A Pratibha Spandan's Journal

CONFLUENCE OF KNOWLEDGE
(A Multidisciplinary International Peer-Reviewed/Refereed Journal)
ISSN 2320–5237 | Volume 13, Issue 03, April 2026 (Special Issue)
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CHARACTERIZING AIR POLLUTION DYNAMICS IN THE BADDI–BAROTIWALA–NALAGARH INDUSTRIAL CORRIDOR: IMPLICATIONS FOR AIR QUALITY MANAGEMENT

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ABSTRACT

The Baddi–Barotiwala–Nalagarh (BBN) industrial corridor in Himachal Pradesh has evolved into one of the most prominent manufacturing hubs in northern India. While this rapid industrial expansion has contributed significantly to regional economic development, it has also exerted growing pressure on the local atmospheric environment. The present study examines the dynamics of air pollution in the Baddi industrial region by focusing on key atmospheric pollutants, including $PM_{2.5}$, PM_{10}, SO_2, and NO_2. The analysis is based on a review of available ambient air quality datasets, supported by selected field observations and insights gathered through interactions with local communities.

In addition to evaluating pollutant concentrations, the study considers several factors that influence air quality in the region. These include industrial emission patterns, increasing vehicular traffic, expanding residential settlements, and the role of local topographical conditions that affect pollutant dispersion and accumulation. By integrating these aspects, the research aims to develop a more comprehensive understanding of the drivers of air pollution within the industrial corridor. The study further emphasizes the importance of linking scientific monitoring with community awareness and participatory environmental governance. Strengthening collaboration among industrial units, regulatory authorities, and local stakeholders is essential for designing effective and locally appropriate pollution control strategies. Ultimately, the research seeks to contribute to improved environmental planning in rapidly industrializing regions and to support evidence-based policy interventions aimed at enhancing air quality and protecting public health.

Keywords: *Baddi-Bharotiwala-Nalagarh (BBN); Air Pollution; PM_{10}; Seasonal Variation; Industrial Emissions; Freight Transport; Air Quality Management.*

Introduction

The expansion of industrial development into ecologically sensitive mountain regions poses unique challenges for environmental governance and long-term sustainability. Himachal Pradesh, situated in the western Himalayan region, has traditionally been known for its relatively low population density and cleaner air compared to many other parts of northern India. However, economic policies introduced in the early 2000s to promote regional development led to a rapid increase in industrial activities, particularly in the lower altitude districts. One of the most notable examples of this transformation is the Baddi–Barotiwala–Nalagarh (BBN) industrial corridor in Solan district, which has undergone substantial industrial growth over the past two decades. This expansion of manufacturing units has been accompanied by a marked rise in freight transportation, infrastructure development, and urban growth in surrounding areas.

Several independent scientific investigations conducted in Solan district and other comparable foothill industrial regions have reported indications of deteriorating air quality. Building upon these existing studies, the present research brings together findings from multiple sources in order to develop a more comprehensive understanding of pollution trends within the BBN corridor and their implications for effective air quality management.

At the same time, the transformation of the region from a largely semi-rural landscape to an increasingly industrialized and urbanized environment has led to significant changes in land-use patterns. The expansion of built-up areas, the decline in natural vegetation cover, and rising anthropogenic heat emissions can all influence local atmospheric behaviour, including the stability of air masses and the dispersion of pollutants. Therefore, any meaningful evaluation of air pollution in the BBN corridor must take into account the combined effects of industrial emissions, transportation activities, and the unique meteorological conditions associated with valley environments. Adopting such an integrated perspective is essential for developing informed, balanced, and sustainable regional planning strategies.

Study Area

The Baddi–Barotiwala–Nalagarh (BBN) industrial corridor is located in southwestern Himachal Pradesh along the Shivalik foothills. The terrain consists of undulating hills and valley depressions, with elevations ranging between 350 and 1,000 meters above mean sea level. This topography strongly influences local airflow patterns and pollutant dispersion.The region experiences four distinct seasons: winter (December–February), summer (March–May), monsoon (June–September), and post-monsoon (October–November). Winter is characterized by low temperatures, weak winds, and frequent thermal inversions that limit vertical mixing. Summer enhances convective activity but promotes dust resuspension due to dry surface conditions. Monsoon rainfall temporarily improves air quality through wet deposition. Valley-oriented terrain restricts horizontal air movement during calm periods, particularly at night, allowing pollutants to accumulate. Winter temperature gradients promote cold air pooling and stagnation. In addition, proximity to the Indo-Gangetic Plain enables episodic regional aerosol transport, elevating background particulate levels prior to local emission buildup.

Methodological Synthesis of the Research Papers

Most of the studies reviewed followed broadly similar methodological approaches focused on assessing ambient air quality. Monitoring was generally carried out at multiple locations representing industrial zones, residential areas, and relatively less disturbed background sites. The primary pollutants examined in these studies were PM_{10}, SO_2, and NO_2. Sampling was typically conducted during major seasonal periods—winter, summer, and the monsoon—to capture seasonal variations in pollutant concentrations. For particulate matter estimation, gravimetric methods were widely applied.

In several cases, researchers also explored the relationship between meteorological variables and pollutant concentrations through correlation analysis, while a few studies attempted preliminary evaluations of long-term trends. However, most of the investigations relied on short-term monitoring campaigns carried out during specific seasons rather than continuous datasets collected over multiple years.

Comprehensive chemical characterization of pollutants and advanced source apportionment techniques were generally not incorporated in these studies. Despite the relatively basic methodological framework, the consistency of observations across independent research efforts provides reasonable confidence in the overall pollution patterns identified for the region. Nevertheless, the lack of high-resolution temporal monitoring limits the ability to capture short-term pollution spikes and daily variations in pollutant levels. Furthermore, the limited application of receptor modelling, isotopic analysis, and detailed chemical profiling restricts the precise identification of pollution sources. Future research could significantly enhance understanding of emission dynamics within the corridor by integrating continuous automatic monitoring systems, advanced analytical techniques, and atmospheric dispersion modelling.

Results and Discussion

Dominance of Particulate Matter (PM10)

Across the studies reviewed, PM_{10} consistently appeared as the most critical pollutant affecting air quality in the region. In many cases, both annual and seasonal average concentrations were found to exceed the limits prescribed under the National Ambient Air Quality Standards (NAAQS), particularly in areas located within major industrial zones. Monitoring stations established inside industrial estates generally recorded significantly higher particulate levels compared to rural or background locations. Elevated concentrations were also observed in nearby residential neighbourhoods, indicating that emissions are not confined within industrial premises and can influence air quality in surrounding communities.

In comparison, sulfur dioxide (SO_2) concentrations were largely reported to remain within regulatory limits, while nitrogen dioxide (NO_2) levels were generally within acceptable ranges except in certain locations characterized by heavy traffic or dense industrial activity. This overall pattern suggests that the pollution burden in the corridor is dominated primarily by coarse particulate matter rather than gaseous pollutants originating solely from combustion processes.

Several activities associated with industrial operations and rapid urban expansion contribute to the generation of dust in the area. These include raw material handling, industrial processing, construction activities, and frequent movement of heavy vehicles. Together, these processes generate large quantities of suspended dust particles, maintaining relatively high background particulate concentrations across much of the year. The continued presence of elevated particulate matter levels, despite the relatively better control of gaseous pollutants, indicates that regulatory interventions have historically focused more strongly on emissions from combustion sources. In contrast, comparatively less attention appears to have been directed toward managing fugitive dust emissions. This imbalance in regulatory emphasis may help explain why particulate matter continues to dominate the overall pollution profile of the BBN industrial corridor.

Spatial Variability and Industrial Clustering Effects

Spatial comparisons among different monitoring locations indicate a clear contrast between industrial areas and non-industrial or rural zones. Monitoring stations located within the Baddi and Nalagarh industrial clusters consistently reported higher concentrations of PM_{10} compared to reference sites situated in relatively less developed rural surroundings. This spatial variation largely reflects the concentration of multiple emission sources within a limited geographic area where industrial activities, transportation networks, and associated infrastructure are densely clustered.

Another important issue is the close proximity between industrial facilities and residential settlements. In several parts of the corridor, residential neighbourhoods are either located within industrial estates or directly adjacent to them. As a result, local residents may be exposed to pollutant levels that are similar to those encountered in occupational or industrial environments. Such conditions can increase the likelihood of prolonged exposure and raise concerns regarding potential public health impacts. From the perspective of atmospheric dispersion, the clustering of multiple emission sources within a confined space can lead to the interaction of overlapping pollution plumes. Under stable atmospheric conditions, these overlapping plumes may combine and result in higher pollutant concentrations near the ground due to cumulative effects. In addition, fugitive emissions originating from open storage areas, raw material handling zones, and transport activities generally lack significant vertical plume rise, allowing pollutants to disperse directly within the breathing zone.

Therefore, the observed spatial differences in pollutant concentrations are not solely determined by the intensity of emissions but are also influenced by factors such as land-use patterns, vehicular activity, and local topographical characteristics. Together, these elements play a significant role in shaping the distribution and accumulation of air pollutants within the BBN industrial corridor.

Seasonal Dynamics and Meteorological Control

All the studies documented a consistent seasonal pattern in pollutant concentrations:

Winter > Summer > Monsoon

Winter Amplification

The highest concentrations of PM_{10} were generally observed during the winter months across most monitoring locations. This seasonal increase can largely be attributed to limited atmospheric dispersion. During winter, the atmospheric boundary layer becomes relatively shallow, wind speeds are typically low, and temperature inversions occur more frequently. These conditions restrict vertical mixing and allow pollutants to accumulate close to the ground surface. The valley-dominated terrain of the region further reduces airflow, creating stagnant atmospheric conditions. Under such circumstances, continuous emissions from industrial activities tend to accumulate gradually, leading to sustained increases in particulate concentrations rather than short-term pollution spikes.

Summer Conditions

During the summer season, stronger solar heating promotes greater atmospheric convection and enhances vertical mixing of air masses. This process generally improves pollutant dispersion and can reduce the tendency for pollutant accumulation near the surface. However, dry ground conditions during this period often increase the resuspension of dust particles. The movement of heavy vehicles along roads and industrial transport routes can re-entrain previously settled dust into the atmosphere, maintaining relatively elevated particulate concentrations even when atmospheric dispersion conditions are more favourable.

Monsoon Cleansing Effect

The onset of the monsoon typically leads to a temporary decline in particulate pollution levels. Rainfall helps remove airborne particles through wet deposition, thereby improving short-term air quality. The magnitude of this cleansing effect, however, depends on the intensity, duration, and frequency of rainfall events. When rainfall becomes less frequent or stops altogether, continuous emissions from industrial operations and transportation activities can quickly restore particulate concentrations to their earlier baseline levels.

Overall Seasonal Influence

Although seasonal meteorological conditions influence the magnitude of pollutant concentrations, they do not fundamentally change the emission-driven character of air pollution in the corridor. The recurring exceedance of particulate matter standards across seasons suggests that persistent and structurally embedded emission sources continue to play a dominant role in shaping the region's air quality profile.

Role of Vehicular Emissions and Freight Movement

Heavy-duty diesel vehicles represent an important contributor to air quality conditions within the industrial corridor. The constant movement of freight vehicles linked to industrial production results in continuous emissions of nitrogen oxides (NO_x) and particulate matter. Although many studies have primarily focused on PM_{10} concentrations, diesel-powered engines are also known to release finer particulate fractions, which add to the overall atmospheric pollution load.

The impact of vehicular activity is not limited solely to exhaust emissions. Frequent movement of trucks and other heavy vehicles, especially during dry weather conditions, can resuspend previously deposited road dust. This process significantly elevates ambient PM_{10} levels in areas with intense traffic activity. Monitoring conducted near major road intersections and transport routes has also revealed localized increases in nitrogen dioxide (NO_2), reflecting the influence of combustion-related emissions in high-traffic zones. In industrial corridors where freight transport occurs almost continuously throughout the day, pollutant exposure tends to remain persistent rather than occurring as isolated or short-term events. As a result, vehicular activity acts as both a direct and indirect driver of air pollution within the region.

Influence of Regional Transport

Regional atmospheric transport also plays a role in influencing local air quality conditions. Air mass trajectory analyses indicate that, under certain meteorological situations, fine particulate matter can be transported from the Indo-Gangetic Plain into the foothill industrial corridor. The arrival of these transported aerosols can raise background particulate concentrations even before the effects of local emissions become fully apparent. Once these fine particles enter the valley environment, stable atmospheric conditions may trap them within lower atmospheric layers. In such situations, the incoming regional pollutants can mix with locally generated dust and industrial emissions, intensifying overall pollution levels and contributing to more severe pollution episodes.

This interaction suggests that observed exceedances in particulate matter concentrations are likely the result of both local emission sources and regional atmospheric influences. Therefore, while strengthening local pollution control measures remains essential, achieving sustained improvements in air quality may also require broader coordination across regions to address transboundary pollution transport.

Long-Term Trends

Available long-term monitoring records indicate a gradual rise in PM_{10} concentrations over recent years. This pattern suggests that the combined effects of industrial growth, increasing freight transportation, and expanding urban infrastructure have contributed to higher overall emission loads. The continued increase in particulate levels appears to be linked more closely to structural changes in regional emission sources rather than to short-term variations in meteorological conditions. As industrial production capacity grows and transport demand intensifies, the additional particulate emissions generated may gradually counterbalance the benefits achieved through existing pollution control measures.

The absence of a clear and sustained decline in pollutant concentrations indicates that current mitigation efforts may not be keeping pace with the scale of industrial and infrastructural expansion occurring in the corridor. Without regular technological upgrades in industrial processes, stronger regulatory compliance mechanisms, and more integrated approaches to emission management, particulate pollution levels may continue to rise over time. These observations highlight the need for more proactive and adaptive air quality management strategies. Strengthening governance frameworks that can respond effectively to both current emission sources and emerging development pressures will be essential for achieving long-term improvements in regional air quality.

Health Risk Implications

Health-oriented investigations conducted in the region indicate a higher occurrence of respiratory complaints among residents living close to industrial estates. Continuous exposure to elevated concentrations of particulate matter can pose significant risks to respiratory health and overall well-being. PM_{10} particles tend to deposit primarily in the upper and central portions of the respiratory system. Repeated inhalation of such particles may lead to irritation of the airways, inflammation of respiratory tissues, and increased sensitivity of the bronchial passages.

At the physiological level, inhaled particulate matter can stimulate the formation of reactive oxygen species within lung tissues. This process may trigger oxidative stress and inflammatory responses that, over time, can contribute to a gradual decline in pulmonary function. Certain population groups, particularly children and older adults, are generally more susceptible because their respiratory defence mechanisms are either still developing or weakened with age.

Although most of the reviewed studies mainly examined respiratory effects, the frequent exceedance of particulate matter standards suggests the possibility of wider cardiopulmonary health implications. Seasonal atmospheric conditions, especially winter stagnation, can further intensify short-term exposure by allowing pollutants to accumulate near ground level, which may aggravate existing respiratory conditions or trigger acute episodes.

Despite the limited availability of long-term cohort studies in the region, the persistent elevation of PM_{10} concentrations indicates that air pollution in the industrial corridor remains an ongoing environmental health issue. Addressing this challenge will require coordinated efforts that combine continuous environmental monitoring, preventive public health measures, and strengthened health surveillance systems to better understand and manage the long-term risks associated with air pollution exposure.

Implications for Air Quality Management

The collective findings from the reviewed studies suggest that air pollution within the Baddi–Barotiwala–Nalagarh (BBN) corridor arises from multiple sources, is strongly influenced by prevailing meteorological conditions, and shows signs of long-term persistence. These characteristics indicate that traditional regulatory approaches focusing on individual emission sources may not be sufficient for managing air quality in geographically confined industrial regions. Instead, air pollution management in such areas requires a broader, air-shed–based strategy that considers the combined influence of industrial emissions, transportation activity, and regional atmospheric processes. Developing comprehensive emission inventories and integrating them into coordinated planning frameworks would allow for more effective and forward-looking pollution control strategies.

Strengthening Industrial Emission Control

Consistent enforcement of emission standards across industrial units remains a key requirement for improving air quality. In addition to regulatory compliance, periodic performance audits of pollution control equipment should be made mandatory to ensure that installed systems continue to function effectively over time. The adoption of Continuous Emission Monitoring Systems (CEMS), connected to centralized regulatory platforms, can facilitate real-time monitoring of emissions and enhance transparency in compliance reporting.

At the same time, effective emission management must extend beyond stack emissions alone. A significant share of particulate pollution in industrial areas often arises from fugitive sources such as raw material handling, open storage yards, and internal transport routes. Systematic assessment and regulation of these emissions are therefore essential. Infrastructure improvements—such as enclosed conveyor systems, covered storage facilities, and designated controlled handling zones—can substantially reduce the release of coarse particulate matter into the surrounding environment.

Furthermore, regular third-party evaluations of pollution control devices, including electrostatic precipitators and bag filters, should be institutionalized. Such independent assessments can help identify performance deterioration caused by inadequate maintenance and ensure that pollution control systems operate at their intended efficiency.

Freight Transport Management

Considering the large number of heavy-duty diesel vehicles operating within the corridor, improving freight transport management is an important component of air quality mitigation. The development of dedicated freight corridors and bypass routes can help divert heavy vehicle traffic away from mixed industrial–residential areas, thereby reducing the exposure of nearby communities to vehicular emissions and road dust.

Operational improvements can also play a meaningful role in controlling particulate pollution. Measures such as regular road maintenance, mechanized street sweeping, and mandatory covering of materials during transportation can significantly limit dust resuspension along transport routes. In the longer term, a gradual transition toward cleaner vehicle technologies—including Bharat Stage VI–compliant engines and the progressive electrification of freight transport—could reduce emissions of nitrogen oxides and fine particulate matter. In addition, the implementation of intelligent traffic management systems within industrial zones may help reduce unnecessary vehicle idling at factory gates and loading areas. Minimizing such delays can contribute to lowering the cumulative emissions generated by freight operations across the corridor.

Institutionalized Dust Suppression

Effective dust control requires a systematic and continuous approach rather than temporary measures implemented only during periods of high pollution. Industrial estates should adopt permanent dust management practices, including the paving of internal roads, stabilization of unpaved surfaces, and routine mechanized vacuum sweeping. Controlled water spraying during dry conditions can further reduce the suspension of dust particles in the atmosphere.

Additional measures such as establishing vegetative buffer zones along major transport corridors and strictly enforcing construction dust management guidelines are also essential for limiting particulate emissions. The introduction of localized real-time dust monitoring systems within industrial estates can help detect small-scale pollution hotspots and support timely, targeted interventions to control particulate releases.

Expansion and Modernization of Monitoring

Current monitoring efforts in the region primarily focus on PM_{10} mass concentrations, which provide only a limited understanding of pollutant composition and associated health risks. Expanding monitoring parameters to include $PM_{2.5}$, elemental carbon, heavy metals, and secondary aerosol components would offer more detailed insights into pollutant toxicity and assist in identifying specific emission sources. Increasing the number of automatic continuous ambient air quality monitoring stations across different micro-environments—including industrial areas, transport corridors, and residential settlements—would improve the temporal resolution of air quality data and strengthen early warning capabilities. Furthermore, integrating advanced meteorological monitoring infrastructure, such as towers equipped to measure boundary layer dynamics and wind profiles, would support more accurate dispersion modelling and air quality forecasting for the region.

Air-Shed Level Governance

The evidence indicating regional transport of aerosols from the Indo-Gangetic Plain highlights the importance of coordinated air quality management beyond local administrative boundaries. In such situations, pollution control measures implemented solely at the local level may not be sufficient to fully prevent episodes of air quality deterioration. Addressing this challenge requires the development of an air-shed–based governance framework that encourages cooperation among neighbouring states and regional authorities.

Such a framework could involve the preparation of synchronized emission inventories, coordinated implementation of mitigation strategies, and the establishment of formal mechanisms for sharing monitoring data and analytical insights. In addition, seasonal contingency planning may help manage periods when atmospheric conditions favour pollutant accumulation. For example, during winter months—when temperature inversions and stagnant air conditions are common—temporary measures such as regulated entry of heavy vehicles or short-term adjustments in industrial operations could help reduce pollution build-up during critical periods.

Urban–Industrial Zoning Reform

Ensuring long-term environmental sustainability in the corridor will require structural improvements in land-use planning and zoning practices. One important measure is the establishment of adequate buffer zones between industrial facilities and residential settlements in order to reduce direct exposure of communities to industrial emissions. At the same time, stricter regulation of new residential development within high-emission industrial clusters can help limit future exposure risks.

Expanding greenbelt areas around industrial zones and along transport corridors can also contribute to improved environmental conditions by providing partial barriers to dust and pollutant dispersion. Urban planning frameworks should increasingly incorporate air quality considerations into decisions related to industrial expansion and infrastructure development. Environmental impact assessments for new industrial projects should evaluate cumulative air-shed emission loads rather than focusing solely on emissions from individual facilities. Integrating such considerations into regional planning processes can help ensure that economic growth proceeds alongside adequate environmental protection and public health safeguards.

Conclusion

The synthesis of findings from the reviewed studies indicates that the Baddi–Barotiwala–Nalagarh (BBN) industrial corridor is experiencing persistent particulate air pollution, with PM_{10} emerging as the dominant pollutant of concern. Elevated particulate levels appear to result from the combined influence of several factors, including industrial emissions, intensive freight transportation, resuspension of road dust, and occasional inflow of aerosols from surrounding regions. Local meteorological conditions—particularly winter temperature inversions and the valley-oriented terrain—further contribute to the accumulation of pollutants near ground level.

Long-term observations suggest that the pace of industrial expansion and transportation activity has gradually increased emission pressures in the region, often exceeding the capacity of existing mitigation measures to deliver sustained improvements in air quality. Evidence from health-related studies also indicates a higher occurrence of respiratory symptoms among communities residing near industrial areas, suggesting that pollution in the corridor represents an ongoing environmental health concern rather than a series of isolated exceedance events.

Addressing this challenge will require a shift toward integrated air-shed–based management strategies. Strengthening industrial emission controls, improving freight transport management, expanding and modernizing air quality monitoring networks, and incorporating air quality considerations into urban and industrial land-use planning are all important components of an effective response. Implementing such coordinated measures will be essential for balancing industrial growth with environmental protection and safeguarding public health within the ecologically sensitive Himalayan foothill region.

Recommendations and Scope of Future Study

Improving air quality in the Baddi–Barotiwala–Nalagarh (BBN) industrial corridor requires stronger control of industrial emissions and better management of fugitive dust. This can be achieved through the installation of continuous emission monitoring systems, regular audits of pollution control equipment, and improved handling and storage of raw materials to limit particulate release. Addressing both stack emissions and ground-level dust sources is essential for effectively reducing PM_{10} concentrations.

Freight transport management is another key area for intervention. The development of dedicated truck corridors, improved road maintenance, mechanized sweeping, and strict covering of transported materials can help reduce dust suspension. Gradual adoption of cleaner vehicle technologies and improved traffic management within industrial areas can further reduce emission loads.

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ISSN 2320–5237 | Volume 13, Issue 03, April 2026 (Special Issue)
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Monitoring systems should be expanded to include continuous measurement of PM_{10} and $PM_{2.5}$, along with chemical characterization of particulate matter and integrated meteorological observations to improve pollution forecasting, particularly during winter inversion periods. Future research should focus on developing detailed emission inventories and applying advanced dispersion and receptor modelling that consider valley topography and regional air-shed linkages with the Indo-Gangetic Plain. Integrating these efforts with improved land-use planning and buffer zone development will be essential for achieving sustainable industrial growth while protecting environmental quality and public health.

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