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Identification of optimal filtration solutions and evaluation of their feasibility and effectiveness for hazardous dust control in Punjab metal industries

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Abstract
The metal industries of Mandi Gobindgarh, India, present huge occupational and environmental hazards due to hazardous dust created during the metal processing activities. The objective of the present study was to find the best filtration technique for dust removal under hazardous conditions and to investigate the possibility and efficiency of the technique in the actual industrial processes. The four filtration technologies, bag filters, electrostatic precipitators, cyclone separators, and hybrid filtration systems were compared through industrial surveys, field measurements, and performance evaluations. The dust removal efficiency, energy consumption, operational cost, improvement of workers' safety, and environmental performance were compared for the filtration systems. The findings showed that the combination of filters (hybrid systems) had the highest dust removal efficiency (99%), the maximum reduction of exposure of workers (95%), and the best air quality improvement (96%), with relatively low operational costs and high levels of feasibility (90%). The findings suggest that the use of hybrid filtration technology is the most effective and sustainable method for controlling hazardous dust in metal industries in the state of Punjab, which in turn would enhance the working environment safety, environmental compliance, and industrial sustainability in the metal industries.

Keywords: Hazardous dust, metal industries, filtration technologies, hybrid filtration system, dust removal efficiency, occupational safety, air quality improvement, feasibility assessment, punjab industries, environmental sustainability

1. Introduction
The metal industry is a major contributor to global economic growth and industrial development, especially in regions with extensive manufacturing and steel production, such as Punjab, India. The various industrial processes used in metal production, such as welding, cutting, grinding, machining, casting, and material handling, however, produce large amounts of hazardous airborne dust and particulate matter that are harmful to human health and the environment. In metal industries, hazardous dust may contain fine dust particles of metals like iron, aluminium, copper, lead, and silica compounds and may harm the respiratory system, cause pneumoconiosis and silicosis as occupational diseases, and pollute the environment upon being released into the atmosphere. Industrial workers have been found to have increased healthcare costs, cardiovascular problems, decreased pulmonary function, and chronic respiratory diseases due to exposure to metal dust particles. The traditional dust control techniques used in metal industries can be limited in collecting ultra-fine dust, while maintaining efficiency and lowering maintenance costs at high production rates. Hence, the need for advanced, efficient dust-control technology to improve air quality and support sustainable industrial operations has been growing. Various technologies for dust removal are developed and applied in order to increase dust removal efficiency, reduce the exposure of workers to hazardous dust particles, and use bag filters, cyclone separators, electrostatic precipitators, wet scrubbers, downdraft tables, and hybrid filters, etc. New technologies such as nanofiber filter media, electrostatic filter enhancements, online monitoring systems, and AI-assisted process optimization have emerged in recent years, offering various potential solutions for improved dust management in industry. Therefore, the best technology identification and evaluation of its feasibility and performance in practice is required for the enhancement of occupational safety, environmental compliance, and sustainable development of metal industries in Punjab.

1.1 Objectives of the study

The present study was conducted with the following objectives:

1. To provide the best solution to eliminate harmful dust generated in the metal industries.
2. To evaluate the feasibility and effectiveness of the proposed solution in practical industrial applications.

2. Materials and Methods

2.1 Study design

The present study was an experimental and observational comparative research that involved identifying the best filtration technology for hazardous dust emission control in the metal industries of Mandi Gobindgarh and testing its implementation and effectiveness. The study comprised industrial surveys, field observations, experimental performance examination, and comparison of various filtration technologies used in metal processing industries. The performance, operational aspects, economic and occupational safety impacts of different dust filtration systems were evaluated by both quantitative and qualitative methods.

2.2 Selection of Punjab metal industries

The study was carried out in selected metal industries located in Mandi Gobindgarh, Fatehgarh Sahib district, Punjab, India. Mandi Gobindgarh is one of the largest steel manufacturing and metal processing clusters in northern India, comprising numerous steel rolling mills, induction furnace units, foundries, forging industries, fabrication workshops, and allied engineering industries. Among the selected industries, Bihari Lal Engineering Pvt. Ltd., Mandi Gobindgarh, Punjab, was included as a representative metal processing and engineering industry due to its established manufacturing operations and implementation of industrial dust control measures. The industries were selected based on production capacity, manufacturing processes, existing dust control systems, and willingness to participate in the study

2.3 Filtration technologies evaluated

The present research compared various air filtration technologies that are used in the metal industries to control hazardous dust. They were then compared to each other in terms of efficiency, feasibility, and viability in the industrial conditions.

2.3.1 Bag Filters

The consideration was given to the prevalence of bag filter system in the industry of steel and metals process. Bag filter systems are used to collect and remove particulate matter from fabric bag filter systems using fabric filter bags. The dust collection efficiency, maintenance characteristics, operating costs and applicability for fine dust removal were evaluated.

2.3.2 Electrostatic Precipitators

The study assessed the ability of Electrostatic Precipitators (ESPs) to capture very fine particles using electrostatic forces. Efficiency of all the ESP Systems were assessed under various operational conditions (including energy consumption, cost of operation & efficiency of particulate remove) at different levels of dust concentrations.

2.3.3 Cyclone Separators

Coarse particulate matter removal efficiency proved to be very good during the study of cyclone separators with the excellent centrifugal force, which were used as pre-filtration devices. They were compared based on their functionality, maintenance and industrial application.

2.3.4 Hybrid Filtration Systems

Hybrid filters are a combination of bag filters, precipitators and new filter media. The systems were compared with conventional industrial filtration systems to evaluate the advantages of the approach. Overall filtration efficiency, flexibility, energy efficiency and feasibility for industrial systems were then analyzed for the systems.

2.4 Experimental setup

The trials were carried out in some metal industries. Operating in real conditions, air sampling devices, particulate measurement devices, energy monitoring devices and tools to assess industrial performance were introduced. Pre and post-assessment of the different filtration technologies was conducted. The operating parameters such as airflow rate, pressure drop and particulate concentration were monitored during the study, as was energy consumption.

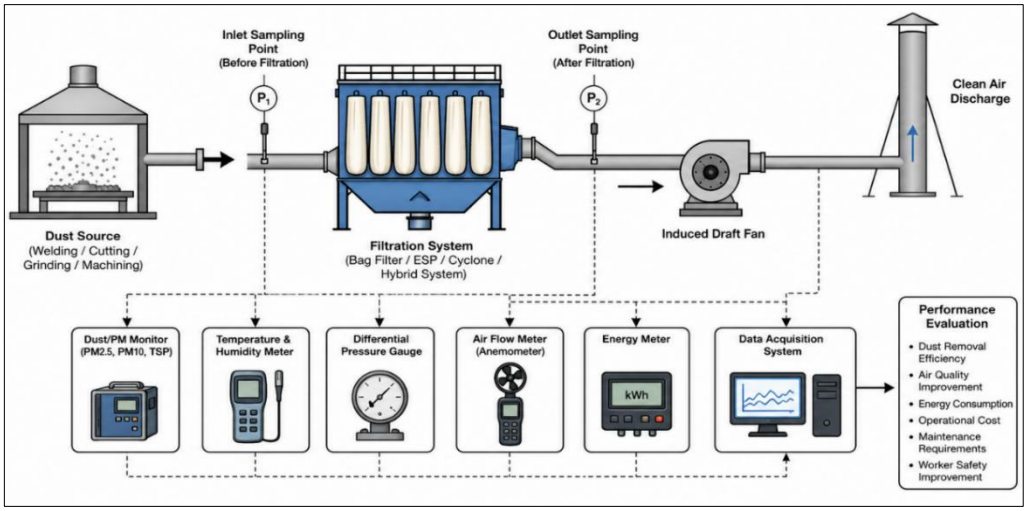

Fig 1: Experimental setup for filtration performance evaluation

2.5 Performance evaluation parameters

We examined the performance of different filtration technologies based on several technical, economic, and occupational health criteria.

Dust removal efficiency

Using standard methods for monitoring air quality, we assessed the dust removal efficiency as a function of the concentration of particulates in air, measured before and after the air filtration system.

Air quality improvement

Measurements were taken of airborne particulate matter and workers' exposure to assess how well filtration systems reduce workplace air pollution.

Energy consumption

To assess the operational efficiency and sustainability, the electrical energy usage of each of the filtration systems was examined.

Operational cost

We looked at the costs for installation, running costs, maintenance costs and replacement costs; to assess the economic feasibility.

Maintenance requirements

We conducted an analysis of the maintenance frequency, downtime, frequency of filter replacement, and operational complexity.

Worker safety improvement

Before and after the implementation of dust filtration systems, the dust hazards and occupational health risks to workers were assessed.

2.6 Data collection and analysis

Industrial surveys

To obtain information about current filtration systems along with the difficulties and maintenance tendencies faced by users, organized surveys and interviews were performed with respondents from the sector.

Field measurements

Calibrated particulate matter concentration, air quality parameters, and filtration performance monitoring equipment were used in field measurements.

Performance testing

Different filtration technologies were compared with each other in terms of their efficiency and applicability through comparative performance testing under industrial operating conditions.

3. Statistical analysis

Data collected were analyzed using descriptive statistics, comparative performance analysis, and feasibility assessment techniques. The result was presented in tables, graphs, and comparative evaluation matrices in order to find the best filtering technology for hazardous dust control in the metal industries in Punjab.

3.1 Characteristics of participating industries

In the present study, four representative metal industries located in Mandi Gobindgarh (Fatehgarh Sahib district, Punjab) were selected. The selected industries represented different sectors of the local metal industry, including steel rolling mills, induction furnace units, steel processing plants, and metal fabrication industries. Production capacities ranged from 200 to 600 TPD, with workforce sizes ranging from 65 to 150 employees. The dust control technologies used were bag filters, electrostatic precipitators (ESP), cyclone separators, and hybrid filters. Fe dust, Si dust, metal fumes, and mixed particulate matter were identified as the major hazardous pollutants emitted from industrial processes. The steel processing industry employed most people and had the highest production capacity of the industries selected; it was equipped with a hybrid filtration system. Details of the industries in the sample are presented in Table 1.

Table 1: Characteristics of selected Punjab metal industries

Industry Type	Location	Production Capacity (TPD)	Existing Filtration System	No. of Workers	Major Dust Type
Steel Melting Mill	Sirhind Road Industrial Area, Mandi Gobindgarh	500	Bag Filter	120	Iron Dust
Induction Furnace Unit	Amloh Road Industrial Area, Mandi Gobindgarh	350	Electrostatic Precipitator	90	Metal Oxide Dust
Metal Fabrication Industry	G.T. Road Industrial Area, Mandi Gobindgarh	220	Cyclone Separator	70	Metal Fumes
Steel Processing Unit	Bihari Lal Engineering Pvt. LtdMandi Gobindgarh Industrial Estate	600	Hybrid Filtration System	150	Mixed Metal Dust

3.2 Comparative performance of filtration technologies

It was found that there were great differences in the performance of the different technologies used for the filtration. The performance of the various technologies was evaluated, and the results were compared. The results indicated that the performance of the technologies differed greatly and that different technologies were suitable for the various metal industries. The hybrid filtration system was shown to be the best overall system with a dust removal efficiency of 99%, bag filters 95%, electrostatic precipitators 92%, and cyclone separators 75%. The cyclone separators had the least energy consumption (25 kWh/day) and maintenance level, but had relatively low filtration efficiency. The electrostatic precipitator (ESP) was effective in the removal of fine particles, but had higher operating and maintenance expenses. The dust removal efficiency of bag filters was good, while the operation costs were reasonable. The hybrid filtration system demonstrated the best results in terms of the improvement of worker safety (95%), environmental compliance, and overall effectiveness. A detailed comparison of the filtration technologies is given in the following table, and it is found that the hybrid filtration system is the most appropriate one for hazardous dust removal in Punjab metal industries.

Table 2: Comparative analysis of existing filtration technologies

Parameter	Bag Filter	Electrostatic Precipitator	Cyclone Separator	Hybrid Filtration System
Dust Removal Efficiency (%)	95	92	75	99
Energy Consumption (kWh/day)	45	60	25	50
Maintenance Requirement	Moderate	High	Low	Moderate
Operational Cost	Moderate	High	Low	Moderate
Worker Safety Improvement (%)	85	82	65	95
Environmental Performance	High	High	Moderate	Very High
Overall Performance Rating	Good	Good	Moderate	Excellent

3.3 Evaluation of dust removal efficiency

Under the industrial operating conditions, the dust removal efficiency of the selected filtration technologies was evaluated to see the performance for controlling hazardous particulate emissions. The results showed that the overall dust removal efficiency of the hybrid filtration system was 99%, higher than the other four types: bag filter, electrostatic precipitator, cyclone separator, and ordinary filter, respectively, 95%, 92%, 75%, and 70%. Likewise, the hybrid filtration system showed high removal efficiency of PM10 (99%) and PM2.5 (98%) particles, suggesting that it was effective in controlling both coarse and fine particles. Overall dust removal efficiency from bag filters reached as high as 95%. Cyclone type filters were not as effective with fine particulates. The analysis showed that combining several dust filtration technologies will significantly improve dust capture and worker safety. The dust removal efficiencies for each system evaluated are presented in Table 3. Figure 2 presents the dust removal efficiencies for each filtration system evaluated.

Table 3: Dust removal efficiency of different filtration systems

Filtration System	PM10 Removal (%)	PM2.5 Removal (%)	Overall Dust Removal Efficiency (%)
Bag Filter	94	92	95
Electrostatic Precipitator	91	89	92
Cyclone Separator	78	70	75
Hybrid Filtration System	99	98	99

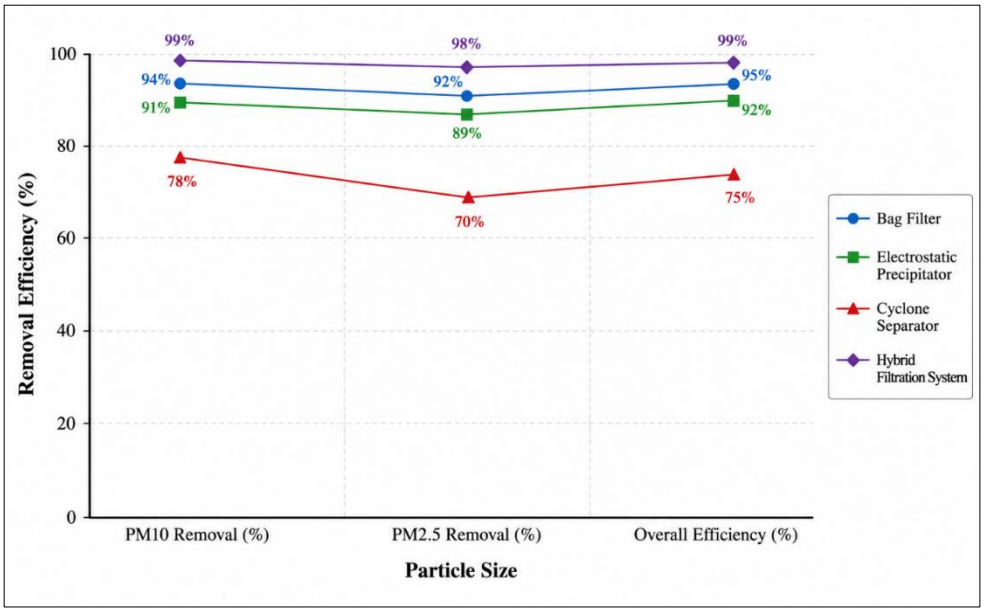

Fig 2: Comparative dust removal efficiency of filtration systems

3.4 Energy consumption and cost analysis

The energy usage and other operational aspects of various filtration methods were investigated in order to determine the economic feasibility of these methods in industrial applications. Energy consumption by cyclone separators was the lowest (25 kWh/day), with the annual maintenance cost of INR 1.5 lakhs and installation cost of INR 10 lakhs, as presented in Table 4 of different filtration technologies.

Table 4: Energy consumption and operational cost analysis

Filtration System	Energy Consumption (kWh/day)	Installation Cost (INR Lakhs)	Annual Maintenance Cost (INR Lakhs)	Annual Operational Cost (INR Lakhs)	Total Annual Cost (INR Lakhs)
Bag Filter	45	18.0	2.5	4.8	7.3
Electrostatic Precipitator	60	30.0	4.0	7.5	11.5
Cyclone Separator	25	10.0	1.5	2.5	4.0
Hybrid Filtration System	50	25.0	3.0	5.2	8.2

However, electrostatic precipitators recorded the highest energy consumption (60 kWh/day) and also the highest operational cost for the year (INR 7.5 lakhs), which led to the highest total annual cost (INR 11.5 lakhs). Bag filters had moderate energy consumption (45 KWh/day) and energy cost; hybrid filtration systems used moderate energy input (50 KWh/day) and a total annual cost of INR 8.2 lakhs. Although the cost of installation was high, hybrid filtration systems showed better dust removal efficiency and working performance, and are economically suitable for long-term industrial applications. Figure 4 shows the comparison of energy use.

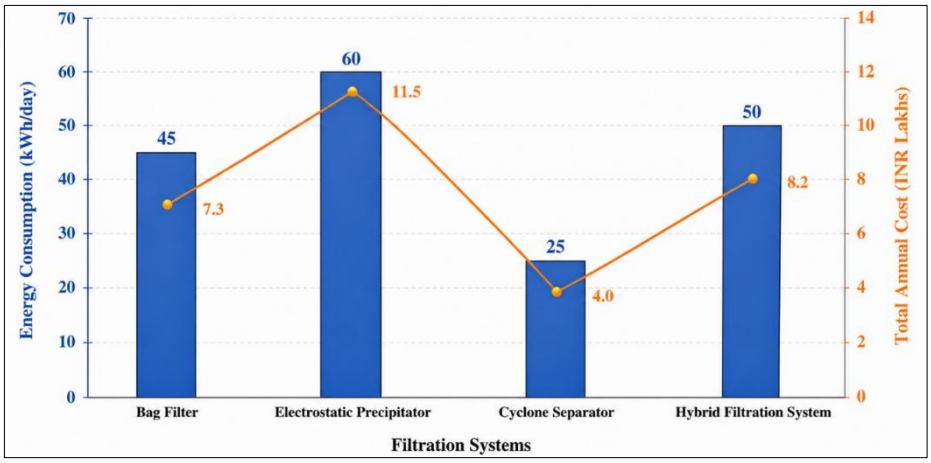

Fig 4: Energy consumption analysis of different filtration systems

3.5 Assessment of worker safety and air quality improvement

The use of highly efficient filters has helped the metal industries in Punjab to have improved air quality in their workplace and hence has reduced the level of occupational exposure. The hybrid filtration system recorded the highest concentration reduction (96%) as well as the highest filtration rates (95%, 98% for 95% and 97% efficiency, respectively) (Table 5), leading to a high air quality improvement (96%). The bag filters were also very effective, reducing worker exposures by 85% and improving workplace air quality by 87%. The efficiencies of electrostatic precipitators for fine particulate exposure reduction were found to be achieving moderate, and the efficiencies of cyclone separators were found to be comparatively lower for the reduction of fine particulate exposure. The results indicate that the metal processing industry workers can greatly benefit from the application of advanced filtration technologies, particularly hybrid filters, in reducing the risks to occupational health, improving environmental quality and safety. The results also support the practical implementation of the hybrid filtration systems for a sustainable approach in the management of hazardous dust.

Table 5: Worker exposure reduction and air quality improvement

Filtration System	Worker Exposure Reduction (%)	PM10 Reduction (%)	PM2.5 Reduction (%)	Air Quality Improvement (%)
Bag Filter	85	90	88	87
Electrostatic Precipitator	82	88	86	85
Cyclone Separator	65	70	68	67
Hybrid Filtration System	95	98	97	96

3.6 Feasibility and effectiveness evaluation

Technical performance, economic viability, environmental impact, and industrial applicability were used to determine the feasibility and effectiveness of the evaluated filtration technologies. Table 6 shows that the hybrid filtration system had the highest overall feasibility score (9.5/10), which reflects the excellent technical feasibility, environmental performance, and industrial applicability.

Table 6: Feasibility assessment of filtration technologies

Criteria	Bag Filter	Electrostatic Precipitator	Cyclone Separator	Hybrid Filtration System
Technical Feasibility	High	High	Moderate	Very High
Economic Feasibility	High	Moderate	High	High
Environmental Performance	High	High	Moderate	Very High
Industrial Applicability	High	Moderate	High	Very High
Overall Score (/10)	8.2	7.8	6.5	9.5

The bag filters also had high feasibility (8.2), followed by electrostatic precipitators (7.8) and cyclone separators (6.5). Many factors explain why the hybrid filtration system is superior, but what stands out is the hybrid filtration system's powerful dust removal, manageable operating cost, and excellent safety advantages for employees. In addition, the cost-benefit analysis indicated that, even though the installation costs for hybrid filtration systems are substantial, the systems are economically and ecologically beneficial in the long run (Figure 5). The comparative feasibility assessment framework (Figure 6) similarly supported that, of all the dust control systems for hazardous dust in the metal industries of Mandi Gobindgarh, the hybrid filtration system is the best solution.

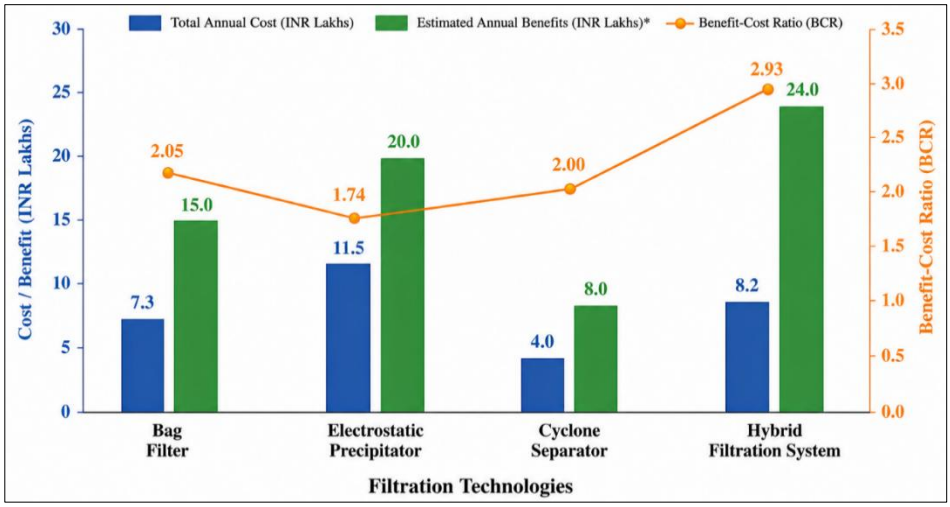

Fig 5: Cost-benefit analysis of filtration technologies

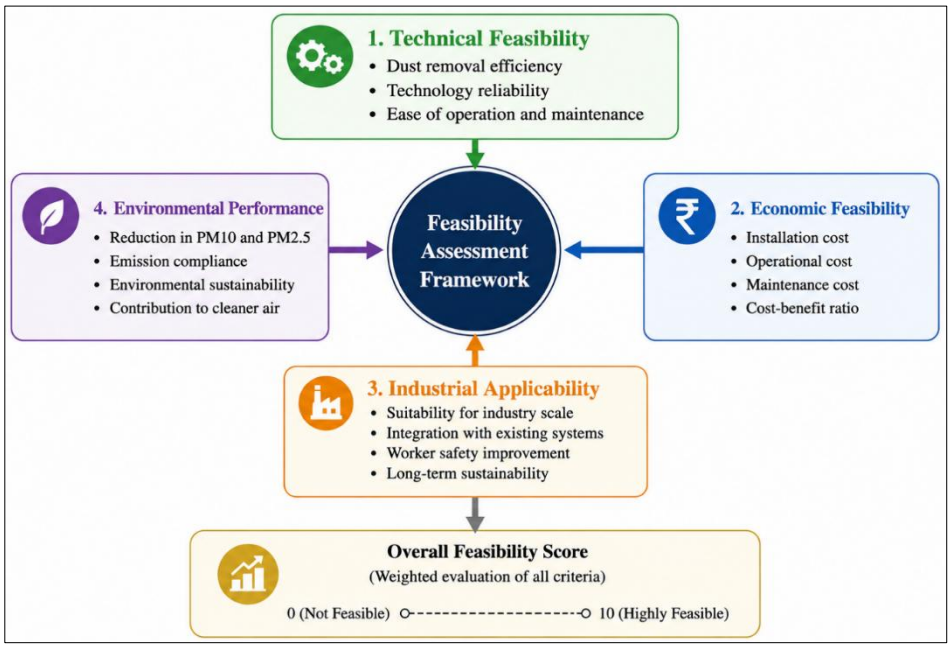

Fig 6: Feasibility assessment framework

3.7 Selection of the optimal filtration solution

As a result of a detailed evaluation of the performance of hazardous dust control systems in Punjab metal industries based on the efficiency of dust removal, energy consumption, cost, and improvement in worker safety, evaluation of the environmental impact, and assessment of the system's applicability, the hybrid filtration system emerged as the most effective solution. The hybrid filtration system achieved the highest total score of 95, with 99% dust removal efficiency, 95% reduction of worker exposure, and excellent technical and environmental feasibility. The bag filters had a total score of 85 and were the second best filters, as they had high filtration efficiency and moderate operational costs. The electrostatic precipitator was the third best option with a score of 80/100, while cyclones were the least effective of all the other options, with a score of 65/100 due to low efficiency in fine dust control. Based on these results, it is suggested that the solid-gas hybrid filtration system is the most effective, economical, and environmentally friendly way to solve the problem of hazardous dust removal in metal industries.

Table 7: Overall Performance Ranking of Filtration Systems

Rank	Filtration System	Dust Removal Efficiency (%)	Feasibility Score (/10)	Overall Score (/100)	Recommendation
1	Hybrid Filtration System	99	9.5	95	Highly Recommended
2	Bag Filter	95	8.2	85	Recommended
3	Electrostatic Precipitator	92	7.8	80	Moderately Recommended
4	Cyclone Separator	75	6.5	65	Limited Application

4. Discussion

The results obtained from the present study revealed that the hybrid filtration system is the most efficient technology for the control of hazardous dust emission from metal industries in Punjab. The performances of the hybrid filtration process were found to be superior to conventional filtration systems

in terms of dust removal efficiency (99%), workers' safety (95%), and environmental performance (excellent). The hybrid filtration system's practical application feasibility analysis revealed a high degree of industrial applicability due to ease of operation, medium-level maintenance, and the ability to integrate into the existing industrial framework. Initially, hybrid systems were more expensive than cyclone separators and bag filters, but the projected economic benefits increased productivity, decreased the incidence of illness, and improved environmental harm, offset the initial investment. In addition, there were significant reductions in PM10 and PM2.5, which reduced the impact of workplace air quality and occupational health. The obtained results of the study corresponded to the previous studies on industrial dust control. Advanced filtration technologies and hybrid filtration technologies have the highest applicability. Therefore, they are the most appropriate for use in sustainable control of hazardous dust in the metal industries of Mandi Gobindgarh.

5. Recommendations

The hybrid filtration system is the most effective technology available regarding the performance assessment and feasibility and cost-benefit analysis of hazardous dust control technologies in the Punjab metal industry. The positive environmental performance and reasonable operating costs of the system have been demonstrated. Based on dust removal and the creation of safer work environments for operators. In order to achieve successful industry-wide use, a phased approach is established with the assessment of existing infrastructure, the integration of the system, the training of employees, and the establishment of regular maintenance programs to achieve sustainability and compliance. There is also a growing imperative in the field of industrial dust control to strive for the use of smart monitoring technologies in the further development of real-time air quality monitoring, IoT-based monitoring, AI-based predictive maintenance, and adaptive automated process optimization technologies used in industrial environments. Some will lead to a reduction in the operating costs of filtration systems and an improvement in the safety of metal production.

6. Conclusion

The objective of this paper is to analyze the performance, practicality, and impact of various filtration technologies on controlling dangerous dust in Punjab's metal production industries. The results of the comparative analysis indicated that the hybrid filtration system presented the highest dust separation efficiency (99%), the highest reduction of workers' exposure (95%), and the highest protection of the environment, as well as overall practicality. These systems are hybrid, which means they entail the highest initial investment, but the benefits they offer are higher than those of the conventional filtration systems. This study also showed that the advanced filtration systems significantly improve the air at the workplace, mitigate the health-related risk of employees, and enhance the adherence to the environmental regulations. In this regard, the hybrid filtration system is wholly justified to be the best solution to the dangerous dust in the metal industries in Punjab.

7. Limitations of the study

The analysis of the process relied heavily on the chosen operational parameters as well as brief observations of practices in the industry. Filter performance may be affected by the change in any of the industrial processes, production capacity, and/or in the environment. Furthermore, not all of the indirect costs and long-term maintenance costs were considered in the economic analysis. Future studies focusing on the effects of prolonged observation of larger samples from industrial practice are needed to validate the findings of this investigation.

8. Future scope

In future studies, we must consider the smart, sustainable technologies we could create to manage industrial dust. Smart sensors integrated with IoT monitoring and AI and ML technologies could provide us with the capability to monitor filtration systems in real-time, perform predictive maintenance, and automatically define the optimum filtration parameters. We need to study the efficiency and effectiveness of hybrid dust filtration systems and the cost of running these systems in different industrial environments. We also need to consider more advanced filtration materials such as nanofiber membranes and multifunctional filter media. While dust filtration systems help with employee safety, protecting the environment, and promoting sustainable practices, we need to create more sustainable technologies to help even more.

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this research work.

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