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A Predictive Framework for Air Environmental Impact Evaluation of Industrial PM_{10} Dispersion Using Atmospheric Modelling

Rohan Patel[1], Darshan Salunke[2]
[1,2] *Department of Environmental Science & Technology, UPL University of Sustainable Technology, Ankleshwar, Gujarat, India.*

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Corresponding Author:
Rohan Patel

Abstract:
Industrial air quality assessment increasingly relies on predictive modelling techniques to evaluate potential environmental impacts prior to project implementation and during routine operations. Although atmospheric dispersion models are extensively applied for regulatory compliance, their integration into Environmental Impact Assessment (EIA) remains largely focused on isolated emission sources, with comparatively limited emphasis on cumulative impacts arising from multiple industrial activities. This study presents a predictive framework for assessing PM_{10} dispersion by integrating regulatory atmospheric dispersion modelling within an Environmental Impact Assessment approach for a representative industrial facility.The proposed framework combines emission characterization, site-specific meteorological analysis, terrain representation, numerical dispersion simulation, and environmental impact evaluation to estimate ambient PM_{10} concentrations resulting from point, area, and transport-related emission sources. Model predictions are interpreted to identify dominant emission contributors, evaluate cumulative particulate loading, and assess compliance with applicable ambient air quality criteria. Rather than serving solely as a regulatory exercise, the modelling outcomes are utilized to support environmental planning, source prioritization, and development of practical mitigation strategies.The assessment demonstrates that near-surface operational activities exert a greater influence on localized PM_{10} concentrations than elevated emission sources because of differences in release characteristics and atmospheric dispersion behaviour. Predicted cumulative concentrations indicate acceptable ambient air quality under representative operating conditions while simultaneously identifying operational activities requiring focused emission control. The study highlights the potential of integrating atmospheric dispersion modelling into Environmental Impact Assessment as a practical decision-support framework for sustainable industrial development, environmental compliance, and proactive air quality management.

Keywords: Environmental Impact Assessment; Atmospheric Dispersion Modelling; PM_{10}; Air Quality Assessment; Regulatory Modelling; Industrial Emissions; Fugitive Dust; Sustainable Environmental Management

1. Introduction

Rapid industrialization has significantly contributed to economic development but has simultaneously intensified concerns regarding environmental sustainability and ambient air quality. Industrial activities generate a wide range of atmospheric pollutants through manufacturing processes, material handling operations, transportation, waste management practices, and fuel combustion. These emissions may alter local air quality, affect ecological systems, and increase human exposure to airborne contaminants. Consequently, predicting and managing atmospheric pollutant dispersion has become an essential requirement for environmentally responsible industrial planning.

Environmental Impact Assessment (EIA) provides a systematic framework for evaluating the potential consequences of developmental activities before and during project implementation. Rather than functioning solely as a regulatory requirement, contemporary EIA has evolved into an important decision-support process that integrates scientific analysis with environmental management. Among the various environmental components considered during EIA, ambient air quality assessment occupies a critical position because airborne pollutants can disperse beyond industrial boundaries and influence surrounding residential, ecological, and commercial areas. Accurate prediction of pollutant behaviour is therefore fundamental for designing effective mitigation measures and ensuring sustainable industrial growth (Canter, 1996; Glasson et al., 2013).

Particulate matter is recognized as one of the most environmentally significant air pollutants because of its persistence in the atmosphere and its potential impacts on public health. In particular, particulate matter with an aerodynamic diameter of less than 10 μm (PM_{10}) can remain suspended for extended periods and be transported over considerable distances depending on prevailing meteorological conditions. Industrial PM_{10} emissions arise from both combustion-related processes and non-combustion activities such as raw material storage, loading and unloading operations, waste handling, vehicle movement, and wind-driven resuspension of surface dust. Numerous epidemiological investigations have associated prolonged exposure to particulate matter with respiratory illnesses, cardiovascular diseases, and reduced pulmonary function, emphasizing the importance of effective particulate emission management (Pope & Dockery, 2006; World Health Organization, 2021).

While ambient monitoring networks provide direct measurements of pollutant concentrations, they are inherently limited to specific monitoring locations and observation periods. Monitoring data alone cannot predict future environmental conditions, evaluate proposed industrial modifications, or quantify the contribution of individual emission sources to cumulative air quality. Consequently, predictive atmospheric dispersion modelling has become an indispensable component of environmental assessment by enabling simulation of pollutant transport under representative meteorological conditions before environmental impacts occur (Holmes & Morawska, 2006).

Regulatory atmospheric dispersion models have undergone substantial development over the past two decades through improved treatment of boundary-layer processes, terrain effects, atmospheric stability, and source characterization. Among these, the American Meteorological Society/United States Environmental Protection Agency Regulatory Model (AERMOD) has been widely adopted for industrial environmental assessments because of its scientific robustness, computational efficiency, and acceptance by environmental regulatory agencies. The model accommodates multiple source configurations including point, area, volume, and line sources allowing comprehensive representation of complex industrial emission scenarios (Cimorelli et al., 2005; Perry et al., 2005; US EPA, 2023).

Recent investigations have successfully applied regulatory dispersion models to evaluate emissions from industrial estates, waste treatment facilities, transportation corridors, thermal power plants, mining operations, and manufacturing sectors. These studies demonstrate that integrating site-specific meteorological observations with detailed emission inventories substantially improves the reliability of air quality predictions and strengthens environmental decision-making (Hongthong & Nakapan, 2023; Pandey et al., 2024; Bayraktar & Mutlu, 2024). However, a review of the available literature indicates that many investigations evaluate individual emission sources independently, whereas comparatively fewer studies examine the cumulative influence of multiple industrial activities within a unified Environmental Impact Assessment framework. In addition, relatively limited attention has been devoted to translating model predictions into practical environmental management strategies that support operational planning and pollution prevention.

Addressing these limitations requires an assessment methodology capable of integrating diverse industrial emission sources while simultaneously evaluating their combined influence on ambient air quality. Such an approach not only enhances the scientific basis of Environmental Impact Assessment but also facilitates prioritization of pollution control measures according to their relative environmental significance. A comprehensive evaluation of cumulative emissions is particularly important for industrial facilities where elevated stacks, operational areas, waste management activities, and transportation systems function simultaneously and interact under changing meteorological conditions.

In this context, the present study proposes a predictive framework for integrating regulatory atmospheric dispersion modelling into Environmental Impact Assessment for industrial PM_{10} emissions. The study evaluates the cumulative influence of multiple emission sources under representative meteorological conditions, identifies dominant contributors to ambient particulate concentrations, and interprets the modelling outcomes from the perspective of environmental planning and regulatory compliance. By shifting the emphasis from software application to environmental decision-making, the proposed framework provides a practical methodology for supporting sustainable industrial development and scientifically informed air quality management.

2. Literature Review

2.1 Evolution of Air Quality Assessment within Environmental Impact Assessment

Environmental Impact Assessment has progressively evolved from a project-specific regulatory requirement into an integrated environmental planning instrument that supports sustainable industrial development. Early environmental assessments primarily relied on baseline environmental monitoring and qualitative impact prediction. However, increasing industrial complexity, stricter environmental regulations, and growing public concern regarding air pollution have necessitated the adoption of quantitative assessment techniques capable of predicting future environmental conditions before project implementation. Consequently, predictive air quality assessment has become an essential component of modern Environmental Impact Assessment, enabling environmental managers to evaluate alternative operational scenarios, estimate cumulative impacts, and formulate scientifically justified mitigation strategies (Canter, 1996; Glasson et al., 2013).

Unlike conventional monitoring programmes that represent existing environmental conditions, predictive assessment tools provide the capability to estimate pollutant dispersion under varying operational and meteorological conditions. Such predictive approaches are particularly valuable during environmental clearance, facility expansion, and industrial planning, where future environmental consequences must be evaluated before implementation (Radzuan & Martin, 2024).

2.2 Complexity of PM_{10} Emissions in Industrial Environments

Industrial PM_{10} emissions originate from diverse operational activities that differ substantially in emission mechanisms, release heights, temporal variation, and dispersion characteristics. While elevated stacks discharge pollutants through controlled release systems, significant quantities of particulate matter may also originate from material transfer operations, waste handling, vehicle movement, loading and unloading activities, exposed storage areas, and wind-induced dust resuspension. The interaction of these emission categories creates a complex atmospheric environment in which cumulative particulate concentrations cannot be accurately represented through isolated source evaluation.

Previous investigations have demonstrated that ground-level fugitive emissions frequently exert greater influence on local ambient particulate concentrations than elevated stack emissions because pollutants are released directly within the human breathing zone and experience limited atmospheric dilution immediately after release (Holmes & Morawska, 2006). Consequently, comprehensive industrial air quality assessment increasingly emphasizes simultaneous evaluation of all significant emission sources rather than concentrating exclusively on regulated process emissions.

In addition to environmental concerns, PM_{10} remains an important public health issue because inhalable particles are associated with respiratory disorders, cardiovascular diseases, and long-term reductions in pulmonary function. Recognizing these impacts, international organizations and regulatory authorities have established increasingly stringent ambient air quality guidelines to minimize population exposure to particulate matter (Pope & Dockery, 2006; World Health Organization, 2021).

2.3 Advances in Regulatory Atmospheric Dispersion Modelling

The increasing availability of computational resources has substantially enhanced the application of atmospheric dispersion models in environmental assessment. Modern regulatory models integrate emission characteristics with atmospheric boundary layer physics, terrain interactions, and meteorological observations to estimate spatial pollutant distributions with improved reliability. These models have become indispensable tools for evaluating industrial emissions because they permit assessment of hypothetical operating conditions that cannot be investigated using conventional monitoring alone.

Among the available regulatory models, AERMOD has become one of the most widely accepted modelling systems because it incorporates advanced boundary-layer parameterization while maintaining computational efficiency suitable for regulatory applications. The model is capable of representing point, area, volume, and line sources within a unified modelling environment, thereby enabling assessment of complex industrial facilities comprising multiple emission categories (Cimorelli et al., 2005; Perry et al., 2005; US EPA, 2023).

Recent developments have expanded the application of regulatory dispersion models beyond compliance demonstration to include environmental planning, cumulative impact assessment, emission source prioritization, infrastructure development, and environmental risk management. Integration with Geographic Information Systems (GIS), remote sensing products, and advanced meteorological datasets has further improved the applicability of dispersion modelling within Environmental Impact Assessment studies (Hongthong & Nakapan, 2023).

3. Methodology

3.1 Research Framework

The present investigation was designed as a predictive environmental assessment aimed at evaluating the influence of industrial PM_{10} emissions on surrounding ambient air quality. Rather than considering atmospheric dispersion modelling solely as a regulatory requirement, the study integrates numerical simulation within the Environmental Impact Assessment (EIA) process to support environmental planning and decision-making.

3.2 Identification of Emission Pathways

A systematic evaluation of facility operations was undertaken to identify activities responsible for PM_{10} generation. Industrial emissions were classified according to their physical release mechanisms rather than operational departments, thereby providing a more representative description of pollutant behaviour within the atmospheric environment.

The assessment incorporated principal emission pathway for surface emissions associated with operational activities and material handling. For emission pathway, relevant source characteristics including emission rate, release configuration, operational schedule, and geometric parameters were compiled to establish the model input database. This source-oriented classification facilitates evaluation of individual source contributions as well as cumulative environmental impacts.

3.3 Atmospheric Representation and Simulation

Accurate prediction of pollutant transport requires realistic representation of prevailing atmospheric conditions. Site-specific meteorological observations describing wind speed, wind direction, ambient temperature, atmospheric stability, and mixing characteristics were processed using the AERMET meteorological preprocessor. Terrain elevations within the modelling domain were incorporated through AERMAP to account for topographic influences on pollutant dispersion.

Subsequently, atmospheric transport of PM_{10} was simulated using the AERMOD, which applies steady-state Gaussian dispersion theory coupled with planetary boundary layer parameterization to estimate ground-level pollutant concentrations. The model is capable of representing multiple source geometries within a single computational environment, enabling simultaneous assessment of emissions from stacks, operational areas, and transportation activities (Cimorelli et al., 2005; Perry et al., 2005).

A receptor network covering assessment domain was established to evaluate spatial variations in PM_{10} concentrations surrounding the industrial facility. The receptor spacing was selected to capture concentration gradients while ensuring adequate spatial coverage for environmental impact evaluation.

3.4 Evaluation of Environmental Impacts

Predicted PM_{10} concentrations obtained from the dispersion model were analysed from an environmental perspective rather than solely as numerical outputs. Individual emission pathways were first evaluated independently to understand their respective contributions to ambient air quality, followed by cumulative assessment considering simultaneous operation of all identified sources.

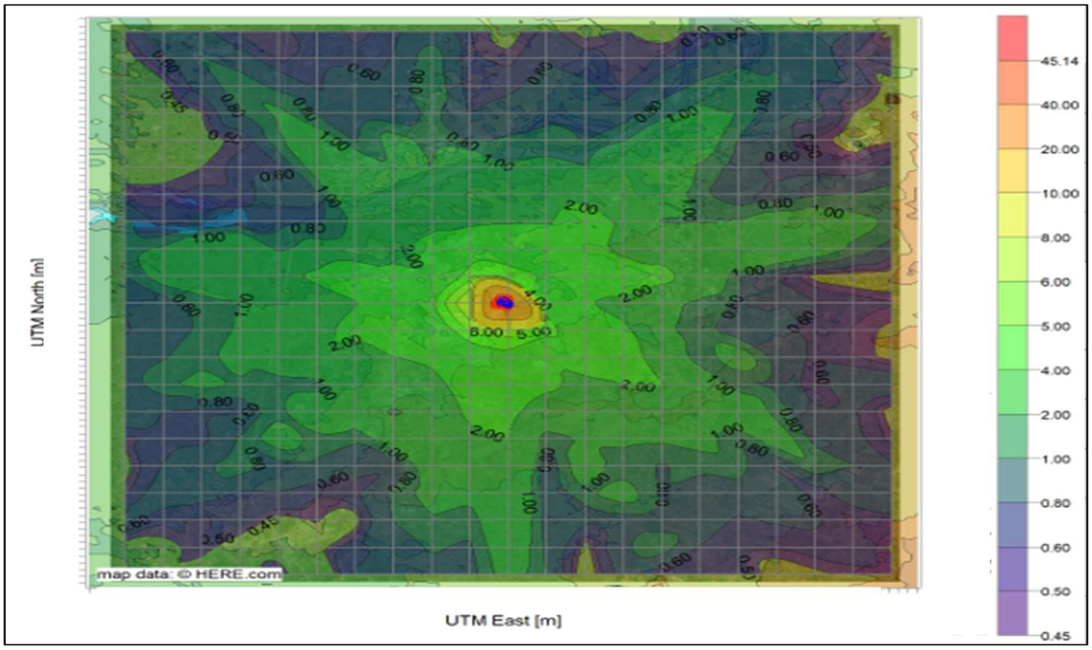
Spatial concentration distributions were examined to identify areas potentially experiencing elevated particulate exposure. Predicted concentrations were subsequently compared with the applicable NAAQS to determine environmental acceptability and regulatory compliance. This integrated evaluation enabled identification of dominant emission sources requiring priority mitigation while simultaneously assessing the overall environmental performance of the industrial facility.

4. Results & Analysis

4.1 Spatial Characteristics of PM_{10} Dispersion

The atmospheric dispersion simulations demonstrated that PM_{10} concentrations were not uniformly distributed across the assessment domain but varied according to emission characteristics, prevailing meteorological conditions, and atmospheric mixing processes. Higher concentrations were generally predicted within the vicinity of industrial operations, whereas progressive dilution resulted in lower concentrations with increasing distance from the emission sources. This behaviour reflects the combined influence of plume dispersion, wind-driven transport, and turbulent atmospheric diffusion, which collectively govern the movement of suspended particulate matter.

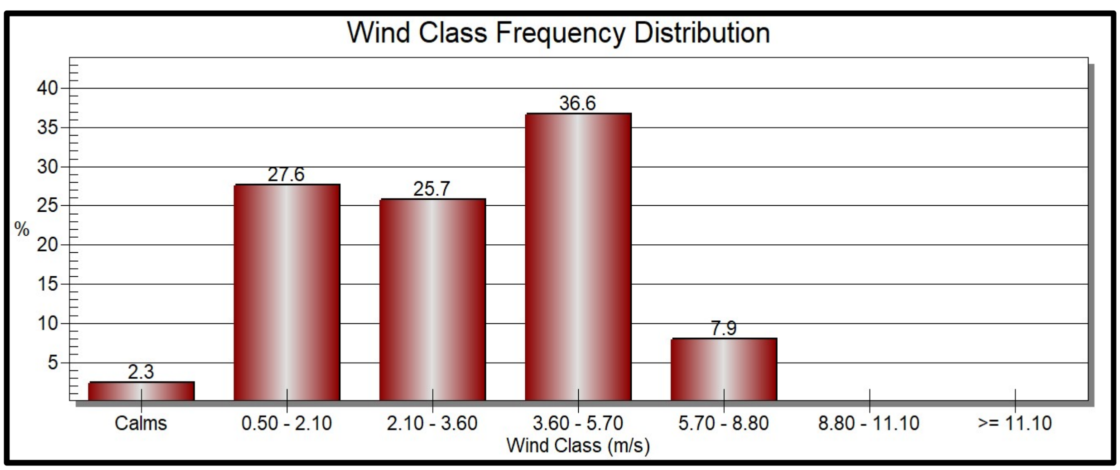
The predicted concentration contours further indicated that pollutant dispersion followed the dominant wind direction observed during the assessment period, producing an asymmetric spatial distribution rather than concentric dispersion around the emission sources. Such behaviour is consistent with Gaussian dispersion theory and demonstrates the importance of incorporating representative meteorological observations into Environmental Impact Assessment studies.



4.2 Influence of Meteorological Conditions on Dispersion

Meteorological conditions were found to play a decisive role in determining the magnitude and spatial distribution of PM_{10} concentrations. Wind direction controlled the preferential transport pathway of particulate matter, whereas wind speed influenced atmospheric dilution and downwind pollutant dispersion. Periods characterized by relatively stable atmospheric conditions reduced vertical mixing and promoted localized accumulation of suspended particles, while enhanced atmospheric turbulence facilitated greater dispersion and lower ground-level concentrations.

The observed relationship between meteorological variability and pollutant behaviour confirms the importance of employing site-specific atmospheric observations during predictive air quality assessments. Generalized meteorological assumptions may not adequately represent local dispersion characteristics, potentially leading to inaccurate estimation of environmental impacts.



4.3 Environmental Significance of the Predicted Air Quality

Evaluation of the cumulative modelling results indicated that the predicted PM_{10} concentrations remained within the applicable National Ambient Air Quality Standards under the representative operating conditions considered in the study. This finding suggests that routine industrial activities are unlikely to produce unacceptable deterioration of ambient air quality beyond the facility boundary.

However, regulatory compliance alone should not be interpreted as the sole indicator of satisfactory environmental performance. The modelling outcomes clearly identify operational activities responsible for comparatively higher particulate contributions, thereby providing valuable information for environmental management and pollution prevention. The ability to distinguish source-specific contributions enables prioritization of mitigation measures according to their relative environmental significance rather than implementing uniform control strategies across all operations.

5. Conclusion

This study presents a predictive framework for integrating regulatory atmospheric dispersion modelling into Environmental Impact Assessment (EIA) for evaluating PM_{10} emissions from industrial facilities comprising multiple emission pathways. Unlike conventional assessments that focus primarily on individual emission sources or regulatory compliance, the proposed framework integrates source characterization, atmospheric simulation, cumulative impact assessment, and environmental interpretation to support informed decision-making throughout the environmental planning process.

The modelling results demonstrated that the spatial distribution of PM_{10} is strongly influenced by source configuration, release height, and prevailing meteorological conditions. These findings emphasize that effective particulate matter management should not be restricted to stack emission control but should also prioritize operational practices capable of reducing fugitive dust generation.

Beyond regulatory compliance, the proposed framework provides practical support for industrial planning, environmental clearance, operational optimization, and sustainable air quality management. Integration of dispersion modelling within the broader EIA process enables quantitative evaluation of cumulative impacts, facilitates prioritization of mitigation measures, and enhances transparency in environmental decision-making.

Although the present assessment employed standardized regulatory modelling procedures and representative site-specific datasets, uncertainties associated with emission inventories, operational variability, and meteorological fluctuations remain inherent to predictive modelling. Future research may incorporate long-term monitoring datasets, seasonal emission variability, model performance evaluation using field observations, and integration of health risk assessment to further strengthen environmental impact prediction. The proposed methodology is transferable to a wide range of industrial facilities and can support environmentally sustainable development by providing a scientifically robust basis for air quality assessment and pollution control planning.

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