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Development and Performance Evaluation of an Automated Spraying System (EcoGate) for Reducing Dust Emissions in Mine Transport

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Abstract

Dust emissions generated during mine transport operations, particularly under dry and windy climatic conditions, have a significant adverse impact on the environment. This study proposes a solar-powered automated geo-ecological spraying system (EcoGate) designed to reduce dust dispersion during vehicle movement. The system comprises a 2.2 kW high-pressure pump, 15 nozzles with diameters ranging from 1.2 to 1.6 mm, and a 3 kW solar power source. The processing time per vehicle is approximately 25 seconds, with a water consumption of 10–14 liters. In addition, a water recirculation mechanism is implemented within the system. The results indicate that the dust suppression efficiency reaches 75–85%. Due to the water reuse system, the total water consumption is reduced by 60–70%. The proposed EcoGate system represents a sustainable, energy-efficient, and economically viable solution for reducing dust emissions in mine transport operations.

1. Introduction

Mining operations, including the extraction and transportation of mineral resources, are among the primary factors impacting the environment. In particular, dust emissions generated during mine transport processes negatively affect air quality and pose serious risks to human health and ecosystem stability (Ghose 2007; Kumar et al. 2018).

In regions characterized by arid and semi-arid climates, such as Central Asia, dust dispersion is further intensified due to high wind speeds and low humidity levels. This leads to the transport of dust particles over long distances and contributes significantly to atmospheric pollution (Gao et al. 2018; Zhang et al. 2021).

Conventional dust suppression methods (Banerjee 2003; Singh et al. 2016), including water spraying, chemical stabilizers, and load covering techniques, provide a certain level of effectiveness; however, they have several limitations. Traditional water spraying methods are associated with high water consumption and relatively low efficiency, while chemical approaches are often environmentally hazardous and economically costly.

In this context, the development of sustainable, energy-efficient, and automated technologies for dust suppression has become a critical challenge.

This study presents the development and performance evaluation of an automated geo-ecological spraying system (EcoGate) aimed at reducing dust emissions during mine transport operations. The system operates based on solar energy, incorporates a water recirculation mechanism, and is automatically activated during vehicle movement.

The main objective of the research is to determine the dust suppression efficiency of the EcoGate system and to compare it with conventional methods. Unlike traditional approaches, the proposed EcoGate system introduces a localized, sensor-based automatic activation and closed-loop dust control

technology designed for application at critical nodes of mine transport systems. The scientific novelty of this study lies in the integration of a symmetrically arranged multi-nozzle spraying system with a real-time automated control mechanism and a water recirculation system.

Whereas conventional methods apply dust suppression along entire haul roads—resulting in excessive water consumption – the EcoGate system delivers targeted treatment at entry and exit points where dust generation is most intense. This approach not only enhances water use efficiency but also improves dust wetting effectiveness. Furthermore, the two-stage hydraulic approach employed in the system optimizes droplet dispersion, thereby increasing interaction efficiency with dust particles.

As a result, the EcoGate system is proposed as an integrated geo-ecological solution that ensures effective dust emission reduction, water conservation, and energy efficiency in mining transport operations.

2. Materials And Methods

2.1. Study area and general approach

The study was conducted at the transport system of “Dehkonobod Potash Plant” JSC, located in Kashkadarya Region of the Republic of Uzbekistan, and the adjacent Tepakuton potash mine area. This region is characterized by a dry and windy climate, in which intensive dust generation is observed as a result of vehicle movement.

The distance between the Tepakuton mine and the beneficiation complex exceeds 40 km. The raw material (sylvinite ore) is transported from the mine to the beneficiation plant by road transport. In addition, solid waste generated after the beneficiation process is transported back to waste storage facilities located within the mine area. As a result of this two-way transport process, a large amount of dust emissions is dispersed into the atmosphere.

Continuous transportation over long distances, the natural condition of the road surface, and the dry climatic environment further intensify dust generation. Consequently, dust particles lifted into the air by vehicle wheels and bodies may disperse over considerable distances (Kumar et al. 2014).

The potassium chloride production process is a resource-intensive technological system. In particular, the extraction of the valuable component from sylvinite ore requires the mining of a large volume of rock mass. Therefore, in assessing production efficiency, it is important to perform a comprehensive analysis not only of the finished product output, but also of ore extraction and waste generation volumes.

Within the scope of the study, production indicators of “Dehkonobod Potash Plant” JSC for the period 2020–2025 were analyzed (Fig. 1). During this period, potassium chloride production increased from 327 thousand tons to 450 thousand tons, representing a 1.4-fold increase. At the same time, the volume of

rock mass extraction increased from 1.21 million tons to 1.6 million tons, while the volume of waste increased from 0.883 million tons to 1.150 million tons.

The obtained data indicate that the share of waste in the potash production process is high (Tiwary 2001; Khayrulina et al. 2019). During sylvinite processing, 65–70% of the total mass is separated as halite (NaCl) and other mineral waste, while 5–10% accounts for technological losses.

Under such conditions, mine transport is considered one of the main sources of dust emissions. In particular, dust concentrations reach high levels at the entry and exit points of heavy-duty trucks. Therefore, it is important to implement dust suppression technologies at traffic-controlled locations.

Accordingly, the main objective of the study was defined as the development of an automated geo-ecological spraying system, EcoGate, aimed at reducing dust emissions during mine transport operations, and the evaluation of its efficiency.

The overall approach of the study is integrated in nature and comprehensively considers technical, hydraulic, and environmental factors. The EcoGate system includes the following functional units:

Automated high-pressure spraying system;

Water recirculation module;

Autonomous solar-powered energy supply;

Sensor-based control system for detecting vehicle movement.

The research methodology is based on a combination of experimental and computational-analytical approaches. At the experimental stage, the operating parameters of the device were evaluated under different operating regimes, while at the computational stage, changes in dust concentration were analyzed using mathematical models.

2.2. The design of the EcoGate device

EcoGate is an automated geo-ecological spraying system designed to reduce dust emissions in mine transport operations, and it is installed at control points along the movement route of transport vehicles.

The main structural element of the device is a spraying arch made of a metal frame, the geometric dimensions of which were selected taking into account the dimensions of the transport vehicles (height: 4.2 m, width: 3.8 m). The frame structure ensures complete coverage of the vehicle.

The overall structure and operating principle of the EcoGate system are shown in Fig. 2. A total of 15 nozzles are used in the spraying system, arranged symmetrically to provide full coverage of the vehicle: 5 in the upper section and 5 on each of the left and right sides. This nozzle configuration makes it possible to effectively wet all zones of the vehicle, including the wheels and lower parts (Wang et al. 2017).

The nozzles were selected in a differentiated manner: smaller-diameter nozzles (1.2 mm) were installed in the upper section, while larger-diameter nozzles (1.6 mm) were installed on the side sections. This configuration helps control droplet dispersion and increases the probability of collision with dust particles (Liu et al. 2014).

The EcoGate system has a modular structure and includes the following main functional units:

Spray system;

Water recirculation module;

Hydraulic supply system (pump and pressure control);

Autonomous solar-powered energy source;

Sensor-based automated control system.

During the spraying process, the used water is directed through a special collection channel to a settling tank, where heavy particles are allowed to settle. The water then passes through a filtration stage and is subsequently pumped back into the spraying system. This recirculation mechanism ensures efficient use of water resources.

The operation of the device is automated, with vehicle movement detected by sensors. As soon as a vehicle enters the spraying zone, the system is automatically activated and operates for a predetermined time.

Overall, the EcoGate device is an integrated structural and functional system designed to reduce dust emissions, conserve water resources, and improve energy efficiency.

2.3. Hydraulic System Parameters

The EcoGate system operates based on a two-stage hydraulic system that ensures both high-pressure water delivery and water recirculation.

The main role in the system is performed by the high-pressure pump:

Main pump:

Power: 2.2 kW

Maximum pressure: 140–160 bar

Water flow rate: 7–8 l/min

This pump is used to supply water to the nozzles. However, the pressure is reduced to a special level through pressure regulation for nozzle operation.

In the EcoGate system, an operating pressure of 3–6 bar is maintained for efficient nozzle performance. This pressure range was selected to optimize dust particle wetting while minimizing water consumption.

Recirculation pump:

Power: 1.0 kW

Water flow rate: 6–8 m^3/h

This pump is used to return the collected water to the system after the settling and filtration stages.

Water supply system:

Clean water tank: 2 m^3

Collection and settling tank: 1.5 m^3

During the spraying process, the used water is directed through the collection channel to the settling tank, where heavy particles are allowed to settle. The water is then filtered and returned to the system through the pump for reuse.

This hydraulic scheme ensures efficient use of water resources and helps reduce overall water consumption. At the same time, the combination of a high-pressure pump and a low operating pressure (Zhou et al. 2010) provides an optimal balance between effective dust particle wetting and energy efficiency.

2.4. Energy Supply

The EcoGate system operates on solar energy:

Solar panel power: 3 kW

Inverter: 3–3.5 kW (hybrid)

Battery: 48 V, 100 Ah ($LiFePO_4$)

This system ensures energy independence and reduces operating costs.

2.5. Operating Mode

The EcoGate device is automatically controlled by sensors:

Vehicle passage time: 25 seconds

Nozzles switch on automatically

Water consumption per vehicle: 10–14 liters

Daily operation:

Number of vehicles: 30/day

Total water consumption: 0.3–0.4 m³/day

2.6. Water Consumption Calculation

In the EcoGate system, water consumption is determined based on the number of nozzles, operating time, and working pressure. The following generalized expression was used to calculate water consumption:

$$Q = n \times q \times t$$

where: Q – is the total water consumption (l); n is the number of nozzles (units); q – is the flow rate per nozzle (l/s); t – is the operating time (s).

In this study, the number of nozzles was taken as n = 15 (5 upper, 5 left, and 5 right), and the operating time was assumed to be t = 25 s.

The flow rate of a single nozzle depends on pressure and is expressed by the following empirical relationship:

$$q = k\sqrt{P}$$

where: P – is the working pressure (bar); k – is the hydraulic coefficient of the nozzle (determined experimentally).

This relationship shows that with increasing pressure, water flow increases according to a square-root law (Zhang et al. 2019). According to experimental results, within the pressure range of 3–6 bar, the total water consumption per vehicle was 10–14 liters.

The efficiency of the spraying process is also determined by droplet size. The droplet diameter is inversely proportional to pressure:

$$d \sim \frac{1}{\sqrt{P}}$$

This indicates that as pressure increases, droplets become finer, increasing the probability of collision with dust particles.

Dust suppression efficiency depends on droplet size and can be expressed as:

$$\eta \sim \frac{1}{d}$$

These relationships demonstrate the importance of optimal pressure selection in the EcoGate system.

2.7. Dust Suppression Efficiency

The efficiency of the EcoGate system was evaluated based on changes in airborne dust concentration. The efficiency was determined using the following relative indicator:

$$\eta = \frac{C_{old} - C_{new}}{C_{old}} \times 100\%$$

where: η is the dust suppression efficiency (%); C_{old} – is the initial dust concentration (mg/m³); C_{new} – is the concentration after spraying (mg/m³).

According to the experimental measurements, the application of the EcoGate system resulted in a significant reduction in dust concentration, with efficiency ranging between 75–85%.

The dust suppression process is primarily based on the mechanical interaction between water droplets and dust particles (Chen et al. 2018). Water droplets capture and agglomerate dust particles, increasing their mass and promoting faster settling onto the ground surface. This process is particularly effective for fine-dispersed particles.

3. Results

3.1. Characteristics of Dust Generation in Mine Transport

The results show that the main share of dust emissions in mine transport is generated by vehicle movement. In particular, freight transportation over the distance of more than 40 km between the Tepakuton mine and the beneficiation plant is considered the main source of dust dispersion.

The observations revealed the following:

The main portion of dust is generated by the interaction between the wheels and the road surface;

Fine particles falling from the vehicle body also constitute a source of dust;

Under dry and windy climatic conditions, dust particles are dispersed over long distances.

Dust concentrations reach their maximum levels particularly at the entry and exit points of transport vehicles.

3.2. Geoecological Characteristics of Dust Dispersion

The dispersion of dust particles depends on wind speed, air humidity, and particle size. Under dry climatic conditions, fine dispersed particles remain suspended in the atmosphere for a long time and spread over wide areas (Seinfeld et al. 2016).

This condition leads to the following environmental impacts:

Atmospheric air pollution;

Accumulation of salt dust on the soil surface;

Negative effects on vegetation cover;

Risks to human health.

3.3. Dust Suppression Efficiency of the EcoGate System

A significant reduction in dust dispersion was observed when the EcoGate device was applied. According to the experimental assessment:

Dust suppression efficiency: 75–85%

Treatment time: 25 seconds

Water consumption: 10–14 liters/vehicle

The high efficiency of the system is explained by the following factors:

Optimal nozzle arrangement;

High-pressure spraying effect;

Agglomeration and settling of dust particles through wetting.

3.4. Analysis of the Dust Suppression Mechanism

In the EcoGate system, dust suppression is based on a physical mechanism. Water droplets collide with dust particles, causing them to agglomerate and become heavier. As a result, the particles do not remain suspended in the air for a long time and settle to the ground surface.

This process is particularly effective for fine dispersed particles, significantly reducing their spread into the atmosphere.

3.5. Comparison with Conventional Methods

When compared with conventional dust suppression methods (Kumar et al. 2023), the EcoGate system was found to have higher efficiency.

Conventional water spraying: 40–60%

EcoGate: 75–85%

It was also found that the water consumption of the EcoGate system is 3–5 times lower than that of conventional methods.

4. Discussion

The obtained results demonstrate that the EcoGate system exhibits high efficiency in reducing dust emissions in mine transport operations. The experimentally determined efficiency of 75–85% is primarily attributed to the hydrodynamically optimized design of the device and its multi-nozzle symmetric spraying configuration. In particular, the overall structure of the EcoGate system and the 5–5–5 nozzle arrangement, as illustrated in Fig. 2, enable simultaneous coverage of the upper, lateral, and lower parts of transport vehicles. As a result, a localized and intensive wetting environment is formed in the primary dust-generating zones.

The dust suppression mechanism in the EcoGate system is based on multistage physical interactions between water droplets and dust particles. In this process, inertial impaction, interception, and diffusion mechanisms play a dominant role. Notably, the increase in the total surface area of fine-dispersed droplets generated under high pressure enhances the probability of collision with dust particles. This effect enables effective capture of fine particulate matter such as PM_{10} and $PM_{2.5}$, thereby reducing key risk factors affecting air quality.

The analysis of hydraulic parameters indicates a nonlinear relationship between water consumption and pressure in the EcoGate system. The experimentally derived curve (Fig. 3) shows a consistent increase in water flow rate as pressure rises from 3 bar to 6 bar.

As illustrated in Fig. 3, increasing pressure leads to a significant rise in water consumption; however, this does not result in a proportional increase in dust suppression efficiency. From a hydrodynamic perspective, this phenomenon can be explained by the fact that droplet dispersion reaches an optimal state within a specific pressure range. While increasing pressure promotes droplet atomization and enlarges the total surface area, beyond a certain threshold, further atomization does not significantly improve efficiency. Therefore, a pressure range of 4–5 bar is identified as the optimal operating regime for the EcoGate system, ensuring the best balance between water consumption and dust suppression performance.

To evaluate the practical advantages of the EcoGate system, its performance was compared with conventional water spraying methods. The comparison results are presented in Fig. 4, where the efficiency ranges of both technologies are clearly illustrated.

As shown in Fig. 4, conventional water spraying methods achieve dust suppression efficiencies in the range of 40–60%, whereas the EcoGate system consistently demonstrates higher values in the range of 75–85%. This difference is mainly attributed to the localized spraying approach, optimized nozzle configuration, properly selected operating pressure, and enhanced interaction intensity between water droplets and dust particles. Furthermore, interval analysis indicates that the EcoGate system not only

provides higher efficiency but also ensures relatively stable performance, making it a reliable technology for industrial applications.

One of the key advantages of the EcoGate system lies in its localized action concept. While conventional dust suppression methods distribute the effect along the entire transport route, the EcoGate system operates effectively at entry and exit points where dust concentration is highest. This approach enables rational resource utilization and improved overall efficiency. International studies have also demonstrated that nozzle configuration and droplet size distribution are critical factors in dust suppression technologies (Wang et al. 2017; Chen et al. 2018; Zhao et al. 2022; Li et al. 2023). In this context, the 75–85% efficiency achieved by the EcoGate system confirms its superiority over existing technologies.

Efficient water resource utilization is another significant advantage of the EcoGate system. Through a recirculation mechanism, total water consumption can be reduced by up to 60–70%, which is particularly important in water-scarce regions, providing both environmental and economic benefits. This feature further enhances the resource efficiency of the EcoGate system compared to conventional open water spraying methods.

In addition, the use of solar energy ensures the system's energy independence and expands its applicability as a sustainable technology. The integration of renewable energy sources allows the EcoGate system to be characterized not only as a technical solution but also as an environmentally sustainable innovation.

It should be noted that the study has certain limitations. In particular, the experimental investigations were conducted under limited transport flow conditions (30 vehicles per day) and specific climatic conditions; therefore, the results may vary under different geographical and operational environments. Moreover, the absence of detailed instrumental analysis of particulate fractions, specifically $PM_{2.5}$ and PM_{10}, represents another limitation of the study. Future research focusing on these parameters, combined with advanced statistical and mathematical modeling, would allow for a more precise evaluation of the EcoGate system's performance.

Overall, the EcoGate system can be considered an integrated geo-environmental solution that ensures dust emission reduction, water conservation, and improved energy efficiency. Its localized, automated, and resource-efficient characteristics support its potential as a promising innovative technology for modern mining operations.

5. Conclusion

In this study, an automated geo-ecological spraying system – EcoGate – was developed to reduce dust emissions generated during mining transport processes, and its effectiveness was comprehensively evaluated. The obtained results confirmed that the EcoGate system has high efficiency in reducing dust

emissions. According to experimental assessments, dust suppression efficiency reached 75–85%, demonstrating a significant advantage over traditional water spraying methods.

At the same time, the water recirculation mechanism implemented in the EcoGate system made it possible to reduce total water consumption by up to 60–70%. This result further increases the practical significance of the technology, especially in arid and semi-arid regions where water resources are limited. The system's automatic activation via sensors and its localized operation mode linked to transport movement ensure rational use of resources and contribute to optimizing both energy and water consumption.

The hydrodynamic approach applied in the EcoGate system—particularly the symmetrical arrangement of nozzles and the optimal selection of operating pressure—enhances the interaction between dust particles and water droplets, thereby improving wetting efficiency. This aspect allows the EcoGate system to be characterized not only as a practical but also as a scientifically grounded solution.

The use of solar energy ensures the energy independence of the EcoGate system and expands its applicability in remote mining areas with underdeveloped infrastructure. This makes it possible to evaluate the technology as a sustainable and environmentally safe solution.

Overall, the EcoGate system is recommended as an integrated geo-ecological technology aimed at reducing dust emissions in mining transport, conserving water resources, and improving energy efficiency. Its implementation across various mining sectors is considered appropriate.

In the future, it is important to test the EcoGate system under different climatic conditions, further optimize nozzle parameters and operating modes, and conduct more in-depth studies on its impact on the fractional composition of dust particles ($PM_{2.5}$, PM_{10}), which remain key scientific tasks.

Declarations

Ethical Approval

This is not applicable

Consent to Participate

This is not applicable

Consent to Publish

All authors are aware and agreed to submit the paper, which is original and unpublished, and agreed to grant the copyright (or publishing license) to the journal.

Competing Interests

The authors declare no competing interests.

Data Availability Statement

All data generated or analyzed during this study are included in this article

Funding

This is not applicable

Authors’ Contributions

T. Yarboboev supervised the research and contributed to the study design and manuscript revision; Y. Nurboboev carried out the main research work, performed GIS and statistical analysis, and prepared the manuscript; I. Ochilov contributed to data interpretation, environmental modeling, and editing of the manuscript; K. Kosimova participated in data collection, literature review, and environmental analysis. All authors reviewed, discussed, and approved the final version of the manuscript.

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This is not applicable

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Figures

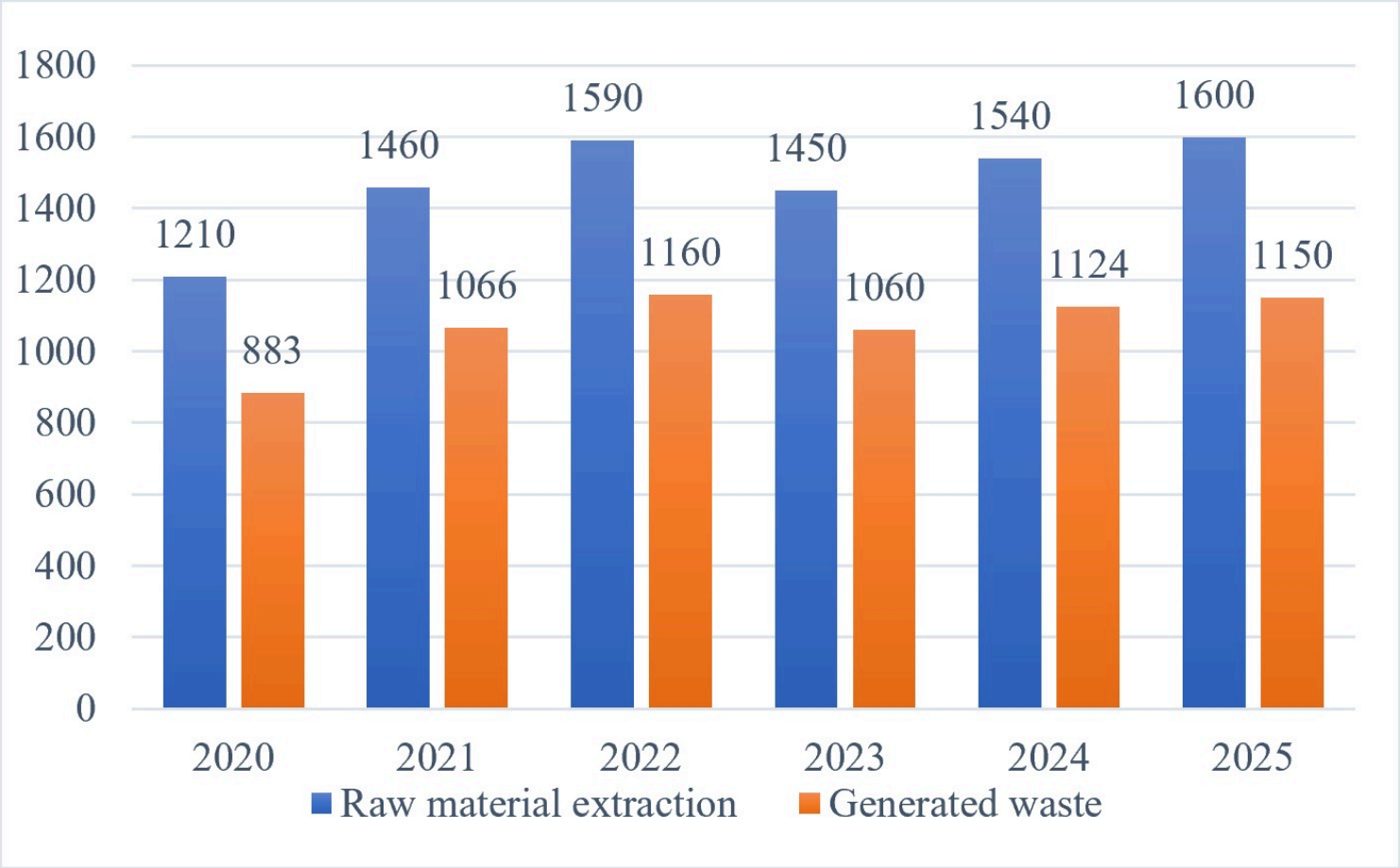


Figure 1

Dynamics of raw material extraction and generated waste volumes at “Dehkonobod Potash Plant” JSC during 2020–2025.

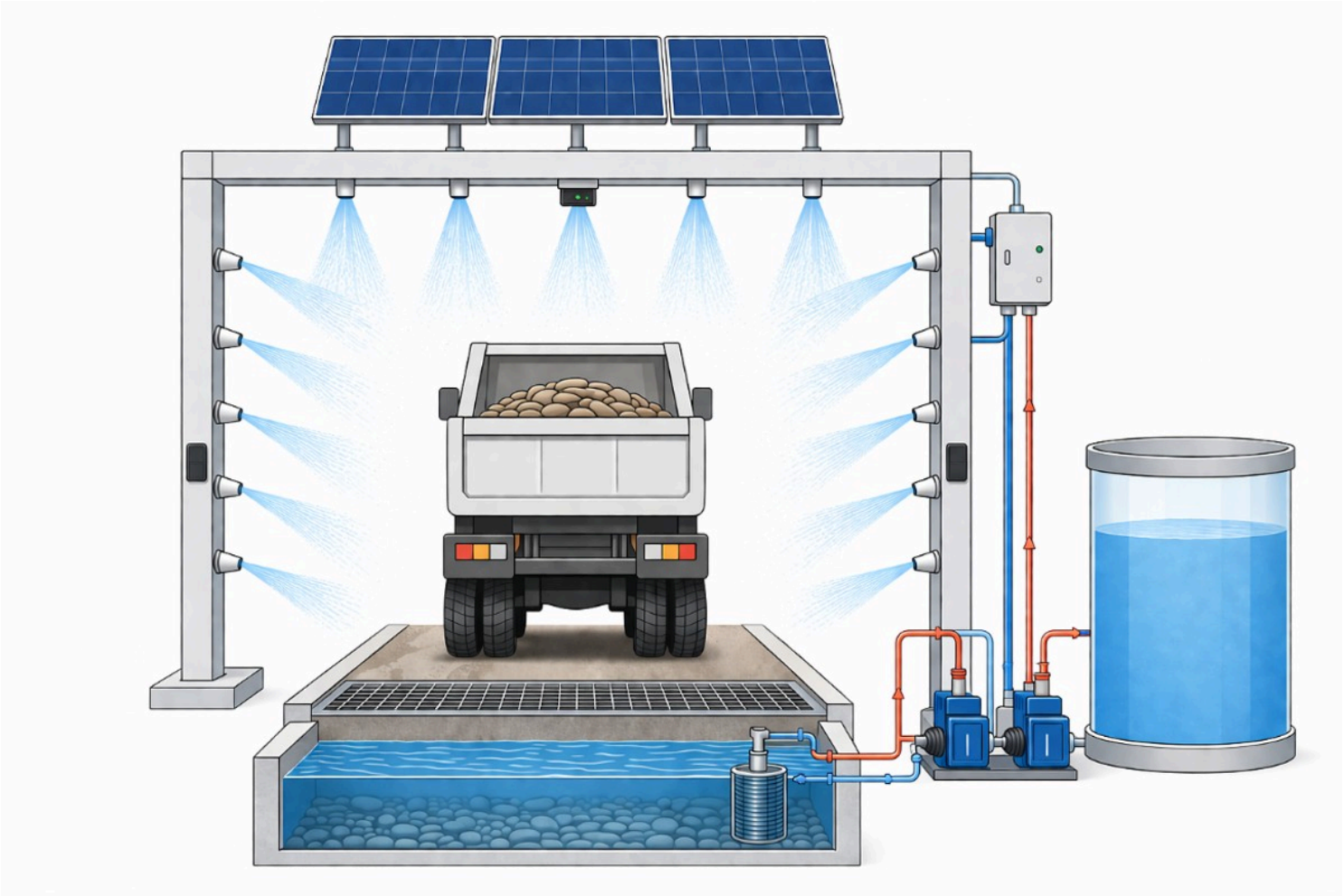


Figure 2

Conceptual schematic of the EcoGate system for dust suppression in mining transport, illustrating a symmetric nozzle configuration and a closed-loop water recycling system powered by solar energy.

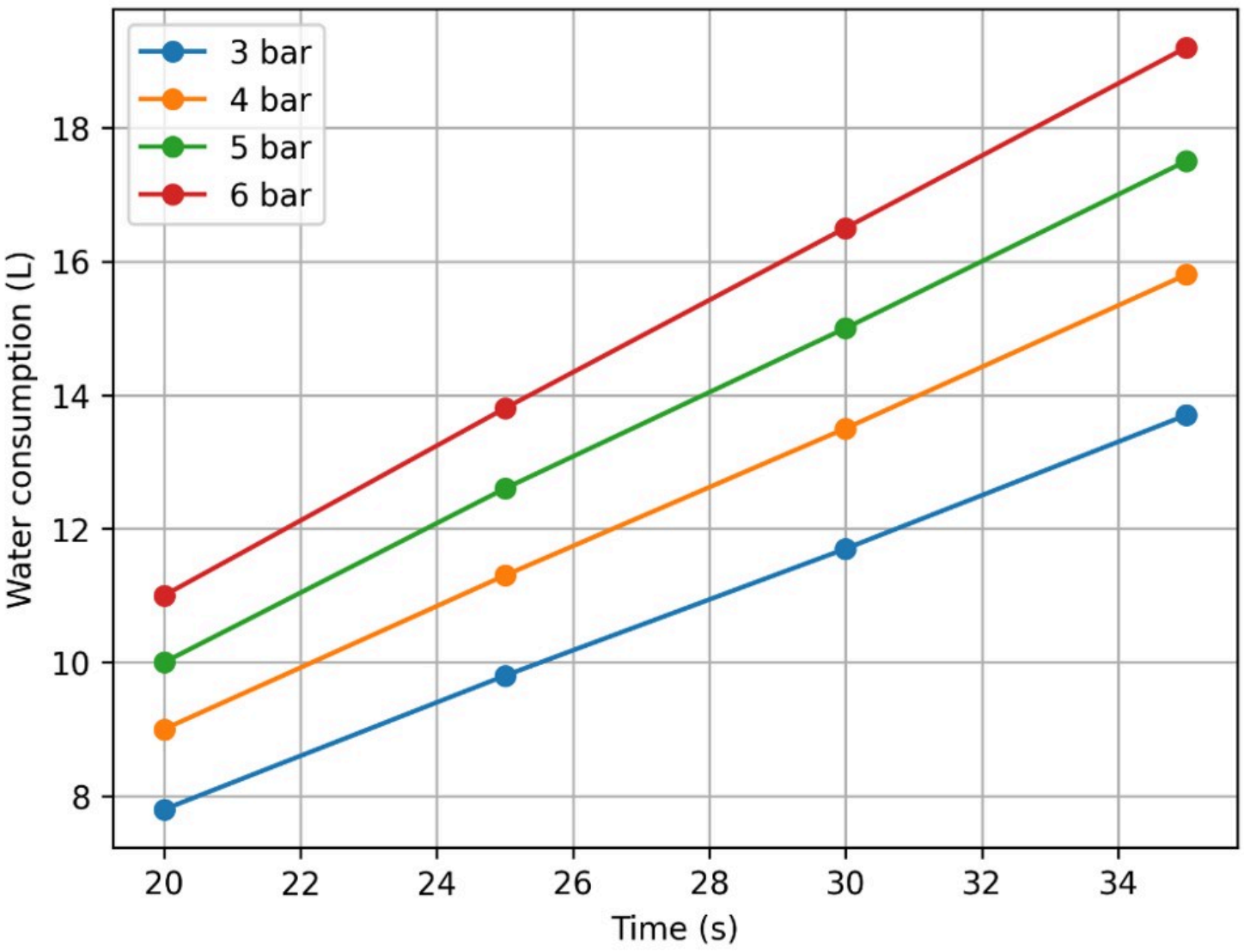


Figure 3

Relationship between pressure and water consumption in the EcoGate system

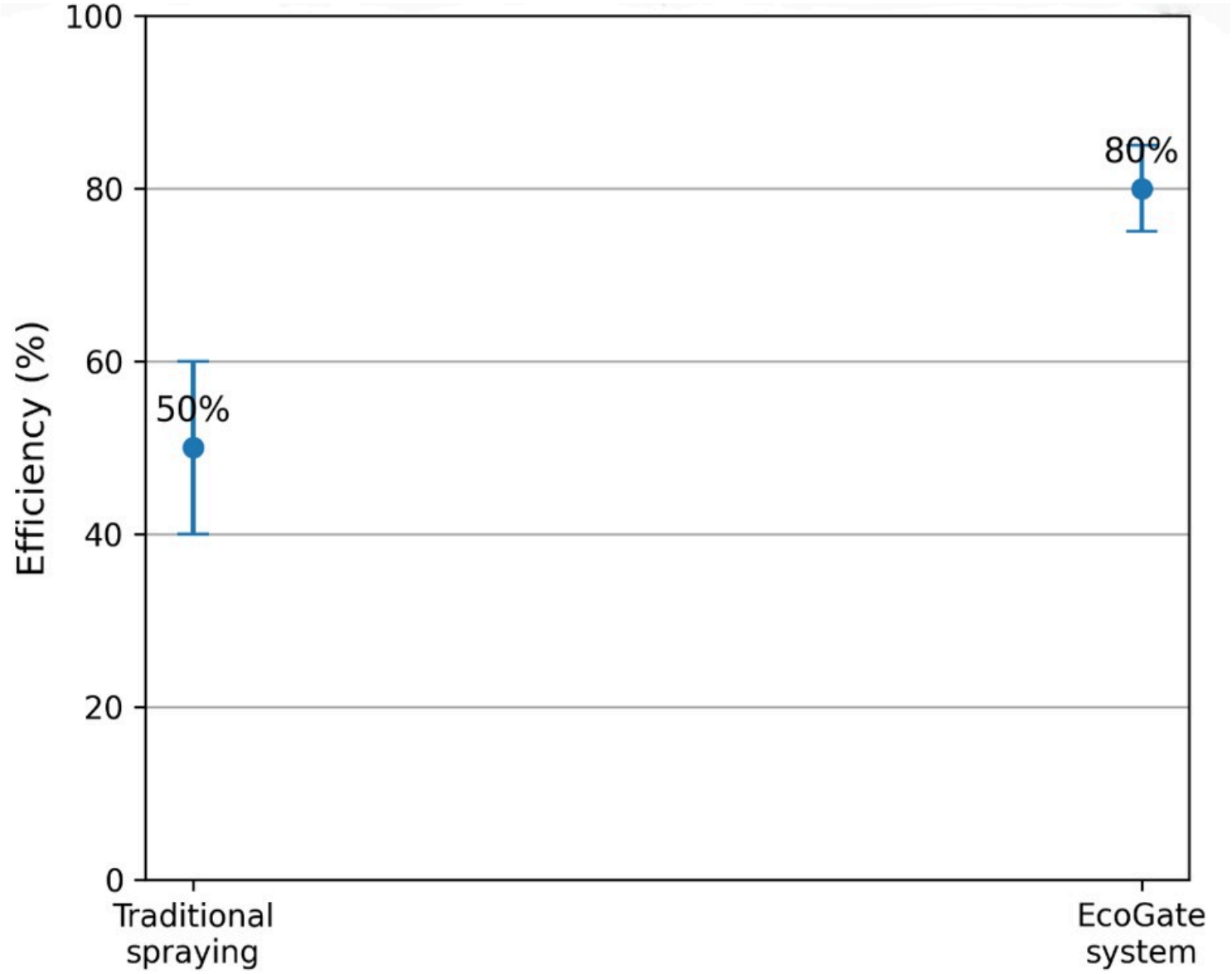


Figure 4

Comparison of dust suppression efficiency between conventional water spraying methods and the EcoGate system

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