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Investigation on Impact of Dust Emission in Work and Buffer Zones of Iron Ore Processing Plant and its Management

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Abstract
There is a steady increase in air pollution in mining and related commercial areas due to the emission of dust. Mining activities generate significant amounts of dust, particularly during the drilling, blasting, crushing, screening, and handling of bulk materials in loading/unloading zones. This study is related to the measurement of the concentration of respirable dust and free silica to assess the effects of dust emissions in the work and buffer zones of an iron ore processing facility and take measures to mitigate it effectively when the threshold limit is crossed. It involves designing, installing, and experimenting with an automated intelligent dust suppression system that functions when dust concentration at those zones increases above permissible limits. The study evaluates the effectiveness of the system by comparing the dust levels before and after installation of the system. The system parameters can also be optimized for efficient dust management using air quality modeling and simulation techniques. The developed dust suppression system is creative and uses intelligent technology that combines hybrid acoustic split nozzles to spray dry fog by atomizing water droplets as small as sub-micron meters in size $(1-20\mu m)$ which allows precise aggregation of $PM_{2.5}$ and PM_{10} dust particles. Both mist fog and dry fog systems add very less moisture to the material, being handled, than requirements, and can be as low as 0.1% and 2% for dry fog and mist fog respectively. The dry fog system has a higher efficacy of dust suppression than the mist fog system.

Keywords
Dust-emission, Buffer Zones, Dust suppression system, Dust emission control, Iron ore processing plant

1. Introduction
Cloud of fine dust particles/airborne dust is formed in some mining activities, especially during drilling, crushing, screening, transferring, and transportation of minerals in bulk [4],[23]. Dust emissions can also be increased by wind erosion and sporadic operations in buffer zones where materials are handled or stored [26]. This airborne dust hurts the surrounding mine environment and ecological system. India has witnessed an exponential rise in the output of minerals in the last few decades. This rise in mineral production has been coupled with the installation and operation of higher capacity ore processing machinery such as crushing and screening plants and, the deployment of bigger-size transportation equipment. Operation of such machinery has generated/produced a significant amount of dust; a good part of it became airborne. The airborne dust, so produced, adversely affects not only on health of persons, working on the plant's nearby habitats, but also has a detrimental effect on nearby ecosystems. Specifically, the particulate matter ($PM_{2.5}$ and PM_{10}) can pose risks to human health in surrounding areas and work persons [24]. Because these particles are so tiny, they can enter the respiratory system and make their way to the lungs. Depending on the dust concentration, this can lead

to health effects like irritation of the nose, throat, eyes, and lungs, as well as coughing, sneezing, runny noses, and shortness of breath. Prolonged exposure may further deteriorate all the said issues. Apart from that, the airborne dust hurts the surrounding mine environment, local ecology, and equipment. Ecological disturbances can result from dust particles precipitating on soil, plants, and water bodies. The presence of metals such as lead and other hazardous compounds in these particles might contaminate both soil and water-based, putting plant and animal life at harm [2]. Furthermore, the air quality can deteriorate due to the presence of dust, which exacerbates general environmental problems like acid rain and climate change.

In the worldwide mineral-dust cycle, dust emission is an essential component that greatly influences the associated nutrient cycle [1]. Every day, dust emissions from mining and associated industries can pollute the air [3]. As the mining sector handles a sizable volume of minerals, it is essential to have an efficient dust management system to promote sustainable growth, increase productivity, maintain ecological balance, and most importantly ensure the safety of work persons i.e. protect their health [5]. Controlling the emission of dust is, therefore, a crucial task for assuring a guarantee of environmentally responsible mining and sustainable growth [6]. There are two ways of controlling the emission of dust which may be either suppression of dust at source or its suppression that became airborne by using different suppression techniques. Because the mining sector handles large amounts of material, it is essential to use efficient dust management measures to boost productivity, ensure a safe working environment, and promote sustainable growth [8]. An effective dust control technique is essential to reduce these emissions and guarantee a healthy working and surrounding environment. These techniques include enclosing conveyor systems, employing water sprays to suppress airborne particles, and installing suitable ventilation systems [27]. But there is no proper solution. In the methodology of a study conducted, the problems could be overcome.

Dust, made up of tiny particles, and becomes suspended in the air that is generated due to different mining operations like extraction, transportation, and dumping [9]. This suspension of dust in the air occurred due to turbulence in wind, movement of different types of machinery including conveyor belts, etc. A system of high-pressure water fogging can be proven as one of the best methods of dust management technique [10]. In this system, 0.2 mm (0.008 inch) nozzles are used to generate fine droplets of 10-40 μm in size. Dry fog droplets, generated by the nozzles, are controlled/altered in the direction of airflow where dust concentration exists. Various dust management systems are used for managing dust in the mining industry, such as water spraying, dust arresters, dust collecting hoods, air circulation fans, etc. [12]. The dust particles and the micron-sized droplets of fog in the dust suppression system of the dry fog system collide and stick to one another, increasing mass [13]. The reason for calling it dry fog is that it doesn't wet the material and instead mimics natural fog [14]. Compressed air energy is used to break up water particles of sizes ranging from 1 to 50 μm (average diameter being 20 μm) to create dry fog [15]. Its similarity to real mist is the source of the phrase mist fog. Once the water pressure reaches 5 kg cm^{-2}, the droplets get smaller until they are less than 200 μm in size [16]. The droplets get finer yet lose speed as they fly through the air as the pressure rises. This system usually adds 0.5 to 2% moisture to the substance being handled, depending on the needs of the particular application [17]. It is often used in small spaces (such as hoods, conveyor skirts, and surge stocks) where adding moisture is not necessary [18].

The compressed air's velocity keeps the dust-laden air from leaving, resulting in a thick fog that covers the dust sources [19]. Without upsetting the surrounding air or producing an airfoil effect, the fog particles hang suspended in the atmosphere for a considerable amount of time [20]. Fine dust particles, therefore, come into contact with the water droplets in the fog, get moist, and gather around the main substance [21]. Furthermore, the water droplets evaporate fast because of their minuscule size, providing less than 0.1% dryness to the material being handled [22].

The remaining section of this research is summarized as follows, Section 2 elaborates related study, Section 3 defines the details of the study conducted, Section 4 describes the measurement of dust concentration and free silica content in work and buffer zones, Section 5 elaborates on the functioning of the system, Section 6 relates to design of an intelligent dust suppression system**,** Section 7 assesses the performance of the system, achieved results and its comparison. Finally, the paper is concluded in Section 8.

2. Related Study

A number of the current dust suppression systems' guiding concepts served as the foundation for the associated study.
An important sector of the economy, the iron and steel sector, contributes significant air pollution. To address this, ultra-low emission control technologies have been developed. To address the multiple pollutants in pellet flue gas, a cost-effective system combining SNCR with ozone oxidation and SDA (software-defined architecture) was developed by Zhu, T., *et al* [28]. The innovation involves using magnesian fluxed pellets in blast furnaces, reducing SO_2 NO_x, and emissions at the source. For coke oven flue gas, low-NO_x, low-combustion with activated carbon controls multiple pollutants. High-resistance filter materials and pre-charged bag dust collectors further reduce fine particle emissions. These advancements, demonstrated in five projects, provide comprehensive solutions for reducing industrial pollution, supporting the industry's green development.

The paper addressed the critical need to assess the influence of strengthened emitting regulations on the quality of air, focusing specifically on the iron and steel industry by estimating emission details at the unit level and using the

CAMx model Tang, L., *et al* [29] and simulate air quality impacts, to identify significant emission hotspots around high crude steel production units in eastern regions. Temporally, dust emissions peak during summer, highlighting seasonal variations in air quality impacts. The study's findings underscore the effectiveness of current emission standards, showing substantial reductions of 92.07% for SO_2 and 72.91% for $PM_{2.5}$. These insights are crucial for refining emission reduction strategies and improving the overall quality of air management in the iron and steel industry.

The smart dry fog DSS (dust suppression system) succeeds in controlling dust emission effectively and reducing concentrations of dust to a safe level, well below permissible limits in the mining and mineral processing industry Saurabh, K., *et al* [30]. Experimenting with the system in an iron ore plant in India showed an encouraging result; lowering dust concentrations in work zones and ambient air, minimizing free silica content and PM_{10}, $PM_{2.5}$ levels by significant margins. This eco-friendly system enhances production efficiency without altering any change in raw material, ensuring minimal water usage. It reduces equipment maintenance costs, improves worker health by mitigating occupational diseases, and operates autonomously with low energy consumption and maintenance needs, making it suitable for diverse mineral processing environments.

Ye, L., *et al* [33] developed a new method to produce DRI (direct reduced iron) using Self-reduction aided by microwaves. They used core-shell composite pellets made from BF (basic oxygen furnace) dust and EAF dust, focusing on adjusting the pellets' structure to enhance efficiency. By optimizing the C/O ratio in raw materials, they achieved a balanced core-shell design that matched microwave impedance. This approach utilized BF dust's carbon content for effective reduction and EAF dust's calcium oxide content to improve pellet strength. After reduction and magnetic separation, they successfully removed zinc from EAF dust, achieving higher purification compared to traditional methods. The resulting DRI powders had high iron content (91.2 wt%) and metallization degree (95.8%), demonstrating efficient utilization of industrial wastes in a sustainable manner.

For controlling coal dust pollution in coal mines using a coal cutter with an external spraying system, researchers identified the optimal nozzle as a round-mouth pressure nozzle with an X-shaped core as found through theoretical analysis, experiments, and simulations Ma, Q., *et al* [32]. They examined the spray fields produced by nozzles of varying sizes and pressures. Results showed that higher spraying pressure and larger nozzle calibers increased droplet concentration and improved dust suppression. At 8 MPa, the spray field effectively suppressed dust, with droplet concentrations over 15 g/m³ and sizes between 30-100 μm. Using a 2.4 mm nozzle at this pressure reduced dust concentration around the operator to 87.21 mg/m^3, demonstrating effective dust control.

The innovative automated DFDSS Chaulya, S.K., *et al* [31] represents a significant advancement in controlling dust emissions in mining operations, especially at the material handling, crushing, and screening locations of the Indian iron ore mine. The system demonstrated remarkable production by reducing fugitive dust emissions from 354-7040 $\mu g m^{-3}$ to 91-300 $\mu g m^{-3}$, reducing the dust level well within the permissible limit of 1200 $\mu g m^{-3}$ at a distance of 25 ± 2 m in the main direction downwind; thereby highlighting its efficiency. Importantly, the system added only a negligible 0.032% moisture content to the handled iron ore substance, well below the acceptable limit of 0.1% (depending on operator to operator), ensuring minimal impact on mineral processing operations. Table 1 represents the challenges of existing works.

Table 1 Challenges of existing works

S. No.	Author name	Methods	Benefits	Limitations
1.	Zhu, T., *et al* [28]	Ultra-low emission control technologies	Low- NO_x combustion with activated carbon technology efficiently removes multiple pollutants and utilizes sulfur.	Advanced emission control technologies may be complex and require significant investment.
2.	Tang, L., *et al* [29]	Air Quality Model with extensions (CAMx) model	Focuses on major pollutants like SO2, aiding prioritization of control measures.	Uncertainties in air quality modeling could affect result reliability.
3.	Saurabh, K., *et al* [30]	Smart dry fog dust suppression system	Significantly reduces dust emissions in mining and mineral processing operations.	Requirements: Requires regular upkeep to ensure optimal performance.
4.	Ye, L., *et al* [33]	DRI using microwave-assisted self-reduction	The high carbon content of the BF dust allows for adequate reduction of the pellets with the help of the microwave.	High-temperature reduction (1050 °C) may involve significant energy consumption, impacting overall efficiency and cost-effectiveness.
5.	Ma, Q., *et al* [32]	Control coal dust pollution in coal mines using a coal cutter	Increased spraying pressure and nozzle caliber result in a higher droplet concentration in the spray field, enhancing dust capture efficiency.	Increased spraying pressure and larger nozzles may lead to higher water consumption, which could be a concern in areas with limited water resources.
6.	Chaulya, S.K., *et al* [31]	DFDSS	Significantly lowers dust emissions, improving air quality.	System size and capacity affect energy use, impacting operational costs and the environment significantly.

3. Experimental Study

The following sums up the main contribution of the investigated study:

- Evaluate dust emissions from various mineral processing activities.
- Measure dust concentration and free silica content in work and buffer zones.
- Design of an Intelligent Dust Suppression System for efficient control of dust emission in mineral processing plants.
- Assess the performance of the dust suppression system in an iron ore processing plant.
- Evaluate the impact of varying parameters on dust emission control.

3.1 Experimental Model at NITK, Surathkal Model Mine

Before conducting a study in the actual field, an experimental set was established in the model mine at NITK, Surathkal to assess the dry fog DSS more efficiently. Moreover, fig.1 represents a line diagram of the experimental setup. The system consists of a network of pipes connected to a water tank, motor, and pressure pump, which work together to supply water to various parts of the mine for dust control. The water tank provides the initial water source, which is then pressurized by the pump. Several PLC (Programmable Logic Controller) units are strategically placed throughout the system to automatically control the operations of valves and other components. The compressor adds air pressure to aid in the spraying process. The system's design includes multiple stages and steps to cover mine areas effectively. The result of the suppression of dust was encouraging to conduct the application of a dust suppression system (DSS) in the field.

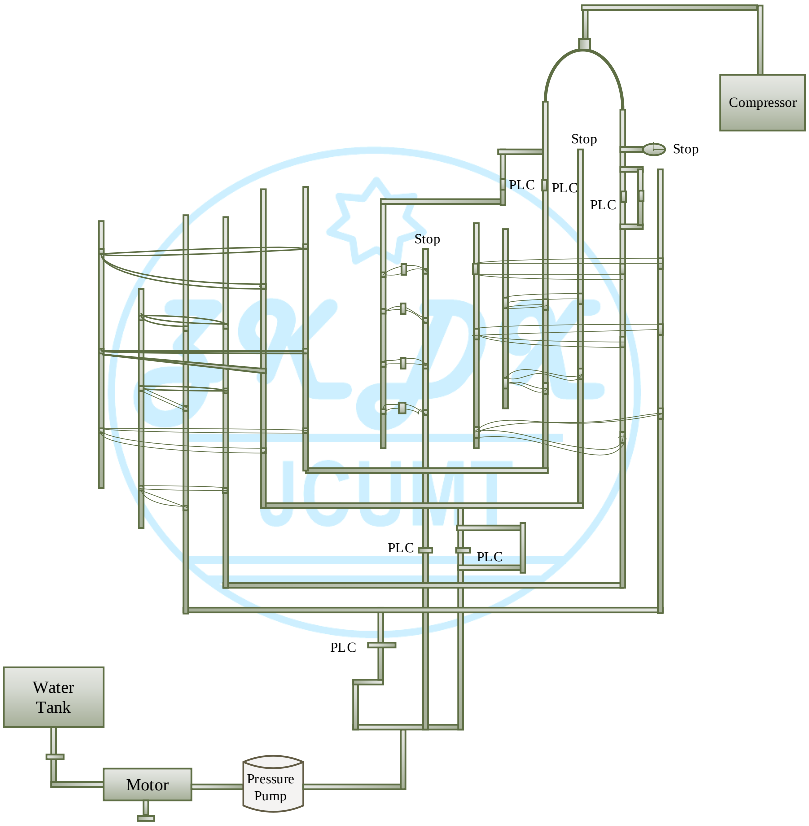

Fig. 1 Experimental Line diagram of dust suppression system installed in Model Mine at NITK, Surathkal

3.2 Field Study

3.2.1 Study Site

The Iron Ore Mine A (IOM A) is situated in Bellary district of Karnataka, India. The opencast mine has been designed with a capacity around 1800t/h.. The ore body of the Precambrian Dharwarian age is located in the Sandur hill range on steep ridges ranging from 580 m to 1050 m in elevation. The deposit spans about 7 km with a NW-SW trend and steeply dipping at 70-75° towards the East. Extraction of minerals is being done from two blocks viz. North Block and South Block, where six ore bodies exist, by the formation of 12 m high benches. Equipment deployed in the mine includes 150 mm rotary percussive drills, hydraulic shovels with 8.0/5.5 m^3 buckets, and 85/100 t dumpers. Annual production of ore from the mine during the financial years 2013-14, 2014-15, and 2015-16 were 5.29 Mt, 5.08 Mt, and 6.06 Mt respectively. Dust sampling and monitoring were done at predetermined downwind locations to assess and control dust emissions. A graphical representation of the study area can be seen in Fig.2. Table 2 shows the location index of the study area.

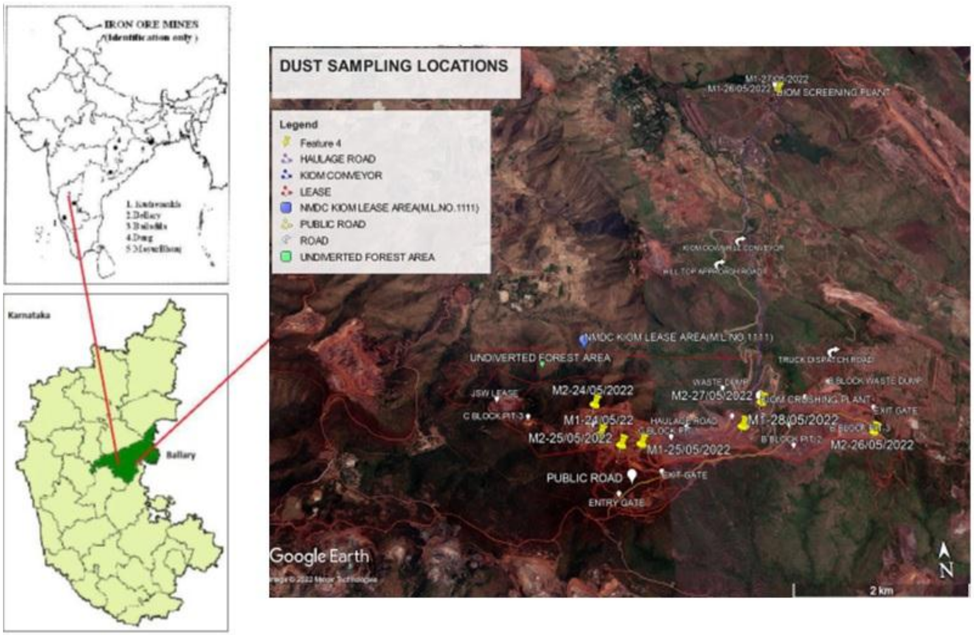

Fig. 2 Study area

Table 2 Location index of study area

Location ID	Location Index	GPS Location	
		Latitude	Longitude
DS1	CP4 View Point	15° 00' 33.53"N	76° 35' 01.94"E
DS2	CP3 Plant Bottom	15° 00 '46.17"N	76° 35' 00.28" E
DS3	C Block Control Room CD2 Weigh Bridge	15° 00' 28.82"N	76° 35' 18.08"E
DS4	CD7 C Block Weigh Bridge (Dispatch)	15° 00' 28.95"N	76° 35' 09.95"E
DS5	B Block Weigh Bridge B1	15° 03' 32.58"N	76° 36' 45.77"E
DS6	Screening Plant DIOM	15° 00' 28.21"N	76° 36' 51.98"E
DS7	Screening Plant DIOM	15° 03' 31.96"N	76° 36' 45.88"E
DS8	Crushing Plant(Top) KIOM Department	15° 00' 42.96"N	76° 36' 08.69"E
DS9	Mining Field Office	15° 00' 33.41"N	76° 35' 59.33"E

Monitoring was conducted at nine key locations within and around the Donimalai Iron Ore Mine (DIOM), which includes View Point, Plant Bottom, Control Room, Weigh Bridge, and several other strategic points. The particulate matter ($PM_{2.5}$/PM_{10}) sampling was conducted both inside and outside the mine, with workplace sampling at the crushing and screening plants and ambient sampling at six external locations. Additionally, personnel sampling from amongst different categories of work persons in different shifts was carried out. In Fig. 3, the crusher plant working area of Kumaraswamy Iron Ore Mine (KIOM) is shown.

Fig. 3 View of the working area of the Crusher plant in KIOM Mine of NMDC Limited

3.2.2 Geology

The Bellary-Hospet region forms a part of the Sandur schist belt referred to as the Dharwars, a group of Precambrian schistose rocks of Mysore. The lithological units include green stones which are the metamorphosed basic igneous rocks occupying the valley regions, while phyllitequartzites form the canopy-shaped amphitheater of hills, trending NNW–SSE and enclosing Sandur. Phyllite is locally shale and quartzites are of the nature of banded hematite jaspers and banded hematite quartzites, interbedded with each other. The general sequence of rock formations found in the area is soil mixed with iron ore float, quartzite exposures, BHQ, iron ore zone, and shale/phyllite.

3.2.3 Climate

Bellary district of Karnataka state is a part of the northern maiden region with an extensive undulating plateau. The district is known for its hot summer and very dry weather for a major part of the year. Annual average rainfall is about 746 mm (Table 3). Wind velocity is moderate and the predominant wind direction is north-east to south-west. Table 3 shows the summary of meteorological data observed at IMD, Bellary.

Table 3 Summarization of micrometeorological data of the study area

Parameter	Value
Average daily maximum temperature (°C)	41.5
Average daily minimum temperature (°C)	20.0
Average daily maximum relative humidity (%)	80.0
Average daily minimum relative humidity (%)	30.0
Average annual rainfall (mm)	746.5

The climate in Donimalai is referred to as a local steppe climate. There is little rainfall throughout the year. This climate is considered to be BSh (hot semi-arid climate) according to the Köppen-Geiger climate classification (Köppen-Geiger, 1961). The average annual temperature is 26.2 °C and precipitation is about 644 mm. The climograph of the region is depicted in Fig. 4.

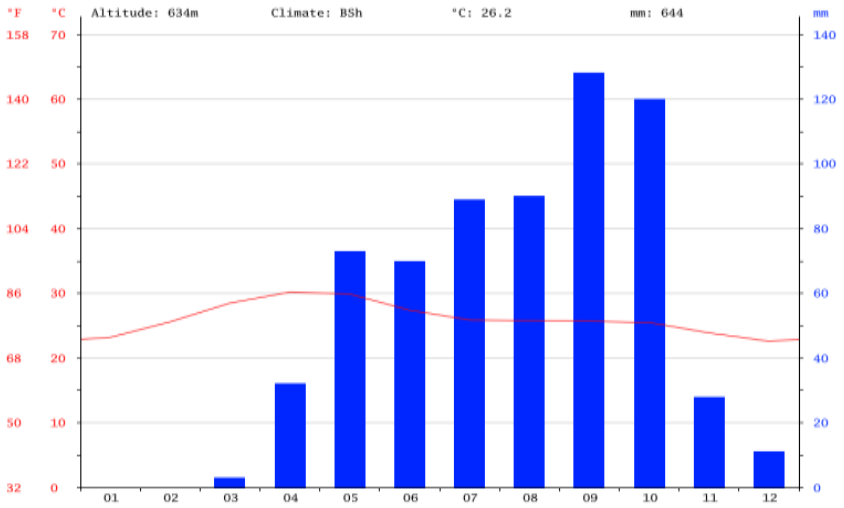

Fig. 4 Climograph depicting the weather conditions

Wind direction and wind speed measurements are important in the quantification and interpretation of air quality monitoring data. The importance of wind data lies in determining the source of pollution in an area, and mixing and dispersal of pollutants. The wind direction and temperature data during the study period are represented in Fig. 5. In Fig. 5 and Fig. 6 distribution of wind direction and wind speed during the study period are exhibited respectively. The predominant wind direction is from NE to SW.

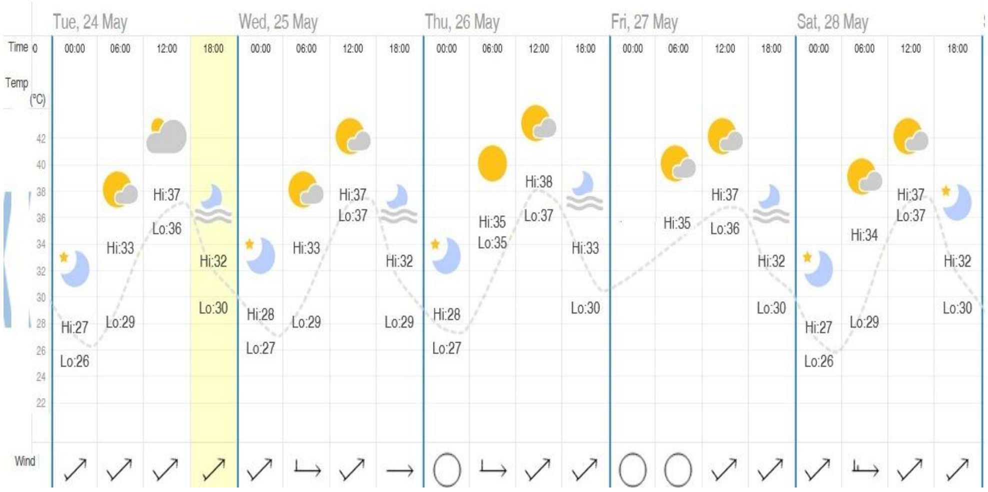

Fig. 5 Wind and temperature data for the sampling period

Table 4 represents the distribution of wind direction and wind speed over a series of dates in May 2022. The table shows the average wind speed in kilometers per hour and the corresponding wind directions recorded at two different times of the day (6:00 AM and 12:00 PM). For most days, the prevailing wind direction is from the southwest (SW), with the average wind speed ranging between 13.5 km/h and 16.5 km/h. On May 25, the wind direction changes from southwest in the morning to west (W) in the afternoon, indicating some variability in wind patterns. This information is useful for understanding local wind behavior and could impact various applications, from weather forecasting to environmental studies. Fig. 7 shows the average wind speed for the sampling period i.e., 24-28 May 2022

Table 4 Distribution of wind direction and wind speed

Date	Average wind speed (Km/h)	Wind direction
24-05-2022	15.5	SW (6:00 Hr) and SW (12:00 Hr)
25-05-2022	13.5	SW (6:00 Hr) and W (12:00 Hr)
26-05-2022	15.5	W (6:00 Hr) and SW (12:00 Hr)
27-05-2022	16.5	SW (6:00 Hr) and SW (12:00 Hr)
28-05-2022	14.5	SW (6:00 Hr) and SW (12:00 Hr)

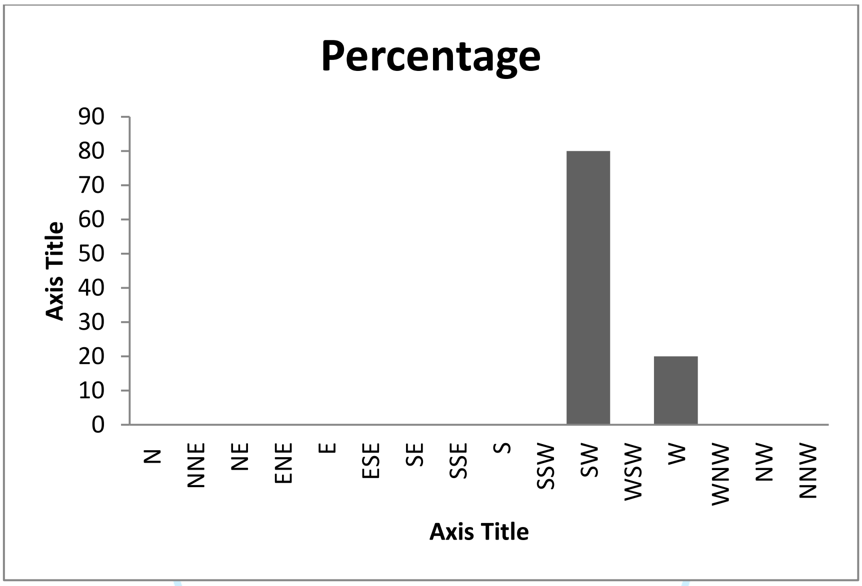

Fig. 6 Wind direction for the sampling period i.e., 24-28 May 2022

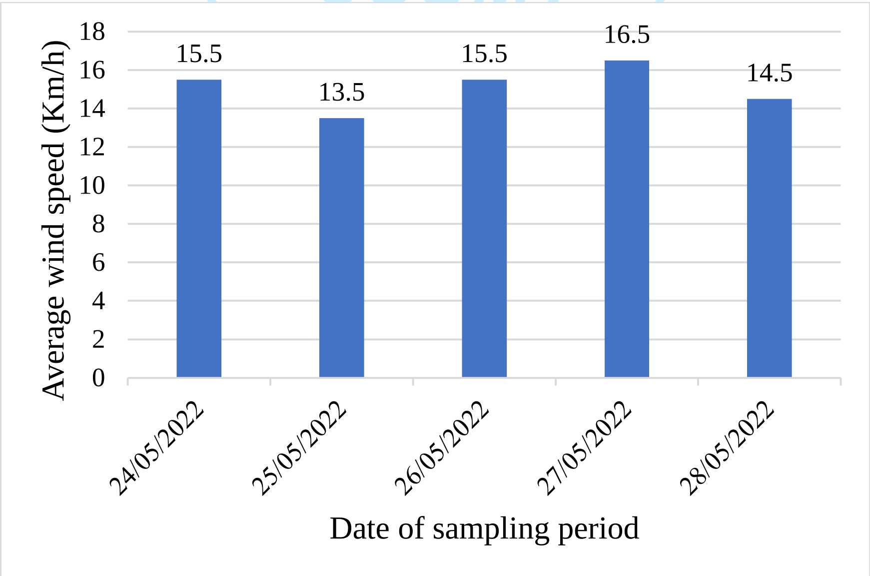

Fig. 7 Average wind speed for the sampling period i.e., 24-28 May 2022

3.2.4 Dust Emission from Different Mineral Processing Activities

Assessing dust emissions from various mineral processing activities involves systematic measurement and sampling techniques to quantify the amount of release of dust into the atmosphere. Typically, high-volume samplers are strategically placed downwind from sources such as crushing, grinding, and material handling operations within processing plants. These samplers collect air samples over specified periods, allowing for the calculation of dust concentrations based on the weight difference of filter papers before and after sampling.

The dust suppression systems were designed to bring the dust level of the Crushing and Screening Plant within Fugitive Emission Standard for iron ore processing as specified by the Ministry of Environment, Forests & Climate Change, i.e., the concentration of particulate matter shall be within 1200 $\mu g/m^3$ at a distance of 25±2 m from the source of emission in the predominant downwind direction. The weight difference $W_2 - W_1$ of the filter paper was divided by the volume of air sampled to get the concentration of dust as per the calculation in Eq. (1).

$$D_c = \frac{W_2 - W_1}{V_s} \tag{1}$$

Where D_c is denoted as Dust concentration, $W_2 - W_1$ is represented as Weight, V_s is the volume of air sampled.

3.2.5 Sampling

A Respirable Dust Sampler (RDS) (Ecotech AAS 190) and a Particulate Sampler (Ecotech AAS127) were used for the sampling process to detect fugitive dust (Fig. 8). Before sampling, the glass microfibre filter paper (8 x 10") was first weighed (W1) and oven-dried for a full day. Next, the filter assembly's plug was unscrewed, allowing the filter paper to be firmly positioned. For every shift, the timer was set for eight hours, and the rate of flow was changed to 1.1m³/min. To determine the total suspended particulate matter, the weight of the dust gathered in the cup underneath the RDS cyclone was added to the Whatman filter paper's weight differential. Using an omnidirectional air intake, sampling of both fine and particulate matter ($PM_{10}/PM_{2.5}$) was done at a rate of flow of 1 m³/h (16.7 lpm). An impactor was used to separate PM10, and a 47 mm WINS impactor was used to separate $PM_{2.5}$.

Fig. 8 Dust sampling using a respirable dust sampler (Ecotech AAS 190) (PM_{10}) and Particulate dust sampler (Ecotech AAS127) ($PM_{2.5}$)

Fig. 8(a) High volume RDS sampler in crusher area

Using a personal dust sampler, workplace monitoring was carried out by DGMS Circular No. 1 of 2004 and Regulation 123 of the Coal Mines Regulations, 1957. The respirable percentage of the dust roughly 10 µm and smaller was extracted from the ambient air passing through a cyclone sampler. Larger undesirable particles fall into the grit pot with the Cyclone Sampler's design, which carries smaller particles into the cassette's filter paper. The Cyclone version does not weigh the entire unit, in contrast to the Institute of Occupational Medicine's (IOM) Sampler cassette/filter paper combo which does. Weighing is done only on the filter paper both before and after sampling. To guarantee correct functioning, this instrument is kept at a rate of flow of 2.2 liters per minute. The respirable dust level at NMDC Limited's work zone has been measured using personal dust samplers**.**

4. Measurement of Work and Buffer Zones Dust Concentration and Free Silica Content

Measuring dust concentration and free silica content in work and buffer zones involves assessing the levels of airborne dust and the presence of respirable crystalline silica in specific areas of a workplace. This procedure is essential for maintaining workplace safety, especially in sectors where employees may be exposed to dangerous dust particles, such as manufacturing, mining, and construction. To gather air samples for measurement, specific tools such as personal air sampling pumps and filters are usually used over a certain length of time. The amount of dust present and the percentage of free silica are then determined by laboratory analysis of these samples. Precise measurement is useful in determining regions where workers' exposure to hazardous materials has to be reduced, gauging the success of dust control methods, and monitoring compliance with regulatory criteria Eq. (2).

$$T_x = [(W_1 \times T_1) + (W_2 \times T_2) + \ldots + (W_n \times T_n)] \quad (2)$$

Where, T_x is denoted as Time weighted average, W_1, W_2,…W_n is represented as the concentration during different periods, T_1, T_2,…T_n is denoted as time. High volume RDS sampler in crusher area is shown in Fig 8(a)

Dust concentration for the first shift and second shift during the study period is exhibited in Table 5 which is represented in the graph in Fig. 9(a),9(b),9(c),9(d),9(e) and9(f). Estimation of Dust concentration (mg/m^3) by personnel dust sampler (PDS) is shown in Table 5(a).

Table 5 PM_{10} and $PM_{2.5}$ dust concentration for first shift and second shift

Location	PM_{10} dust concentration in µg/m^3 (First shift)	PM_{10} dust concentration in µg/m^3 (Second shift)	$PM_{2.5}$ dust concentration in µg/m^3 (First shift)	$PM_{2.5}$ dust concentration in µg/m^3 (Second shift)
DS1	553.9504	551.0146	14270.0245	14271.4879
DS2	1471.8652	1470.4878	1378.8837	1377.1541
DS3	2296.484	2299.4874	10662.4468	10665.1874
DS4	840.5184	845.4848	6423.6838	6428.1548
DS5	1433.3	1430.5883	1455.9081	1454.7889
DS6	1431.5801	1435.5548	3710.7454	3719.5487
DS7	1709.1403	1710.0546	9266.9062	9268.0545
DS8	710.5371	718.2656	2840.3946	2844.8913
DS9	1254.7723	1253.1548	27269.0087	27263.1248

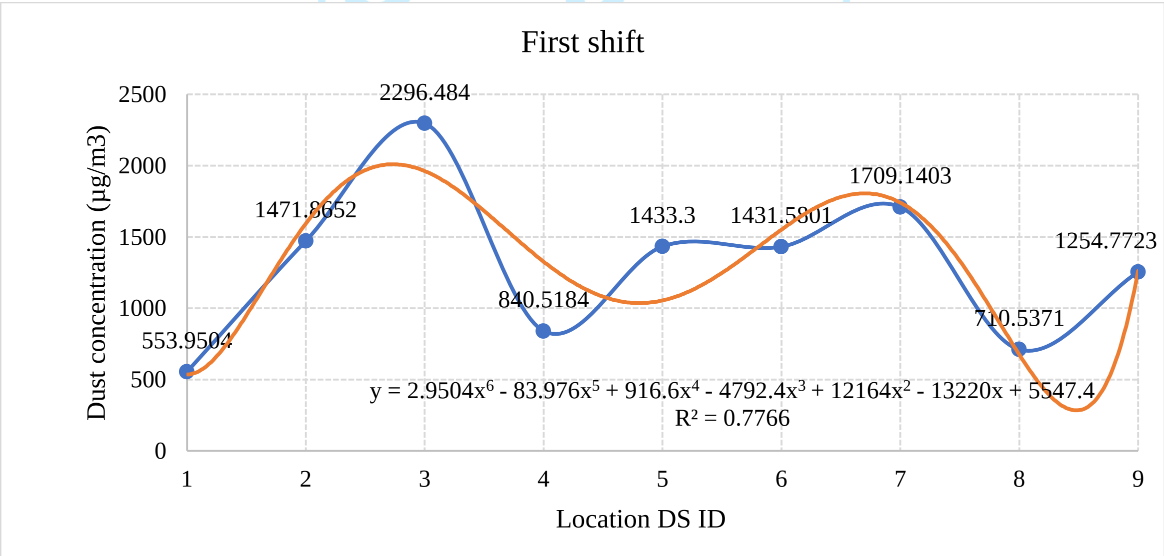

Fig. 9 (a) PM_{10} dust concentration (µg/m^3) in first shift

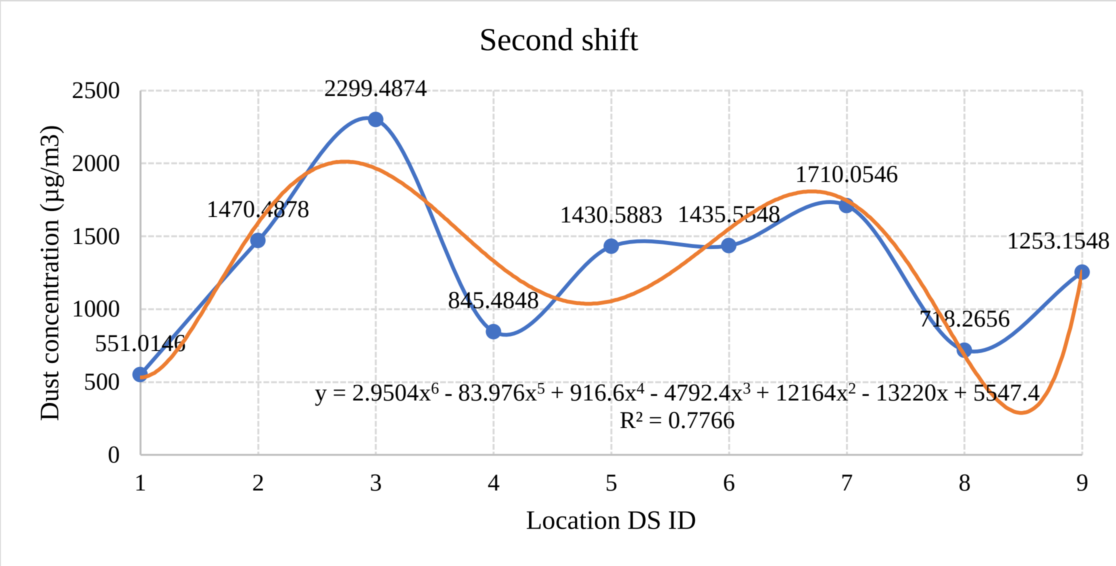

Fig. 9(b) PM_{10} dust concentration (µg/m^3) in second shift

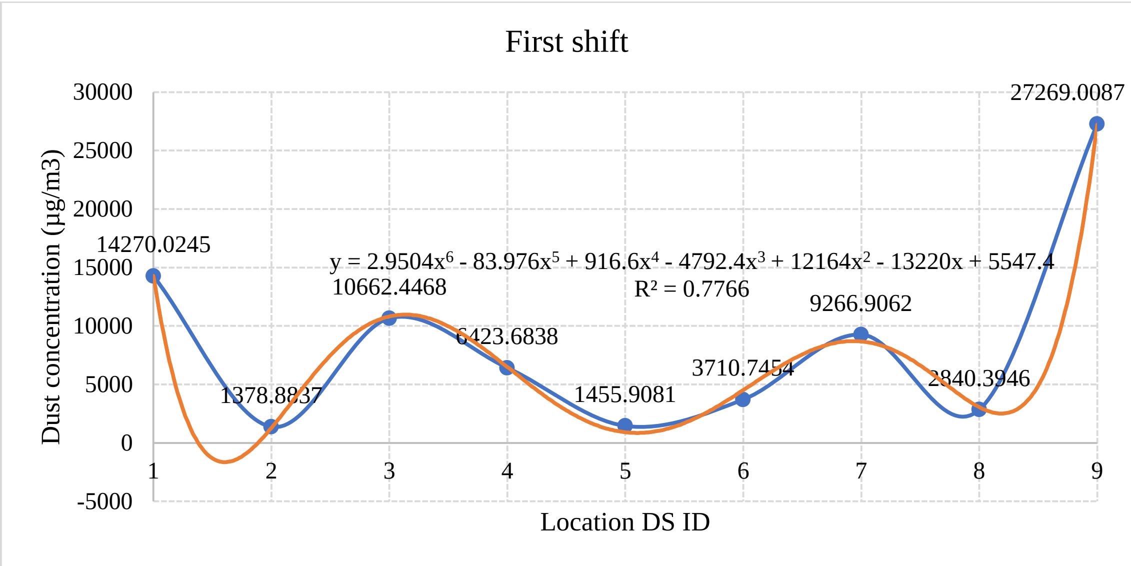

Fig. 9(c) $PM_{2.5}$ dust concentration (µg/m^3) in first shift

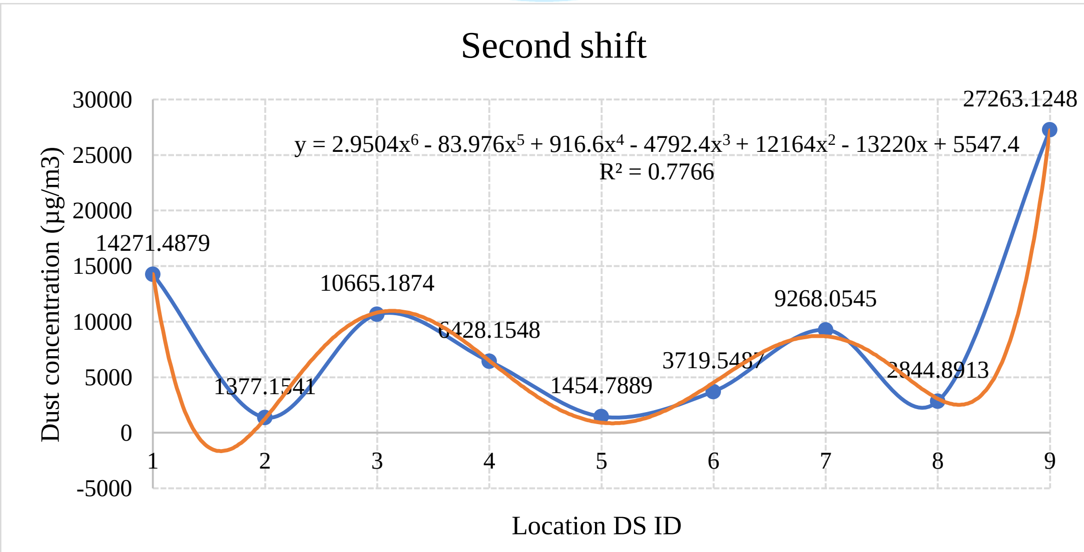

Fig. 9(d) $PM_{2.5}$ dust concentration (µg/m^3) in second shift

Table 5(a) Estimation of Dust concentration (mg/m^3) by personnel dust sampler(PDS)

Sample ID	Category of operation	Date of sampling	Difference in weight=W1-W2	Flow Rate 10^{-3} m^3/min	Duration Of Sampling hrsx60	Dust Concentration mg/m^3	Free silica (%)
PDS 1	Driller Operator	25-05-2022	0.044	2.2	480	0.044	8.55
PDS 2	Foreman	25-05-2022	0.0387	2.2	480	0.0387	8.44
PDS 3	Plant	25-05-2022	0.0498	2.2	480	0.0498	8.32
PDS 4	Excavator operator	25-05-2022	0.0134	2.2	480	0.0134	8.56
PDS 5	Wheel load operator	25-05-2022	0.0417	2.2	480	0.0417	8.22
PDS 6	Drilling operator	25-05-2022	0.0173	2.2	480	0.0173	8.55
PDS 7	Dump Supervisor	26-05-2022	0.0296	2.2	480	0.0296	8.4
PDS 8	Dispatch loading helper	26-05-2022	0.0338	2.2	480	0.0338	8.35
PDS 9	Drill operator	26-05-2022	0.0303	2.2	480	0.0303	8.1
PDS 10	Drill operator	26-05-2022	0.0327	2.2	480	0.0327	8.47
PDS 11	Dump Supervisor	26-05-2022	0.0175	2.2	480	0.0175	8.45
PDS 12	Dispatch loading helper	26-05-2022	0.0311	2.2	480	0.0311	8.37
PDS 13	Shovel	27-05-2022	0.0279	2.2	480	0.0279	8.56
PDS 14	Loader	27-05-2022	0.0219	2.2	480	0.0219	8.54
PDS 15	Dumper	27-05-2022	0.0331	2.2	480	0.0331	8.45
PDS 16	Dumper	27-05-2022	0.0184	2.2	480	0.0184	8.6
PDS 17	Dumper	27-05-2022	0.0341	2.2	480	0.0341	8.45
PDS 18	Excavator	27-05-2022	0.0341	2.2	480	0.0341	8.3
PDS 19	Shovel	28-05-2022	0.0334	2.2	480	0.0334	8.22
PDS 20	Grader	28-05-2022	0.0141	2.2	480	0.0141	8.43
PDS 21	Dumper	28-05-2022	0.0376	2.2	480	0.0376	8.35

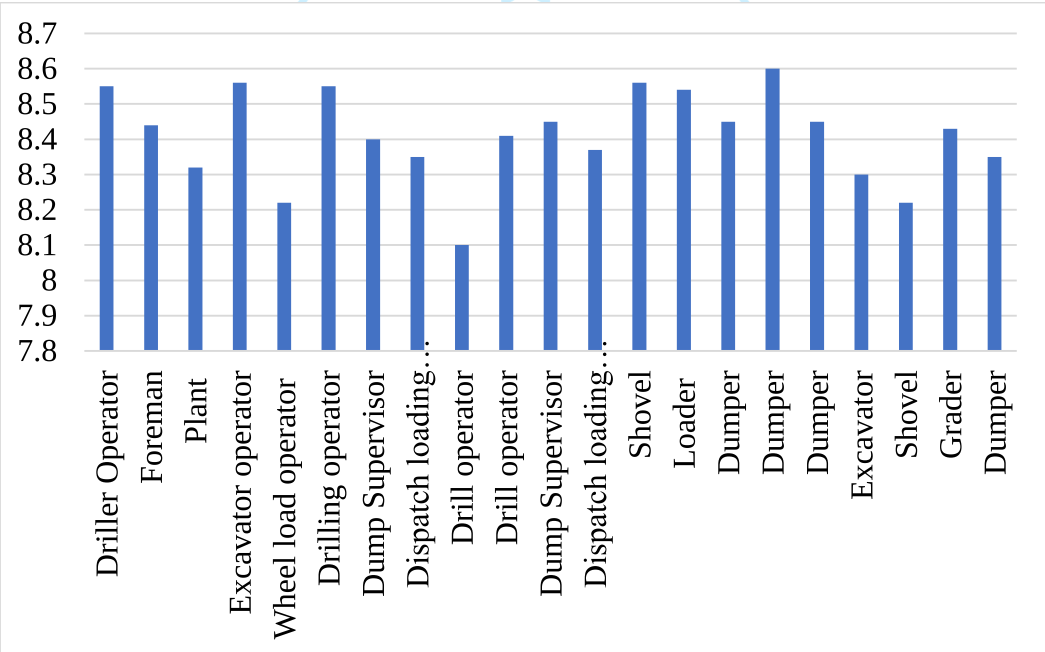

Fig. 9(e) Free silica (%) collected in PDS

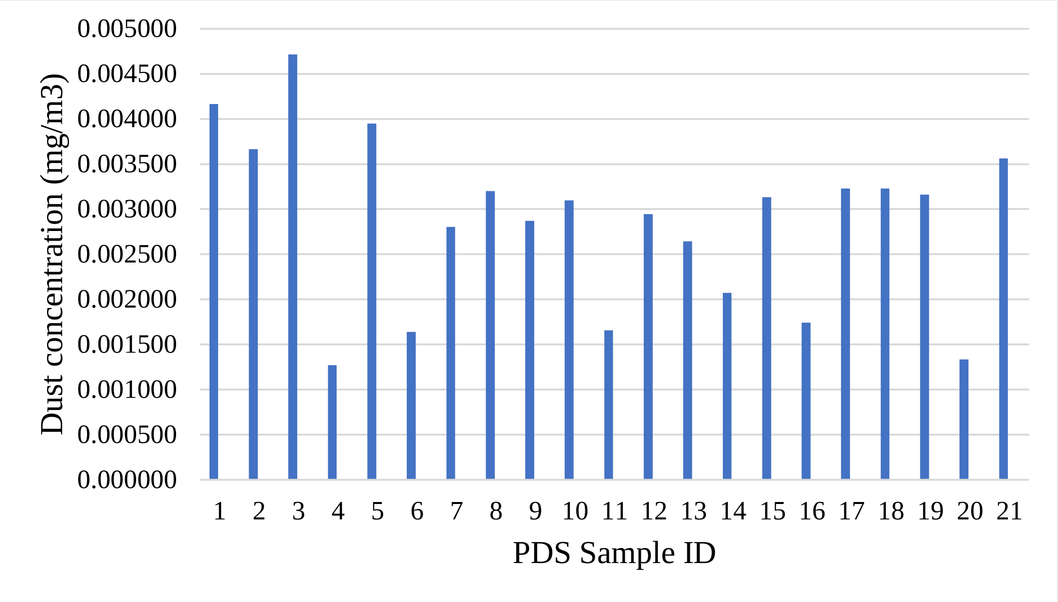

Fig. 9(f) Dust concentration (mg/m^3) collected in PDS

Among the selected sites of air monitoring stations, the fugitive dust emission values of PM_{10} and $PM_{2.5}$ were measured and also verified whether these measured values of PM_{10} and $PM_{2.5}$ are within the permissible limit of 1200 μg/m^3 monitored at 25±2m at the main direction downwind near at View Point, Plant Bottom, Control Room, Weigh Bridge, Weigh Bridge(Dispatch), Screening Plant, DIOM Screening Plant, DIOM Crushing Plant(Top), and KIOM Department Mining Field Office (MoEF & CC notification, G.S.R. 809E, dated 04.10.2010). The dust concentrations of PM_{10} in the viewpoint, weighbridge (dispatch), and crushing plant (KIOM) were 556.950 μg/m^3, 840.51 μg/m^3, and 710.537 μg/m^3 which is within the permissible limit of 1200 μg/m^3. The concentrations of PM_{10} were in the range of 1254.772 μg/m^3 to 2296.484 μg/m^3 for all other mining regions. The concentrations of $PM_{2.5}$ were in the range of 1378.883 μg/m^3 to 14270.265 μg/m^3 in different mining regions. The concentrations of PM_{10} and $PM_{2.5}$ for almost all the areas were higher than the permissible limit of 1200 μg/m^3 as per the National Ambient Air Quality Standard, 2009 and proper action has to be taken to lower the dust concentration to below the allowable threshold. Consequently, the 8.1% to 8.56% range was set as the free silica percentage. Further, the polynomial regression modeling was carried out on the results of fugitive emissions to develop a suitable mathematical model. The R^2 value of more than 0.80 shows the highest effectiveness of the developed mathematical model with test results.

5. System Model

The method for addressing dust emission in mineral processing plants involves a comprehensive approach starting with the assessment of the sources and activities involving dust emission. This will be followed by the measurement of dust concentration and free silica content in both work and buffer zones to establish baseline data. Using this information, an intelligent dust suppression system has been designed, leveraging advanced sensors and control algorithms to optimize dust control measures dynamically. The system will then be implemented in an iron ore processing plant, where its performance will be rigorously assessed. Additionally, the study will analyze the impact of various parameters, such as humidity, temperature, and material properties to showcase the system's effectiveness in controlling dust emissions. Fig.10 manifests the methodology used in the DSS.

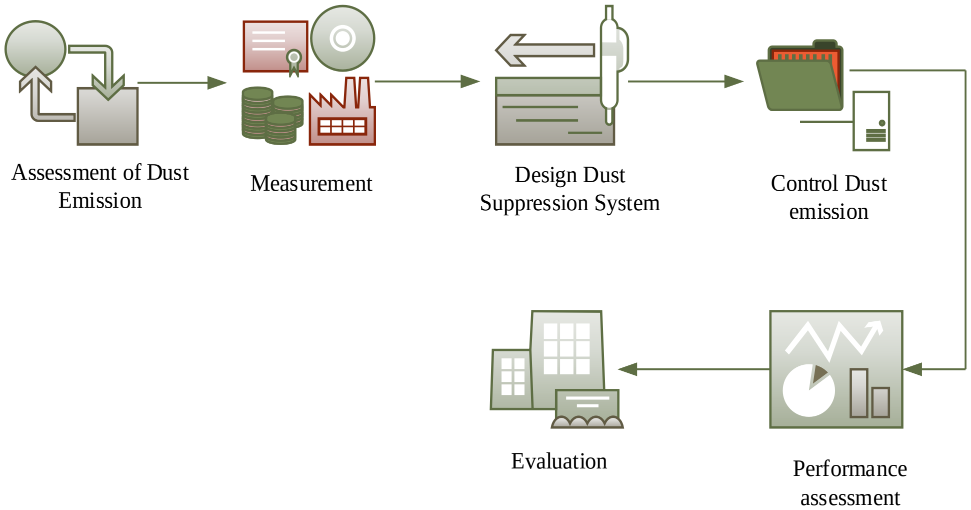

Fig. 10 Methodology

5.1 System Description

The control panel of the DSS is designed to manage and regulate the electrical components required for efficient operation. It includes a Miniature Circuit Breaker (MCB) having 230V input power, a set of relays (R_1, R_2, R_3) interfacing with a Programmable Logic Controller (PLC), and various power supplies such as a 24V Switch Mode Power Supply (SMPS) for the system's operation and an optional 5V SMPS to be activated whenever required. The wiring from the PLC to the relays is clearly labeled, and the input power connections are color-coded for easy identification. Additionally, terminals are designated for as SV_1, SV_2, and SV_3 that control the flow of water or air in the suppression system.

5.2 System Function

This dust suppression system functions to control and reduce emissions of dust in industrial environments. It operates by activating terminals (SV_1, SV_2, and SV_3) based on signals received from the PLC, which processes inputs such as dust levels and operational status. When activated, the solenoid valves release water and air to suppress dust, ensuring a cleaner and safer working environment. The control panel ensures that all electrical components are properly managed, providing necessary power and relaying control signals to maintain efficient dust suppression operations.

5.3 System Operation

The dust suppression system operates by receiving a 230V input power through the Miniature Circuit Breaker (MCB), which is then stepped down to 24V by the Switch Mode Power Supply (SMPS) for the control circuits. The Programmable Logic Controller (PLC) processes inputs such as dust levels and sends signals to the relays (R_1, R_2, R_3), which in turn control the terminals (SV_1, SV_2, and SV_3). When dust levels exceed a pre-set threshold value, the PLC activates the appropriate relay, powering the corresponding solenoid valve to release water to suppress the dust. The system continuously monitors and adjusts the operation of the solenoid valves based on real-time data to ensure effective dust suppression, while safety features like circuit breakers protect against electrical overloads. Regular maintenance ensures the system functions efficiently.

5.4 Hybrid System

The intricate turbine design, which combines atomizing and ultrasonic properties, is the system's central component. Through a semi-circular arc, compressed air enters through an air intake. One end of a swirl chamber is connected to the water input, while the other end leads to a tiny aperture. Through a water intake, pressurized water is introduced into the nozzle system. There, it is directed into the swirl chamber, where rotational fluid motion is created to improve water atomization and produce a solid cone spray pattern. To achieve high pressure, the spinning fluid is driven through a tiny aperture, atomizing water droplets to sub-micron sizes (10–20 µm) for efficient agglomeration with dust particles in the air. Dry fog is produced at the semi-circle arc by the mixing of compressed air from the air input with pressured water from the tiny aperture. The frustum, which is fastened to the hybrid nozzle with wings for flexible movement, controls the dry fog's spreading area and direction.

6. Design of an Intelligent Dust Suppression System for Controlling Dust Emission from Mineral Processing Plant

Designing an intelligent dust suppression system for mineral processing plants involves integrating advanced technologies to effectively mitigate dust emissions from various operational activities like material handling, crushing, and screening. The system typically incorporates automated mist fog and dry fog systems that activate only during active processing operations, minimizing water usage and optimizing dust control efficiency. For dry fog systems, water particles of optimal size are dispersed using compressed air, creating a fine mist that binds with airborne dust particles without wetting the material. Mist fog systems, on the other hand, use higher water volumes to effectively suppress dust, adhering to industry-specific moisture addition limits (typically less than 0.1% to 2% of material weight). Because of the way they are made, nozzles may be strategically positioned and controlled in response to real-time monitoring of dust levels and environmental factors like wind direction and speed. This intelligent approach not only enhances dust control effectiveness but also improves operational safety, reduces maintenance costs, and promotes environmental sustainability within the mineral processing plant. Fig. 11 shows the circuit diagram of the Control Panel for the dust suppression system.

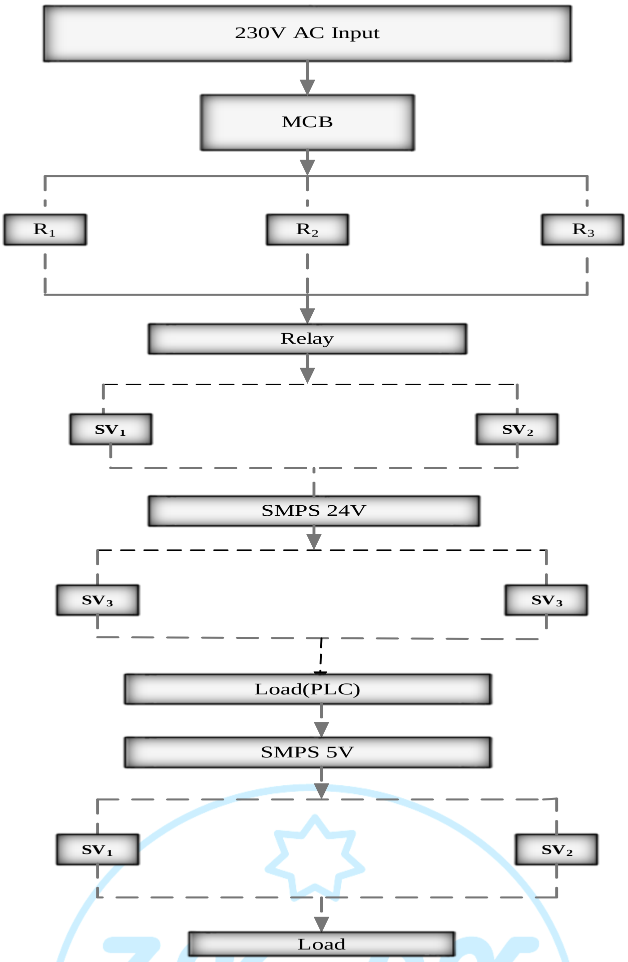

Fig. 11 Control Panel of the dust suppression system

Fig. 12 Display Unit Display and Unit Settings

Fig. 12 shows the Display Unit Display and Unit Settings. The technology was put in place in the crushing and screening facility at Donimalai Iron Ore Mine (DIOM) of M/s NMDC to reduce airborne fugitive dust that was produced and suspended in the environment as a result of plant operations. Measuring the amount of dust in the air and evaluating the amount of moisture added to the item being handled are two ways to gauge how successful the system is. Fig. 13 depicts a typical DSS.

Fig. 13 Dry fog dust suppression system

A DSS is designed to minimize airborne dust particles generated during industrial operations such as mining, construction, and material handling. By utilizing methods such as water sprays, fogging, and chemical agents, these systems help to improve the quality of air, minimize health hazards, and uphold regulatory compliance Eq (3).

$$D_s = \frac{[(Vc_1 - Vc_2)\times 100]}{Vc_1} \tag{3}$$

Where D_s is denoted as dust suppression system, $(Vc_1 - Vc_2)mg\ m^{-3}$ is denoted as before and after installation of DSS. DSS involves applying water or chemicals to materials to prevent fine particles from becoming airborne or to capture airborne particles and return them to the material bed. This method is advantageous because it eliminates the need for additional material handling, as the suppressed dust reintegrates into the main body of the conveyed material. Various systems are employed for dust suppression, ranging from simple garden hose techniques to advanced foam, fog, and spray systems for water and surfactants. Each technology introduces different amounts of moisture to the material, ensuring effective dust control while maintaining operational efficiency.

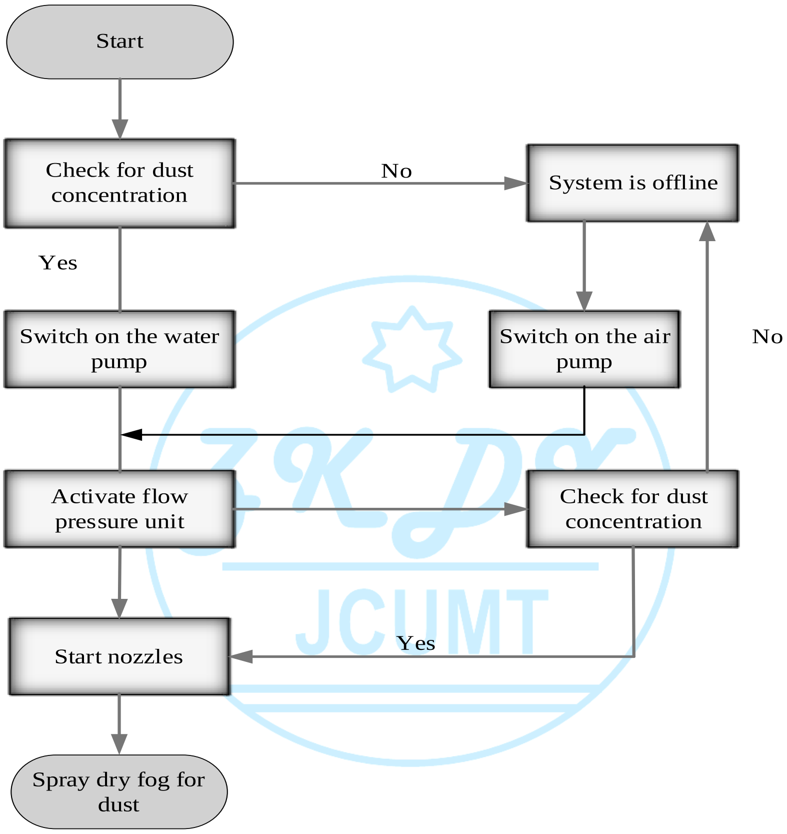

Fig. 14 Flowchart for the method framework

Fig.14 shows the processes for managing dust concentration using a dry fogging system. It begins by checking the dust concentration. If dust is detected, the water pump is activated, followed by the flow pressure unit, and then the nozzles spray dry fog, reducing the dust. If no dust is detected, the system goes offline. Periodically, the air pump is switched on to reassess dust levels, reactivating the sequence if dust is detected again. This cyclical process ensures continuous monitoring and control of dust levels using dry fog.

7. Performance Assessment of DSS in a Mineral Processing Plant

The performance assessment of the DSS in a mineral processing plant will focus on multiple key parameters to determine its efficacy. Primarily, the evaluation will compare the reduction in dust emissions at various sources within the plant, analyzing the information gathered both before and after the system was installed. Additionally, the ambient dust concentration in the buffer zone will be monitored to assess any improvements in air quality. The concentration of free silica in the work zone, a critical health indicator for work persons, will also be measured to ensure that the system significantly mitigates this hazardous component. Furthermore, the analysis will include an evaluation of the addition of moisture to the substance being handled, which plays a crucial role in dust suppression. The study compares metrics to clarify the impact of the system on dust control and health outcomes.

Further, the amount of water sprayed was measured, and the moisture content in iron ore samples that were taken both before and after the application of DSS at different points throughout the screening plant and crushing plant. These techniques were applied to assess the addition of moisture to the handling substance Eq (4).

$$M_c\% = \frac{(W_s + C) - (D_s + C)}{W_s - C} \times 100 \tag{4}$$

Where M_c is denoted as Moisture Content, W_s is represented as a Wet Sample, C is a container. The addition of moisture was analyzed using two different approaches: (i) based on the collection of iron ore samples, and (ii) based on the amount of water sprayed from nozzles. i.e. the amount of water thrown and the total number of nozzles that were in operation for a given amount of time were recorded. The following formula was used to determine the amount of water put into the handling material Eq (5):

$$M_c\% = \frac{T_n}{A_n} \times 100 \tag{5}$$

Where M_c is denoted as Moisture Content, T_n is denoted the total quantity of water blasted out of nozzles and A_n is represented as the quantity of a substance that gets into the nozzles.

8. Result and Discussion

Fugitive dust emissions in mines and allied plants, predominantly from processes like drilling, crushing, transferring, and transportation of minerals in bulk, pose significant monitoring and regulation challenges due to their dispersion by wind and other natural forces. To control the emission, Dry Fog Dust Suppression System (DSS) was implemented at various points in an iron ore processing plant. The effectiveness of the DSS was evidenced by a dramatic reduction in dust concentrations.

8.1 Fugitive Dust Emission (FDE)

FDE to the release of particulate matter into air during different mining activities like drilling, crushing, transferring, and transportation of minerals in bulk. Unlike emissions from controlled sources like smokestacks, fugitive dust is typically dispersed by wind and other natural forces, making it challenging to monitor and regulate. Dust concentrations at different monitoring locations were found varying from 363.18 to 7220.30 µg/m³ before installation of DSS which is much more than the maximum limit of 1200 µg/m³ recommended by MoEF&CC for iron ore processing plant. These values dropped dramatically from 95.60 to 300 µg/m³ when the DSS was put into use. The efficiency of DSS was demonstrated by the noticeable drop in the level of dust. Table 5 and Fig. 9 show the PM_{10} and $PM_{2.5}$ dust concentrations for the first shift and second shift in the processing plant.

8.1.1 At Screening Plant

A screening plant is a facility used in various industries to separate materials based on size or other physical properties. It uses a series of screens or sieves to sort materials like aggregates, soil, or waste into different categories for further processing or disposal. Screening plants are essential in mining, construction, and recycling operations to ensure efficient material handling and quality control.

Table 6 The quantity of dust in the screening plant both before and after the DSS

S. No.	Location	Dust concentration		Dust suppression efficiency of DSS (%)	Type of system installed
		Before installation of DSS	After installation of DSS		
1.	DF1	6050	80.50	98.66	Dry fog
2.	DF2	6900	89.25	98.62	Dry fog
3.	DF3	6925	98.75	98.57	Dry fog
4.	DF4	7400	108.30	98.53	Dry fog
5.	DF5	7870	117.25	98.51	Dry fog

Table 6 and Fig. 15 show the quantity of dust in the screening plant both before and after the use of the Dry Fog Dust Suppression System (DFDSS). The effectiveness of a (DFDSS) in a screening plant was examined at five different locations (DF1 to DF5). Before the installation of DFDSS, the dust concentrations in the said locations ranged from 6,050 to 7,870 µg/m³, suggesting a considerable amount of dust in the air. Once the DFDSS had been installed, the dust concentrations dramatically decreased to levels between 80.50 and 117.25 units, demonstrating the system's efficiency. The dust suppression efficiency of the DFDSS became consistently high, with values around 98.5% across all locations. This drastic reduction highlights the effectiveness of DFDSS in minimizing dust and improving air quality in the screening plant.

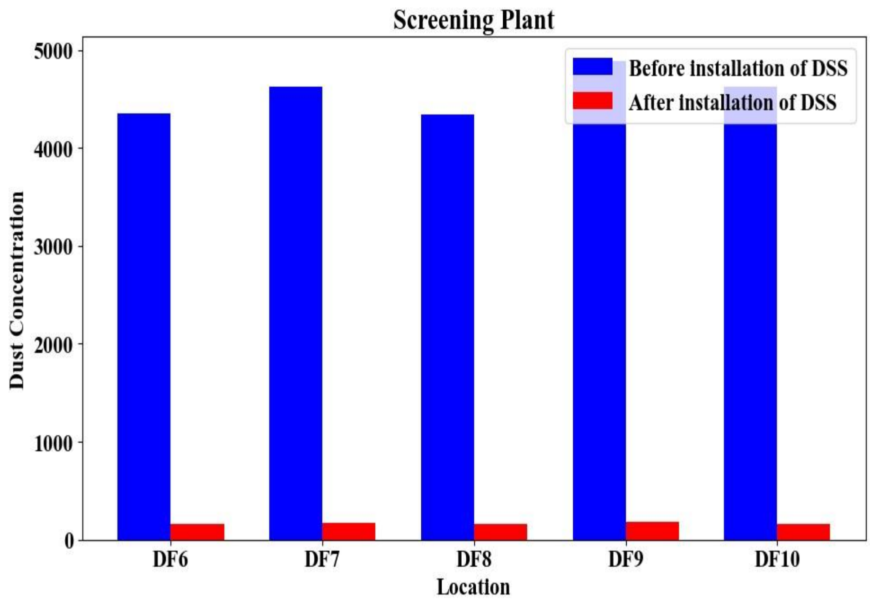

Fig. 15 The quantity of dust in the screening plant both before and after the DSS was installed

8.1.2 At Crusher

A crusher is a type of machinery used to break up big rocks into smaller pieces of rock, gravel, or dust. It works by applying force to break down materials through compression, impact, or shear. Crushers are commonly used in mining, construction, and recycling industries to process various types of raw materials.

Table 7 The quantity of dust in the Crusher both before and after the DSS

S. No.	Location	Dust concentration		Dust suppression efficiency of DSS (%)	Type of system installed
		Before installation of DSS	After installation of DSS		
1.	DF6	4350	155.50	96.4	Dry fog
2.	DF7	4620	166.8	96.3	Dry fog
3.	DF8	4340	156.3	96.3	Dry fog
4.	DF9	4890	178.2	96.3	Dry fog
5.	DF10	4630	165.4	96.4	Dry fog

Table 7 and Fig.16 represent data on dust concentration levels and the efficiency of a DFDSS installed at various locations around a crusher, identified as DF6 through DF10. Before the installation of the DFDSS, dust concentrations were significantly high, ranging from 4,350 to 4,630 units.

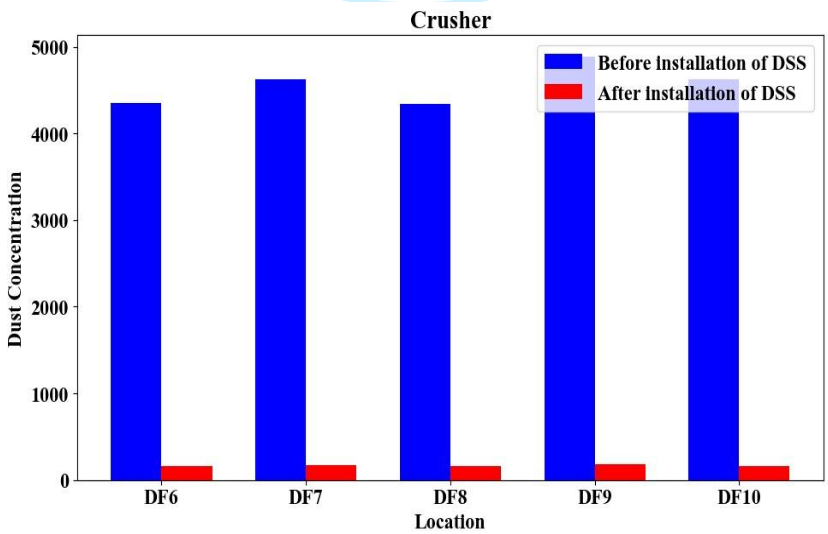

Fig. 16 The quantity of dust in the Crusher both before and after the DSS was installed

After the installation of DF DSS, there was a substantial reduction in dust levels, with concentrations dropping to between 155.5 and 165.4 units. The dust suppression efficiency of the system became consistently high across all locations, with values around 96.3-96.4%. This indicates that the DFDSS is highly effective in controlling emitted dust at these sites, leading to a safer and cleaner environment.

8.1.3 *At Surge Pile*

A surge pile is a large, temporary storage pile used in mining and allied operations to manage the flow of material between mining or quarrying operations and processing plants. It acts as a buffer to ensure a steady supply of material, helping to maintain consistent production levels even when there's a fluctuation in the feed from a quarry or primary crusher. Surge piles also allow for continuous operation during equipment maintenance or other disruptions

.

Table 8 The quantity of dust in the Surge pile both before and after the DSS

S. No.	Location	Dust concentration		Dust suppression efficiency of DSS (%)	Type of system installed
		Before installation of DSS	After installation of DSS		
1.	DF11	855.3	425.8	50.2	Mist fog
2.	DF12	890.7	453.8	49.0	Mist fog
3.	DF13	852.5	422.5	50.4	Mist fog
4.	DF14	925.2	451.5	51.1	Mist fog
5.	DF15	960.2	475.3	50.4	Mist fog

Table 8 and Fig. 17 reflect the impact of the Mist Fog Dust Suppression System (MFDSS) on dust concentration levels at various locations (DF11 to DF15) around a surge pile both before and after the use of MFDSS. Before the installation of the MFDSS, dust concentrations ranged from 855.3 to 960.2 µg/m³. After the installation of the system, these levels dropped significantly, with concentrations ranging from 425.8 to 475.3 µg/m³.

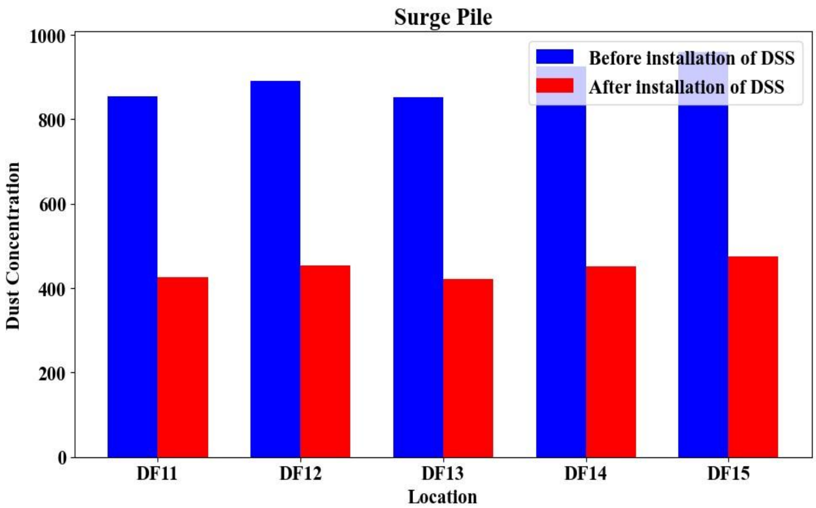

Fig. 17 The quantity of dust in the Surge pile both before and after the DSS was installed

The Dust Suppression Efficiency (DSE) across the locations varied slightly but remained consistent, with values between 49.0% and 51.1%. This indicates that the Mist Fog Dust Suppression System was effective in reducing airborne dust by approximately half across all monitored sites. This reduction is significant, demonstrating the reliability of the system in controlling airborne dust, thereby making the environment healthy.

8.1.4 At Conveyor

A conveyor is a mechanical system designed to transport materials from one location to another within a facility. It typically consists of a belt or chain that moves over rollers or a flat surface, driven by motors. In several sectors, conveyors are utilized, such as manufacturing, mining, and logistics to efficiently move goods, materials, or products, helping to streamline processes and reduce manual handling.

Table 9 The quantity of dust in the Conveyor both before and after the DSS

S. No	Location	Dust concentration		Dust suppression efficiency of DSS (%)	Type of system installed
		Before installation of DSS	After installation of DSS		
1.	DF16	1650.5	110.2	93.3	Dry fog
2.	DF17	1778.2	120.4	93.2	Dry fog
3.	DF18	1906.6	130.2	93.1	Dry fog
4.	DF19	1653.4	109.4	93.3	Dry fog
5.	DF20	1770.8	115.3	93.5	Dry fog

Table.9. illustrates the impact of DFDSS on dust concentration at various locations. Before the installation of DFDSS, dust concentrations ranged from 1650.5 to 1906.6 mg/m³. After installation of the system, dust levels decreased significantly between 109.4 and 130.2 mg/m³. Despite some variation in the actual dust concentrations, the efficiency of the DFDSS in reducing dust became consistently high, ranging from 93.1% to 93.5%. This demonstrates the effectiveness

of Dry Fog systems in maintaining high levels of dust suppression across all locations, thereby significantly improving air quality by reducing dust that became airborne during the operation of the conveyor system.

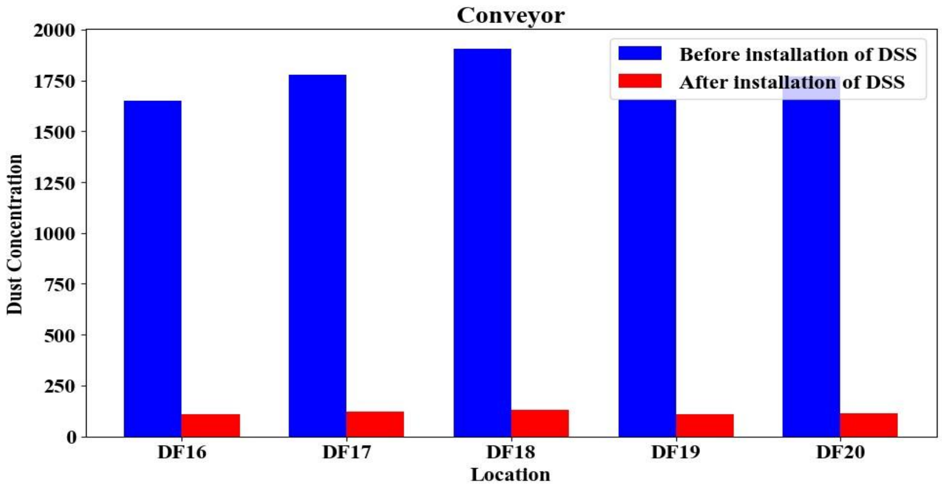

Fig. 18 The quantity of dust in the Conveyor both before and after the DSS was installed

Fig.18 illustrates the dust concentration at various conveyor locations (DF16 to DF20) before and after the installation of the System. The blue bars represent the dust concentration levels before the DSS installation, while the red bars represent the levels after the installation. The data clearly shows a significant reduction in the concentration of dust at all locations following the installation of DFDSS, thereby showing its effectiveness.

A comprehensive representation of the level of airborne dust at all locations during the study both before and after installation of the DSS is shown in Table 10 and Fig. 19 showcasing the effectiveness of the applied Dust Suppression System.

Table 10 The quantity of dust before and after the DSS was installed

S. No.	Location	Dust concentration (µg m^{-3})		Dust suppression efficiency of DSS (%)	Type of system installed Before installation of DSS
		Before installation of DSS	After installation of DSS		
1.	Screening plant	7220.30 (±394.25)	95.60 (±8.16)	98.6	Dry fog
2.	Crusher	2651.60 (±228.45)	172.50 (±12.44)	93.4	Dry fog
3.	Surge pile	896.78 (±27.41)	445.80 (±26.73)	50.2*	Mist fog
4.	Conveyor	1752.00 (±110.64)	117.00 (±10.91)	93.28	Dry fog

Key: * Effected due to open space on every side of the surge pile.

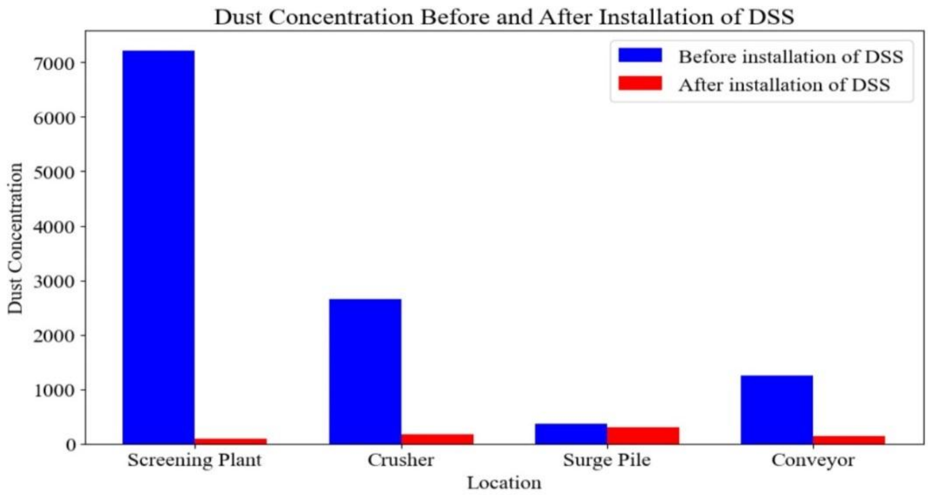

Fig. 19 The quantity of dust in the crusher and screening plant both before and after the DSS was installed

From Table 10 and Fig. 19, it was found that dust concentrations dramatically dropped, from 896.78–7220 µg/m³ to 95.60–445.80 µg/m³. The screening plant's dust concentration significantly decreased from 7220 µg/m³ to 95.60 µg/m³ as a result of the efficient installation of dry fog nozzles, which surrounded the emission source in a dust fog cloud. Dust concentrations at the crushing plant decreased from 2651.60 µg/m³ to 172.50 µg/m³. This was due to the effective installation of dry fog nozzles and the use of hybrid nozzles with built-in direction mechanisms to regulate the fog's direction. Furthermore, applying mist fog at the surge piles decreased the amounts of dust from 896.78µg/m³ to 445.80 µg/m³. The material moved by belt conveyors saw a drop in dust concentration from 1752 µg/m³ to 117 µg/m³ due to the application of dry fog and the placement of rubber skirts around the hoods. After the automated dust suppression system was installed, it was found that dust concentrations at all sites inside the crushing and screening plant decreased substantially below the allowable limit of 1200 µg/m³. The efficient design of the system, which considered several variables including the plant's operating capacity, the properties of the material, the climate, the region, the capacity of the crushing and screening plant, the technology employed in the process, the quality and availability of the water, power requirements, automation needs, and the amount of moisture that could be added to the material being handled, resulted in an effective reduction of dust emissions. In the current investigation, the dry fog system's efficacy at suppressing dust varied from 93.28% to 98.6%.

8.2 Addition of Moisture to Ore Material

By monitoring the quantity of water sprayed on the substance by nozzles and comparing the moisture content of iron ore samples obtained at various locations in the crushers and screening plant before and after the application of DSS, the amount of moisture added to the material was determined.

9. Conclusion

The developed dust suppression system effectively combines hybrid ultrasonic and atomizing nozzles to create a sub-micron dry fog for accurate dust agglomeration, settling particles with minimal moisture addition. Operating in both manual and automated modes via PLC and various sensors, it ensures continuous operation and remote control capabilities. The pollution sensor triggers the system to maintain dust levels within the 1200 $\mu g/m^3$ standard at a distance $25 \pm 2m$ from the source. A creative, inventive, and intelligent gadget, the DSS uses an atomizing nozzle in conjunction with hybrid ultrasonic nozzles to spray dry fog by atomizing water droplets as small as sub-micron meters in size($1-20\mu m$ size), allowing for precise aggregation with $PM_{2.5}$ and PM_{10} dust particles. The fugitive dust emission is primarily downwind from the dust-generating source at a distance of $25 \pm 2m$, far inside the 1200 $\mu g/m^3$. Future advancements in real-time dust monitoring and analysis will leverage AI, IoT, and nanotechnology to achieve unprecedented accuracy and predictive capabilities, significantly enhancing environmental and health safety measures. Significantly less water was introduced to the material by mist fog and dry fog systems than the maximum limits of 2% and 0.1%, respectively. The dry fog system has a higher efficacy of dust suppression than the mist fog system.

Compliance with Ethical Standards

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Ethical Approval: This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to Participate: All the authors involved have agreed to participate in this submitted article.

Consent to Publish: All the authors involved in this manuscript give full consent for publication of this submitted article.

Authors Contributions: All authors have equal contributions in this work.

Data Availability Statement: Data sharing not applicable to this article.

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