<td>75.5–88.2</td>
<td></td>
<td>(Yen et al., 2021)</td>
</tr>
<tr>
<td></td>
<td>PM₁₀</td>
<td>30% CaCl₂, 35% MgCl₂, brine</td>
<td>Traditional spraying</td>
<td></td>
<td>10</td>
<td>70.7–84.5</td>
<td></td>
<td>(Raveh Amit et al., 2022)</td>
</tr>
<tr>
<td></td>
<td>TSP, PM₁₀, PM₂.₅</td>
<td>-</td>
<td>Conventional sprinkler</td>
<td></td>
<td></td>
<td>97–100</td>
<td></td>
<td>(Lee et al., 2022b)</td>
</tr>
<tr>
<td></td>
<td>Taiwan</td>
<td>TSP, PM₁₀, PM₂.₅</td>
<td>Water + surfactant</td>
<td></td>
<td></td>
<td>89–91</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>water</td>
<td></td>
<td></td>
<td>73–76</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dust</td>
<td>-</td>
<td>Dry fog system</td>
<td></td>
<td></td>
<td>83.9–90.2</td>
<td></td>
<td>(Saurabh et al., 2020)</td>
</tr>
<tr>
<td></td>
<td>PM₁₀</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td>51.4–60.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td>69.7–71.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Zhenjiang city, China</td>
<td>50 g L⁻¹ of urea EC-PVAC</td>
<td>Sprinkler</td>
<td></td>
<td>540</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₁₀, PM₂.₅</td>
<td>water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>NaOH + Potato starch + gelatine</td>
<td>Sprinkler</td>
<td></td>
<td></td>
<td>23–32</td>
<td></td>
<td>(Hu et al., 2020)</td>
</tr>
</tbody>
</table>
Table 3. (continued).

<table>
<thead>
<tr>
<th>Type of dust</th>
<th>Location</th>
<th>PM Size</th>
<th>Wetting agent</th>
<th>Spraying mechanism</th>
<th>Consolidation layer strength (kPa)</th>
<th>Wind speed (m s(^{-1}))</th>
<th>Suppression efficiency (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>Taiwan</td>
<td>TSP, PM(<em>{10}), PM(</em>{2.5})</td>
<td>water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>PM(_{10})</td>
<td>7% (v/v) Hydrophilic</td>
<td></td>
<td>20</td>
<td>87</td>
<td></td>
<td>(Lee et al., 2022b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PM(_{2.5})</td>
<td>polyethylene glycol</td>
<td></td>
<td></td>
<td>86</td>
<td></td>
<td>(Lee et al., 2019b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PM(_{10})</td>
<td>3% (v/v) PEO–PPO–PEO</td>
<td></td>
<td></td>
<td>91</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>PM(_{2.5})</td>
<td></td>
<td></td>
<td></td>
<td>89</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>PM(_{10})</td>
<td>oxidized corn starch and gelatin</td>
<td></td>
<td>78.7</td>
<td>89</td>
<td></td>
<td>(Dang et al., 2017)</td>
</tr>
<tr>
<td>All dust</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>62.8</td>
<td>96.9</td>
<td></td>
<td>(Huang et al., 2021)</td>
</tr>
<tr>
<td>Respirable</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>86.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SCMC represents sodium carboxymethyl cellulose.
ASQ represents amino silsesquioxane polyelectrolyte complexes.
EC-PVAC represents enzymatic calcification with polyvinyl acetate.
EICP represents enzyme-induced carbonate precipitation.
AA/SD/2-AA–2-2MPA/CAN/mMBA represents Acrylic acid + saw dust + 2-acrylamide-2-methylpropanesulfonic acid+ ceric ammonium nitrate + m-methylene-bisacrylamide.
ammonium chitosan chloride agglomerates coal dust particles causing significant dust suppression (Liu et al., 2018b). Glycerin, a byproduct of biodiesel has dust suppression potential (Yan and Hoekman, 2012).

4.2.2 Hybrid wetting agents composed of biopolymers and chemical agents

As presented in Table 3, the most critical hybrid surfactant is sodium carboxymethyl cellulose, which results when cellulose is modified using the carboxymethyl group. Its suppression efficiency for coal dust ranges from 96%–99% (Borowski et al., 2020; Liang et al., 2022). The performance of lignosulfonates on dust suppression decreases drastically in heavy rains. To solve this, Sodium-LS is crosslinked with acrylamide and methylene diacrylamide (Parvej et al., 2021). The resultant compound has higher dust suppression efficiencies. However, it corrodes equipment and impacts aquatic species adversely. In an investigation by Zhou et al. (2023a), a hybrid surfactant composed of cellulose, polyvinyl alcohol, and polyacrylamide had suppression efficiency > 90% for coal dust. Lastly, a chemical agent comprising sawdust, acrylic acid, and other additives suppressed coal dust with notable efficiencies of 85%–90% (Zhou et al., 2023b). Hybrid surfactants composed of humic substances, amino silsesquioxane, and carboxymethyl cellulose had coal dust suppression efficiencies of 77%–85%, implying insignificant improvements compared to plain water (Volikov et al., 2023). The suppression efficiency for urban dust using a hybrid surfactant composed of
NaOH, Potato starch, and gelatine was 56% and 57% for PM$_{10}$ and PM$_{2.5}$, respectively. This was a significant improvement compared to the application of plain water, whose PM$_{10}$ and PM$_{2.5}$ efficiencies were 33% and 23%, respectively (Hu et al., 2020).

4.2.3 Inorganic wetting agents

Inorganic surfactants, including chloride salts, silicates, sodium dodecane sulfonate (SDS), sodium dodecyl benzenesulfonate, sodium dodecyl sulfate, and triton, decrease the surface tension of water. Since they are hygroscopic, they attract dust particles, suppressing fugitive dust through primary and secondary dust suppression mechanisms. Chloride salts like NaCl, MgCl$_2$, and CaCl$_2$ quench fugitive dust through their hygroscopicity. They have been applied to suppress radioactive PM$_{10}$ dust from the Negev desert with efficiencies ranging from 97%–100%, as presented in Table 3 (Raveh-Amit et al., 2022). Magnetized surfactants are hydrophilic and suppress fugitive dust through agglomeration (Sivrikaya and Arol, 2013). Foam is mainly applied for dust suppression through a primary mechanism whereby it forms a thick blanket, effectively covering and immobilizing dust particles. When generating foams for dust capturing, attention should be paid to ensure they have high cohesion and viscosity.

5 CHALLENGES AND PERSPECTIVES

Many valuable tools have been developed recently, including WRF-Chem, a Weather Research and Forecasting (WRF) model coupled with Chemistry that is applied to study the transformations and dispersion of aerosols (Lee and Lee, 2022). Adopting an efficient blend of dust suppression approaches is essential to enhance the local air quality surrounding mining and mineral processing industries. Foliar capture of dust is one of the recent methods and has been applied to road dust in Hangzhou, China. Besides mineral particles, this approach has been practical for soot, fly ash, and biological particles. This concept can be adopted for raw material storage sites (Dang et al., 2022). In 2007, China adopted the policy of promoting the big and quashing the small (PBQS) to alleviate air pollution from coal-powered power plants. This policy can be extended to other industries in other sectors, especially where large quantities of mineral aggregate materials are required (Wang et al., 2022).

Gravel mulching, commonly applied to suppress dust in construction sites, has the potential to quench dust in raw material stockpiles. After applying dry fog, less than 0.01% of water mass is added to the raw material. These approaches are appropriate for situations where excessive moisture increases the burden of subsequent handling processes (Saurabh et al., 2022). Industries could benefit from the synergistic effects between polymers’ liquid state and amphiphilic properties (Lee et al., 2019b). Electrically charged monodispersed droplets have been applied to suppress dust (Lee et al., 2019a), where their efficiencies for PM$_1$ exceeded those for PM$_{10}$ and PM$_{2.5}$. In other investigations, a mixture of degraded gelatin (gel) and oxidized corn starch (OCS) have been applied for dust mitigation. Proper system maintenance is critical for optimal performance of the abovementioned dust suppression methods. Nevertheless, there is a need for threshold limit values to define the line between safe and hazardous concentrations for mineral dust emissions from industrial stockpiles. This will require predictive models to estimate point and non-point emissions and dust dispersion modeling to assess the performance of dust control approaches. By combining this information with local meteorological data, models can predict dust deposition near the stockpiles. Biodegradable dust suppressants, for instance, mucilages from biomass such as psyllium plants (genus Plantago) and chia seeds (Salvia hispanica L.) have high hydration and dust suppression potentials and hence are more reliable in terms of environmental sustainability. Adopting a circular economy in suppressing mineral dust aerosol is a more feasible approach for sustainability. On top of adopting the strategies mentioned earlier for PM reduction, it is prudent to adopt best management practices such as reducing material handling activities in windy conditions and applying personal protective equipment such as masks and respirators for workers exposed regularly.
6 CONCLUSIONS

The propensity for mineral dust emission in coal exceeds that of other raw material stockpiles, including limestone, gypsum, iron ore, magnetite, and bauxite, due to smaller particles and low specific gravity. Mineral dust is less complex than dust emitted from chemical processes. The average density for mineral dust is 2.65 g cm\(^{-3}\). The size distribution is essential to understand the degree of spread for dust particles, whereby > 30 µm and 10–30 µm deposit within 100 m and 200–500 m from their origins, while smaller PM have the potential for long-range transportation. The shape and arrangement of stockpiles determine the concentration of dust emitted, whereby flat-topped piles emit 13%–60% less dust than conical-shaped piles. Wet techniques for suppressing mineral dust aerosols are more versatile and practical than dry suppression techniques, whereby dust fixation rates within one hour of applying a conventional sprinkler was 80%, while that for a fog cannon was 87%. Surface wetness of 1%, 2%, and 3% attained respective peak dust suppression efficiencies of 37%, 40%, and 65%. Water is an ineffective binder. Therefore, biopolymers, chemical agents, and inorganic surfactants with suitable properties, such as humectants, hygroscopic, and agglomerating agents, are added to plain water to improve dust suppression efficiencies. While organic surfactants have acceptable dust suppression efficiencies and are the most environmentally friendly, hybrid surfactants (biopolymer and chemical agents) and inorganic surfactants possess reasonably high dust suppression efficiencies but with complex preparation methods, and questionable implications for human health and the environment.

REFERENCES


