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Impact of Economic Activity on PM2.5 Levels in India: An empirical study on selective Indian Districts

Introduction

Air pollution remains one of the most urgent environmental and public health crises of the 21st century. Among its various components, fine particulate matter—commonly referred to as PM2.5—has become a particular focus of concern. PM2.5 consists of airborne particles with a diameter of 2.5 micrometers or smaller—roughly 1/30th the width of a human hair(EPA). Due to their microscopic size, these particles can bypass the body's natural defenses, penetrate deep into the lungs, and even enter the bloodstream. As a result, PM2.5 exposure has been strongly linked to a wide range of health problems, including cardiovascular and respiratory diseases, neurological disorders, and premature deaths (WHO, 2018).

Historically, most scientific attention has centered on PM2.5 emissions in urban and industrial regions. However, emerging research indicates that rural India is now experiencing PM2.5 concentrations that often rival—or even exceed—those in urban centers, especially during periods of intense economic activity such as agricultural residue burning or seasonal industrial operations (Pandey et al., 2021). This shift underscores the need for a more nuanced understanding of how economic development, in both rural and urban areas, contributes to air-quality degradation.

Contrary to the common perception that rural areas are insulated from pollution due to limited industrialization, studies have shown that seasonal and localized economic activities—particularly those rooted in agriculture—play a significant role in rural air quality degradation. One of the most critical sources is agricultural stubble burning (ASDG), especially in northern states such as Punjab and Haryana, where mechanized harvesting and intensive cropping cycles have led to widespread post-harvest residue combustion (CPCB, 2020). This seasonal practice emits large quantities of PM2.5 and other hazardous pollutants, creating widespread haze not only in the immediate vicinity but also affecting air quality in downwind urban and peri-urban regions (Venkataraman et al., 2014). Beyond agriculture, a range of rural economic activities further contribute to PM2.5 emissions. Diesel-powered irrigation systems and rural transport machinery, along with the construction of roads, housing, and small-scale industrial sheds, contribute significantly to rising PM2.5 levels in rural India. Additional sources, such as brick kilns, informal manufacturing clusters, and unpaved roads that generate fugitive dust, further intensify the pollution burden. Together, these factors form a complex and dynamic pollution profile that fluctuates with seasonal and economic activity patterns, posing serious health and environmental risks to the nearly 65% of India's population living in rural areas (Census of India, 2011).

However, rural India remains severely under-monitored(CSE). The national air quality monitoring infrastructure is disproportionately concentrated in urban centers, leaving rural PM2.5 emissions poorly quantified and largely invisible in national policymaking(NAMP). This presents a critical data and governance gap. Without adequate measurement, the health and environmental costs of rural pollution are underestimated and under-addressed, leading to ineffective or absent mitigation strategies (Guttikunda & Jawahar, 2018).

Furthermore, rural economic growth, driven by government schemes, electrification projects, infrastructure development, and expanding markets, while beneficial for livelihoods, is also introducing new pollution sources. Construction dust, vehicular exhaust, and industrial emissions are often unregulated and unmeasured, allowing air quality to deteriorate silently in regions once presumed clean (CPCB, 2020).

Literature Review

Recent studies have increasingly drawn attention to the elevated concentrations of PM2.5 in rural India, often exceeding nationally prescribed safe limits due to localized economic activity. Pandey et al. (2021) found that household biomass burning remains the predominant contributor to PM2.5 levels in villages, particularly during colder months when indoor heating demands rise. Additionally, seasonal agricultural practices, such as stubble burning and the use of diesel-powered machinery, combined with vehicular dust from rural transport, exacerbate PM2.5 spikes during harvest and sowing periods. Guttikunda and Jawahar (2018) argue that the contribution of rural sources is systematically underrepresented in national pollution models due to insufficient ground-level monitoring in non-urban zones. This gap is further supported by the Central Pollution Control Board (CPCB, 2020), which has acknowledged that stubble burning in Punjab and Haryana significantly increases PM2.5 concentrations, affecting not only local air quality but also transporting pollutants across state borders. Furthermore, Venkataraman et al. (2014) emphasized that rural emissions play a critical role in regional haze formation and transboundary pollution transport, yet remain poorly quantified.

Among all the economic activities, the mining industry is mentioned as a major contributor to particulate matter emissions, especially in mineral-rich regions, by many scholars. Studies have established a strong correlation between mining operations - particularly coal, iron ore, bauxite, and limestone extraction- and growth in substantial amounts of suspended particulate matter (SPM) and fine particulate matter (PM2.5 and PM10) through drilling, blasting, material handling, and transport (Ghose & Majee, 2000; Tiwary, 2001). Coal mining in rural areas of Jharkhand, Chhattisgarh, and Odisha has been found to have elevated PM2.5 concentrations, often surpassing permissible levels recommended by the National Ambient Air Quality Standards (CPCB, 2009). Studies link opencast mining, in particular, to higher emission intensity due to larger exposed areas and mechanized excavation, mostly indicating the methods, engineering, and type of operation we follow in the sector (Chaulya & Chakraborty, 1995).

Joshi & Dubey (2020) argued that regional air quality management is often hampered by overlapping administrative jurisdictions and a lack of district-level pollution monitoring. Integrated policy frameworks, such as linking NCAP with sustainability plans, especially involving the local governing bodies in management, are recommended for effectively addressing these region-specific challenges.

A dominant feature of rural livelihoods in India is dependence on traditional biomass—such as firewood, cow dung cakes, and crop residue- for cooking and heating. Some studies have shown that this energy dependence is a critical source of indoor air pollution, significantly raising PM2.5 and PM10 concentrations inside homes (Chafe et al., 2014; Balakrishnan et al., 2013). According to the Global Burden of Disease study (IHME, 2020), household air pollution from solid fuel use was one of the top five risk factors reducing life expectancy in India. Women and children who are exposed to cooking smoke more are particularly vulnerable to respiratory diseases and long-term morbidity (WHO, 2016).

Recent studies have emphasized the environmental externalities of rural economic practices such as deforestation for fuelwood, livestock grazing, and unplanned agricultural expansion, increasing the social cost of human development. These activities, although crucial for subsistence, exaggerated land erosion and air pollution through dust storms, biomass combustion, and the reduction of vegetative buffers (Ravindra et al., 2019). Pandey and Chaudhuri (2020) observed that the degradation of common lands and forests in rural India has increased the impact of environmental pollution at the community level. The loss of natural reservoirs such as forests and wetlands weakens the region's ability to absorb pollutants, especially PM2.5, leading to localized pollution concentrations. Moreover, the exposure to environmental pollution, being intertwined with poverty and unsustainable living practices, often compels rural households to suffer more, creating a vicious cycle of ecological and health vulnerability.

Research Gap - These findings collectively highlight a critical research gap in district-level air quality studies, particularly in disaggregating pollution sources by economic activity and seasonal behavior. This paper builds upon this foundation by contributing real-time, localized data from all Indian districts, divided into zones as per their geographic locations; directly linking PM2.5 fluctuations to specific economic events, such as harvesting, mining, construction, and manufacturing sector growth patterns. By establishing a cause-and-effect framework between livelihood patterns and pollution data, this work aims to strengthen the case for decentralized monitoring systems and targeted air quality interventions at local levels.

Research Objective

This study seeks to:

1. Analyze **zone-wise distribution of PM 2.5 levels to assess the air quality at the district level**, with a particular focus on rural regions.
2. **Quantify the relationship** between rural economic activity and PM2.5 concentrations using real-time air quality sensor data, field observations, and satellite imagery.
3. **Propose targeted policy interventions, as well as analyze existing policies** for village contexts, such as decentralized air quality monitoring, awareness campaigns, and incentive-based clean technology adoption.

Methodology

District-level data for major Indian States is used for this study. The study uses secondary data retrieved from SHRUG datasets (PM 2.5, Forest Cover), ICRISAT district-level GDP at constant prices(2004) dataset, and Census of India (2011) Tables (PCA, HL_14 household amenities) as required.

Mean PM 2.5 level in each district is the main concerned indicator of air pollution in this study. The study aims to understand the status of air pollution, in terms of its regional and spatial distribution, as well as its association with different economic indicators, implying the varied standard of living in the country, through a cross-sectional district-level analysis on datasets of the year 2013. For regional analysis, the study also categorized these states (UTs excluded)* into different zones using code-based identifiers. The **West zone** included states Rajasthan, Gujarat, Goa and Maharashtra; the **North zone** included Jammu and Kashmir, Himachal Pradesh, Punjab, Haryana, Uttarakhand and Delhi; the **East zone** included West Bengal, Bihar, Jharkhand and Odisha**;** the **Central zone** comprised Uttar Pradesh, Madhya Pradesh and Chhattisgarh; and the **South zone** consists of Karnataka, Kerala, Andhra Pradesh, Telangana and Tamil Nadu.

*(Note: North-east was excluded from the study due to majorly unavailability of data; and the study majorly focused the major states,excluding all UTs)

The PM 2.5 dataset of SHRUG was analyzed to find the quartile division and range of air pollution zone-wise, which helped in mapping pollution contributors spatially for geostatistical modeling. By focusing on the **upper-quartile data points**, this analysis identifies not just where pollution exists, but **where it is most intense and episodic**, providing a sharper lens for targeted environmental interventions.

Further, to understand the major economic factors contributing to regional air quality level, a multivariate regression analysis has been framed on selective larger districts, in each zone, using PM 2.5 level, Spatial concentration of agricultural as well as industrial production (measured by Millions/sq KM for all the districts), Forest cover (measured as percentage of geographical area under forests from Forest Survey of India reports), and use of different types of cooking fuel (measured in percentage of households in Census tables), are used as major economic activity indicators in this study; to estimate the impact of each causal variable on air pollution. As understood from per capita income, growth, and poverty estimates, India is a quite diversified country, where regional inequality in standard of living, growth in different sectors of the economy, and different cultures and lifestyle traditions are always present. To have a meaningful insight, the importance of the causal factors that vary from one region to another, the analysis was done separately for each zone*. *(In the regression analysis, Jammu and Kashmir as well as Delhi, was excluded from the North Zone ; Goa excluded from West zone due to unavailability, large variance and lack of credibility on the data available for district level). To conduct this, multivariate regression on the said variables, for the year 2013, is used in the following form of equation, for each different zones as classified above :

$$Y_i = b_1x_{1i} + b_2x_{2i} + b_3x_{3i} + b_4x_{4i} + b_5x_{5i} + e_i$$

Where,

i = each district in the specific zones

y= PM 2.5

x1 = Spatial concentration of secondary sector,

x2= Spatial concentration of primary sector,

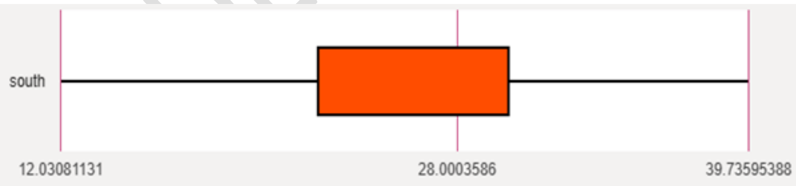
x3= Forest cover,

x4= Use of Biomass cooking fuel (category firewood, crop residue, and cow dung cakes taken together from census tables)

And x5 = Use of cleaner cooking fuel (category LPG/CNG, electricity, biogas taken together from census tables).

Data Analysis and Research Findings

SOUTH:



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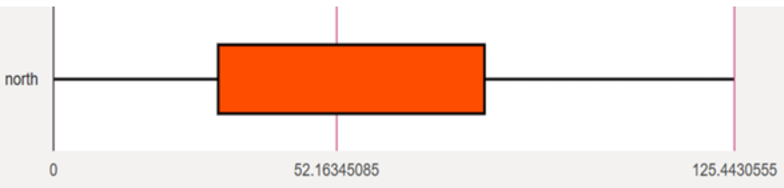

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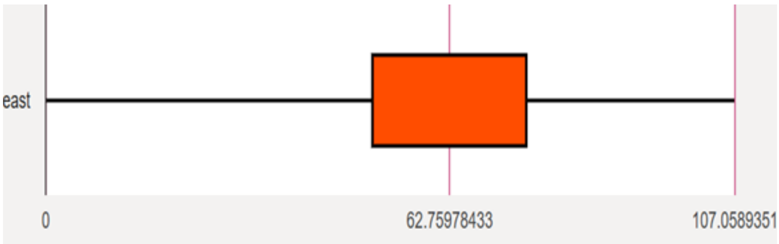

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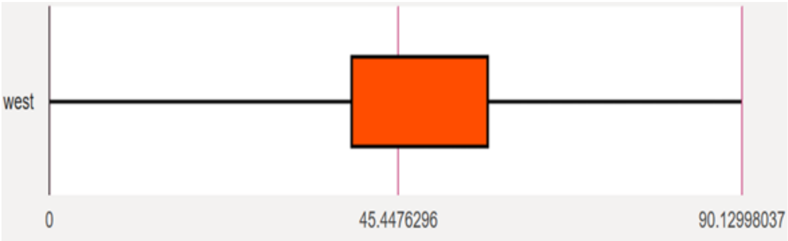
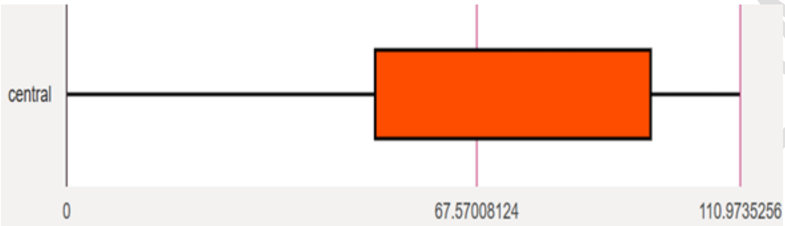


CENTRAL



The cross-sectional analysis on the distribution of PM2.5 levels (2013) across India provides an understanding of the spatial distribution and regional disparities in air-quality. The study of regional patterns of PM 2.5 level is based on a **zonal analysis**, dividing the dataset into five regions **North, South, East, West, and Central**– based on geographic proximity and administrative classification. Each zone included a **larger dataset of around 90-140 districts**. The **data points above the third quartile (Q3)** are analyzed as **major pollution contributors**, since they represent the highest PM2.5 values within each region.

For **South India**, out of the total 99 **districts**, **14 from Andhra Pradesh, 5 from Karnataka, and 4 from Tamil Nadu** were identified as exceeding Q3, indicating these specific rural locations experienced concentrated pollution episodes, possibly linked to vehicular emission, biomass burning, forest fire, industrial pollution, construction (Larsen, 2020; Sharma et. Al. 2021).

In the **North zone**, out of the total 98 **districts**, the Q3 outliers included **9 districts from Delhi, 13 from Haryana, and 3 from Punjab**, all reflective of areas impacted by stubble burning, urban-industrial spillover, and vehicular emissions even in peripheral villages. (Ghosh et. Al., 2014)

The **East zone** was dominated by **38 high-PM2.5 districts from Bihar**, out of the total 112 **districts**, reinforcing the heavy burden of pollution caused by agricultural practices and lack of clean cooking fuels in densely populated rural regions. (Guttikunda and Jawahar, 2020)

In **Western India**, as compared to Maharashtra and Gujarat, Rajasthan stood out with a highly elevated PM 2.5 level. Out of the total 98 **districts**, **30 districts from Rajasthan** were flagged above Q3, despite slower industrialization likely due to dust from unpaved roads, natural dust events, urbanization, and informal construction, etc, anthropogenic sources. (Guttikunda and Jawahar, 2020)

Lastly, **Central India**, Uttar Pradesh, shows a large deviation from its neighbouring states, as very high PM 2.5 values show the state has very poor air quality. **35 districts from Uttar Pradesh**, out of the total 140 **districts in the central zone**, were identified to exceed the Q3. The air pollution being concentrated in these areas in this zone points to persistent pollution sources such as crop burning, brick kilns, and poor road infrastructure (Guttikunda and Jawahar, 2020). Also, Jethva et al. (2019) states that the adverse impact of stubble burning in northern India is a major cause of pollution in some rural regions of UP.

While comparing the median values, we find the PM 2.5 level to be highest in the Central zone(67.57), followed by the East zone (62.75), whereas the South zone records the lowest value (28.00). These high-PM2.5 rural clusters serve as red flags for future air quality monitoring, clean energy initiatives, and emission control policies.

Numerous empirical studies have identified a range of causal factors contributing to air pollution in India. This paper examines the relationship between economic activity, standard of living, and environmental degradation, with a particular focus on the economic cost of rapid development in India- one of the most densely populated and rapidly growing developing economies in the world.

As traditional methods of burning crop residue, pollution channeled from mining industry, emission of different volatile compounds through gaseous industrial waste, ashes of thermal power plants etc. have already been identified as major air pollutants, our objective is to investigate the impact of spatial concentration of structural sectors (primary and secondary) in terms of real GDP produced per unit area- shows the reliability or growth pattern of the concerned sector in each district; whereas the regression coefficient describes the rise of pollution level due to unit increase in the spatial concentration, that is, rise of production in each sector. The Spatial concentration, however, in this case specifically draws its focus into the regional distribution or concentration of a sector, especially if some specific industry, or economic activity is forming clusters in a region.

In the **Central** zone, the study finds the spatial concentration of industries to be insignificant, with too high p-value, whereas the spatial concentration of agricultural and mining production have a significant positive impact on rise of air pollution (1.89), implying around 2% of the variance in rise of PM 2.5 could be explained by unit rise in spatial concentration of primary sector. In the **North zone,** though the contribution of the manufacturing sector could be merely statistically significant (p=0.08), it shows a low positive correlation with a rise in PM level (0.25), and primary production shows a higher contribution (b2=1.24).In the **West zone**, however, both factors are statistically insignificant with too high p-values. Whereas, the **East zone** manufacturing sector is found to be a statistically insignificant contributor, as compared to the agricultural and mining sector, with a much higher impact of 1.86 and statistically significant. Being the mining heart of the country, and a major producer of coal, mica, iron, manganese, bauxite, etc. The significant impact of this sector on worsening air quality levels in the east and central zones is especially noteworthy. For **South Zone,** the secondary sector is found to be merely statistically significant (p=0.053) with a positive impact of 0.5, while a noteworthy observation comes as being host to a large number of copper, gold, bauxite, iron etc. mines, as well as rich in agriculture & forest produce, the impact of primary sector is negative and statistically significant, -0.18.

This study, however, considers the real GDP contribution of all manufacturing sectors taken together, as per NIC classifications (2008), and does not investigate the impact of each type of industry in this case. Further scope could lie in investigating the contribution of different types of industries, as the emission types of each vary largely.

Simultaneously, the study addresses the environmental consequences of expanding human settlements, particularly in terms of forest cover depletion. The increasing demand for habitable land due to urbanization and population pressure is closely associated with deforestation, which in turn undermines the ecological capacity to buffer against pollution. The regression framework employed in this study quantifies the relationship between green cover loss and air quality deterioration, thereby highlighting the ecological costs of unsustainable urban expansion. The **Central zone** shows a strong and significant negative impact of forest cover on air pollution, that is, 1% loss in forest cover is capable of raising 3.2% of the air pollution. On the contrary, the **North zone** also shows a strong negative impact, -1.89, though not as high as the central zone. The **West zone** also shows a highly significant negative impact of -2.14. In the **Eastzone,** a strong negative impact of -0.96 was found, but the effect was lower compared to other regions. For the **South zone,** the impact of deforestation has been the lowest, shown as -0.41.

Comparing the forest cover and urbanization pattern of India, we can observe, the highest rate of urbanization has been agglomerated in the southern and western zone; whereas, the central and eastern zone also records a moderate rate of urbanization (Census of India, 2011; ISFR, 2021). On the other hand, the East and Central zone, along with the hilly patches of the Himalayas and Western Ghats, hosts most of the dense forests of India, national parks, and reserve forest areas as well (ISFR, 2021; MoEFCC, 2020). Therefore, the regression coefficients draw a special concern towards the West zone, hosting many metro cities of India, where the effect on air pollution due to decreasing forest cover has been highest, followed by the North and Central zones, emphasizing the catastrophic ecological cost of rapid urbanization (Census of India, 2011; ISFR, 2021; CPCB, 2020).

Furthermore, data from the Census of India (2011) reveals that a substantial segment of the population continues to rely on biomass-based cooking fuels due to poverty and limited access to modern energy sources. This reliance has been shown to contribute significantly to indoor and ambient air pollution. Conversely, rising per capita income and improvements in literacy are associated with a transition towards cleaner cooking fuels such as liquefied petroleum gas (LPG), electricity, and biogas. However, this transition may also entail increased demand for fossil fuels at the aggregate level. This paper, therefore, investigates the dual environmental implications of fuel choice, estimating the respective impacts of both biomass and cleaner fuels on air quality. For the **Central zone,** both the fuels tend to increase the impact on the PM 2.5 level - cooking with cleaner fuel (0.82) and biomass (0.99), while other statistical parameters furnished in the table suggest the strongest association between PM 2.5 and the use of biomass fuel. **North zone and West zone** also give similar insight, usage of both types of cooking fuel raised the pollution level (0.91 and 0.89; 0.60 and 0.67, respectively). In the **East zone,** biomass fuel is found to be a stronger factor (0.93) as compared to cleaner fuel (0.71), impacting the PM 2.5 level in the air. The effect of biomass fuel (0.39) is found to be higher than cleaner fuel (0.28) in the **South zone**, though the impact has been lower compared to other zones. It is noteworthy that both types of fuel demand exaggerate air pollution, but generally use of biomass fuel has been a greater concern in regional districts.

Altogether, the study finds a wide cross-sectional disparity in air quality levels at both intrazonal and interzonal levels. Among the major causal activities, mining, traditional agricultural methods, green cover loss, and large dependency on fossil fuel could be attributed as the most impactful causes of worsening the air quality countrywide. It is especially notable that, aside from the regional variance in PM 2.5 level concentration, the impact of the causal factor also varies largely from one zone to another. The findings of the study aim to contribute to the broader discourse on sustainable development by offering empirical insights into the complex trade-offs between economic growth, energy transition, and environmental sustainability in the Indian context.

Policy Implications

This study highlights substantial regional disparities in PM2.5 concentration across India, rooted in variations in economic activity, fuel usage, forest cover, and urban expansion. While the Southern region shows maximum particulate matter concentration to be lower than 40, in the Northern zone, it can go as high as 110. The large variance in causal factors also shows that, due to the differentiated pattern of economic growth and development, not all the factors affect all the regions equally. The findings point towards the significance of advancing region-specific strategies toward environmental sustainability.

The findings show that **primary sector activities**, especially agriculture and mining, are significant contributors to high PM2.5 levels in the **Central and Eastern zones**, where dependence on biomass fuels remains high. In the **Northern zone**, stubble burning, brick kilns, and vehicular exhaust are the largest drivers of seasonal pollution peaks, particularly in the Indo-Gangetic Plain. In the **Western zone**, rapid industrialization, power generation from coal, and desert dust events exacerbate PM2.5 concentrations. Although the Government of India launched the **National Clean Air Programme (NCAP)** in 2019, aiming to reduce PM2.5 concentrations by 20–30% in 131 non-attainment cities by 2024, the continued presence of severe pollution in both rural districts and peri-urban belts underscores a critical policy gap (MoEFCC, 2019).

While specific state-level interventions—such as the **Punjab and Haryana Crop Residue Management Scheme** (to curb stubble burning), the **Perform, Achieve and Trade (PAT) Scheme** for industrial energy efficiency, and state-specific electric vehicle policies—have been introduced, evidence of their effectiveness remains mixed. For example, stubble burning persists despite subsidies for crop residue management machinery, due to farmers' cost constraints and time pressures. Similarly, while NCAP's city-focused approach has created monitoring frameworks, it has not adequately addressed transboundary rural-urban pollution flows, meaning northern smog episodes continue despite regulatory measures. In the Western zone, stricter norms for coal plants and industrial emissions have improved compliance in some states, but enforcement gaps and rising energy demand continue to offset gains.

The Central and Eastern zones, where dependence on biomass and coal remains high, require urgent clean energy transitions. Expanding access to LPG, biogas, and electricity through subsidies, rural infrastructure, and behavioral campaigns is vital to reducing reliance on polluting fuels. Yet, as even cleaner fuels can generate PM2.5 emissions, energy policy must also incentivize efficiency and emission-reduction technologies. In parallel, agricultural and mining activities remain critical pollution sources in these regions. Regulation of open mining, investment in sustainable farming practices such as zero-stubble burning and bio-fertilizers, and strict enforcement of industrial norms are necessary to mitigate emissions while safeguarding rural livelihoods.

Deforestation and land-use change, particularly in the Central and Western zones, strongly correlate with rising PM2.5 concentrations. Addressing this challenge requires embedding forest protection into urban and regional planning. Policies should prioritize afforestation drives, green buffer zones, and mandatory environmental impact assessments for urban expansion. While national programs like the **National Afforestation Programme (NAP)** and **CAMPA** exist, their uneven implementation across states underscores the need for stronger monitoring, decentralized forest governance, and community-led conservation initiatives. Integrating green infrastructure into cities and restoring degraded forest cover would simultaneously reduce pollution and strengthen ecological resilience.

Finally, this analysis highlights the need for decentralized and region-sensitive air quality management. A one-size-fits-all approach is insufficient, given the diverse causes of PM2.5 across India's zones. Strengthening the capacity of State Pollution Control Boards, devolving greater authority to district-level institutions, and integrating them into the **NCAP framework** would allow interventions to target local high-risk clusters, especially in rural districts often overlooked by city-centric policies. By aligning national missions with local governance systems, India can move towards a multi-sectoral strategy that balances economic growth with environmental sustainability.

Conclusion

This study demonstrates that rural economic structures, particularly agriculture and mining, are central drivers of air pollution in India, with their impacts most visible in the Central and Eastern regions. The persistence of biomass fuel reliance, coupled with deforestation and rural industrial activities, underscores how traditional practices and expanding economic pressures converge to exacerbate both ambient and household air pollution. While green cover provides some mitigation, its diminishing presence highlights the fragility of ecological buffers against rising emissions.

The analysis employed a mixed-method approach integrating quantitative air quality data with contextual socioeconomic indicators to capture the multifaceted nature of PM2.5 pollution in rural India. Ground-based monitoring records were utilized to establish temporal and spatial variations in particulate concentrations, while econometric methods enabled the identification of correlations between peaks in PM2.5 levels and periods of heightened economic activity, such as crop residue burning, industrial emissions, and vehicular transport. Statistical modeling was further applied to account for confounding variables, including meteorological patterns, population density, and land-use changes. This methodological framework not only ensured robustness in detecting pollution trends but also provided theoretical grounding for linking environmental degradation with systemic socioeconomic drivers, thereby reinforcing the necessity of interdisciplinary approaches in environmental research.

The findings suggest that policy responses must move beyond urban-centric strategies and instead prioritize decentralized, region-specific interventions that integrate clean fuel adoption, forest conservation, and sustainable livelihood diversification. Embedding these measures within national frameworks such as the NCAP and CAMPA can strengthen environmental governance at the district level and align development pathways with sustainability imperatives. Addressing rural air pollution, therefore, is not only an environmental necessity but also a public health and equity imperative, requiring a balance between economic progress and ecological resilience.

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