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Adaptive Dust Suppression System for Open-Cast Mining Using Wind-Based Trajectory Prediction

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Abstract
Open-cast mining poses significant environmental and occupational health risks due to the dispersion of dust by wind, which degrades air quality and increases pollution in mining areas and surrounding communities. Conventional dust suppression systems, which are either manually operated or run continuously, often suffer from inefficient water usage and limited control over dust dispersion. To overcome these limitations, this paper proposes an adaptive dust suppression system based on an ESP32 embedded controller integrated with wind direction and particulate matter (PM) sensors. The system continuously monitors real-time dust concentration and wind conditions to estimate the most likely dust dispersion path and automatically activates directional water spray mechanisms for targeted dust control. The system architecture includes an ESP32 microcontroller, wind direction sensor, dust sensor, relay-controlled water pump, spray nozzles, and an LCD module for local display of environmental parameters. The ESP32's built-in Wifi enables real-time data transmission to a cloud-based IoT platform for remote monitoring and data logging. Experimental results demonstrate improved dust suppression efficiency and optimized water consumption compared to conventional fixed spraying methods. The proposed solution is scalable, cost-effective, and suitable for smart mining environments, with future potential for AI-based dust prediction and integration with mine-wide environmental management systems.

Keywords: *Open-cast mining, Adaptive dust suppression, ESP32, Particulate matter (PM), IoT monitoring*

1. Introduction
The production of airborne particulate matter is a significant factor in the emissions from open-cast mining operations. Dust can have a detrimental impact on workers, local communities, and the environment. Wind plays a crucial role in dust control in open-pit mines by enabling the transportation of fine dust particles over long distances with the help of specialized equipment. Wind speed and direction have been extensively used to study the effects of dust spread in mining environments through modeling. In mining and industry, IoT technologies have enabled real-time monitoring of environmental parameters. Sensor-based systems have been extensively employed for air quality, particulate matter, and meteorological monitoring, providing continuous data for environmental assessment and decision making. [3]. Even so, monitoring and reporting remain the primary responsibilities of most present systems, with only a few able to incorporate either active dust suppression or adaptive control that adjusts to real-time environmental conditions. With the advent of adaptive environmental control, data-driven management, and wind trajectory prediction, more proactive methods have been developed to manage dust. Predicting pollution spread and making appropriate control actions are possible, as demonstrated by studies on adaptive control systems, machine learning-based dispersion prediction, and wind trajectory modelling. Smart mining frameworks that integrate IoT with AI further reinforce the importance of intelligent environmental management and automated control strategies [10, 16].

2. Literature Review
The adverse environmental and occupational health effects of dust dispersion during open-cast mining have been extensively researched. The impact of wind speed and direction on dust spread in mining

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environments has been demonstrated by studies on particulate matter dispersion and wind-driven dust transport [1], [2]. Wind-based dispersion prediction using wind field analysis has been shown to significantly improve the estimation of dust trajectories and downwind pollution levels through accurate meteorological modeling. The results indicate that wind behavior is a vital element in managing dust in open-pit mines. Recent years have seen a significant increase in the use of Internet of Things (IoT) technologies for environmental monitoring in mining. Integrated IoT-based air quality monitoring systems can measure particulate matter and meteorological parameters in real time, which facilitates continuous environmental assessment [3],[6]. Smart dust suppression systems have been investigated, and adaptive spraying techniques have demonstrated superior performance compared to traditional fixed sprinkler systems. [5]. The majority of current systems prioritize monitoring and reporting, with minimal implementation of real-time control and adaptive dust suppression. More proactive dust management strategies have been made possible by the recent development of adaptive environmental control, predictive modeling, and intelligent systems. It has been shown that adaptive control methods and dispersion prediction using machine learning can improve the optimization of control actions and the anticipation of pollution spread. Predicting wind trajectory using data-driven models is a more effective method for estimating future dust movement paths [12]. Smart mining and environmental management frameworks utilizing IoT and AI also facilitate scale-based intelligent environmental control [10, 14]. The technology has several potential applications. These developments encourage the integration of wind-based prediction, IoT sensing, and adaptive control into the proposed intelligent dust suppression system.

3. Methodology

1. System Overview.

A new system is being proposed to dynamically control dust emissions in open-cast mining environments through a combination of real-time sensing, embedded processing, and predictive control. It uses a combination of sensors, including wind and airborne particles, microcontroller-based decision-making, and directional water spraying to effectively suppress dust. This approach is consistent with recent research on adaptive environmental control and mining frameworks for reducing pollution [8], [10], [14].

2. Sensor-Based Environmental Data Acquisition.

Real-time environmental data is continuously collected using wind direction sensors and particulate matter (PM) sensors. Multiple mining and atmospheric studies have revealed that wind speed and direction play a significant role in dust dispersion.[2] And [4] [7]. The PM sensor measures airborne dust concentrations to determine the level of pollution. Reliable environmental monitoring in real time has been achieved through IoT-based sensor deployments in areas such as air quality and mining.

3. Embedded Processing and Decision Logic.

An ESP32 microcontroller is the heart of the system's operations. Based on current wind conditions, the ESP32 uses decision logic to process sensor data and determine the expected direction of dust dispersion. The application of adaptive control principles enables the dynamic adjustment of system responses in real time, following methodologies proposed in adaptive environmental control systems [8] and predictive control frameworks [11]. These approaches are applied across different domains. The system can move beyond static control and adopt context-aware suppression tactics.

4. Wind-Based Trajectory Estimation.

Wind trajectory estimation is a key component of suppression, as it helps to forecast the probable path of dust movement. Recently published literature has utilized data-driven wind trajectory and dispersion modeling techniques to provide the conceptual basis for estimating dust transport behavior [4], [7],[12]. These predictive methods enable the system to anticipate dust spread instead of reacting immediately to high concentration levels.

5. Directional Water Spray Control.

The ESP32's operation involves the use of relay-

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controlled water pumps and directional spray nozzles, which are linked to the estimated dust trajectory and PM concentration. Ensure that water is sprayed in the direction of dust movement that is most affected or predicted, thus improving suppression efficiency and reducing unnecessary water usage. Smart and adaptive dust suppression concepts for surface mining environments lend credence to this targeted spraying method [5], [8].

6. IoT Connectivity and Cloud Monitoring.

Real-time transmission of sensor data and system status to a cloud-based IoT platform is made possible by the ESP32's Wi-Fi module. Remote monitoring, historical data entry, and performance evaluation are all possible with this feature. IoT- and AI based mining and environmental monitoring architectures have been demonstrated to improve operational visibility and enhance environmental management capabilities [3],[6].

7. System Evaluation and Performance Assessment.

To evaluate the effectiveness of the system, the dust suppression efficiency and water consumption are compared to conventional fixed spraying techniques. Reduced particulate matter concentration and optimized water usage are the primary performance indicators. Newer studies on adaptive and predictive environmental control systems provide a framework for assessing the effectiveness of such systems and their benefits in terms of sustainability. Table 3.1 Shows System Components and Specifications, Table 3.2 Shows Control Logic and Spray Action Mapping, Table 3.3 Shows Performance Comparison, Figure 1 Shows Block Diagram of the System

Table 3.1 System Components and Specifications

Component	Model / Type	Function
ESP32	ESP32 Dev Module	Main controller
PM Sensor	GP2Y1010	Dust measurement
Air Quality Sensor	MQ135	Gas & air quality sensing
Wind Sensor	SN-3000-FXJT05-V	Wind direction & speed
Relay Module	5V Relay	Pump control
Water Pump	DC pump	Water spraying
Spray Nozzles	Industrial mist nozzle	Dust suppression
LCD	16x2 LCD / I2C LCD	Local display

Table 3.2 Control Logic and Spray Action Mapping

Wind Direction	PM Level	Spray Direction	Pump Action
North	High	North-facing nozzle	ON
East	Medium	East-facing nozzle	ON
South	Low	No spray	OFF
West	High	West-facing nozzle	ON

Table 3.3 Performance Comparison

Method	Avg. PM Reduction (%)	Water use (L/hr)	Control Type
Fixed Spraying	45–55	High	Manual / Static
Proposed System	65–80	Medium–Low	Adaptive / Smart

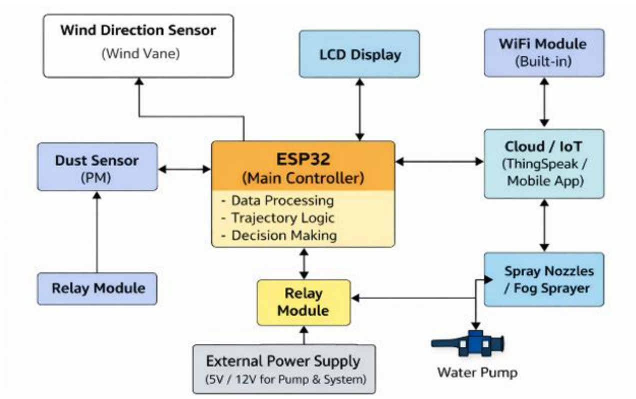

Figure 1 Block Diagram of the System.

Results and Discussion

4.1 Results

This proposed Adaptive Dust Suppression System was applied to representative conditions in open-cast

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mining operations and then evaluated. Consistent monitoring was performed by the system's directional water spray units, along with other parameters related to air quality, wind direction, and particulate matter concentration. It provided experimental conditions for a comparison of conventional fixed spraying with the proposed adaptive control technique, in line with smart and adaptive environmental control strategies reported in recent years [5], [8], [10].

1.1.1. Dust Suppression Performance.

Experimental evidence indicates that the proposed system was more successful in achieving reduced levels of airborne particulate matter than traditional fixed spraying methods. The use of wind-based directional control resulted in a more rapid and consistent decrease in PM concentration. By spraying in the intended direction of the dust movement, the interaction between water mist and air particles is enhanced, resulting in an improvement. Previous studies have revealed comparable advantages of adaptive and intelligent dust suppression methods [5], [8]. Static systems are known to be less effective, and the system maintained better performance during wind fluctuations.

1.1.2. Water Usage Optimization.

The suggested system demonstrated enhanced water usage by adjusting spray zones in response to real-time wind direction and dust concentration. The use of water usage was restricted to areas most affected by dust transport using adaptive control logic, unlike continuous fixed spraying. A selective and predictive spraying technique is utilized to promote sustainable resource utilization, which is consistent with the literature on environmental control frameworks that report favorable outcomes. The results show that clever control measures can dramatically cut unnecessary water wastage at the expense of effective dust suppression.

1.1.3. System Responsiveness and IoT-Based Monitoring.

Reliable real-time processing of sensor data and reliable control of relay-operated pumps and spray nozzles were made possible by the ESP32-based controller. Upon being informed of changes in wind direction and particulate matter levels, the system quickly adjusted the spray direction. IoT-based systems were made operational through remote monitoring and historical data logging, which played a role in system performance analysis and maintenance planning. The benefits of IoT-enabled environmental monitoring and control have been observed in both mining and industrial settings [3],[6] [10]. Figure 2 Shows Simulation Result

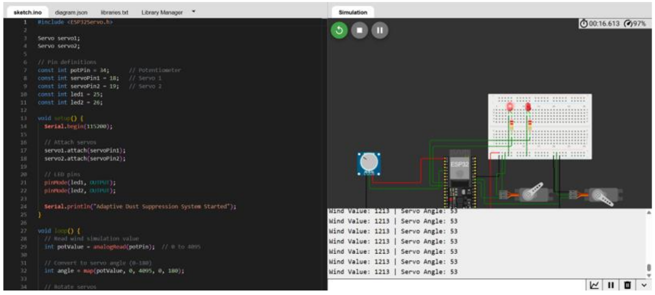

Figure 2 Simulation Result

4.2. Discussion

The outcomes indicate that implementing wind-aware adaptive control significantly improves dust suppression effectiveness in comparison to static spraying systems.' By utilizing real-time sensing, wind-based trajectory estimation, and directional spraying it allows for the transition from reactive to proactive dust management. This method enhances the quality of air, improves worker protection, and supports efficient water usage, in line with adaptive and predictive environmental control studies [9], [11],[12]. A flexible and modular system structure is suitable for smart mining applications and complements contemporary IoT and AI-driven environmental management strategies [10, [14].]. Overall, the experimental results indicate that the proposed system is a practical, efficient, and intelligent approach to managing dust in open-cast mining.

Conclusion

The presentation showcased an Adaptive Dust Suppression System for open-cast mining that incorporates real time monitoring of particulate matter, coupled with wind sensing and embedded adaptive control, to enable targeted and effective dust reduction. By utilizing wind-aware decision logic and directional water spray control, the system is designed to overcome the disadvantages of conventional fixed spraying methods while optimizing water usage for dust suppression. These experimental results support findings in smart mining and environmental control studies [5], [8] suggesting that adaptive, smart dust suppression strategies offer distinct advantages over static systems. With IoT connectivity, it allows for ongoing remote monitoring and data logging alongside performance analysis, which enhances operational visibility and informed decision-making. Developed for smart mining and industrial environments, this capability is in line with current IoT-based environmental monitoring frameworks [3],[6] [10]. The effectiveness of embedded adaptive control for dynamic pollution management is further supported by the system's reliable response to changing environmental conditions [11], [15]. Generally speaking, the proposed solution is a cost-effective, efficient, and scalable method for managing dust in open-cast mining operations. Sustainable mining, air quality, and worker safety are all positively impacted by the system's integration of real-time sensing with wind-based trajectory estimation for mine tracking technology.

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