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SECTOR-WISE ANALYSIS OF PARTICULATE MATTER AND GASEOUS POLLUTANTS IN LUCKNOW (2023): A COMPARATIVE ASSESSMENT WITH EMISSION LOADS OF KANPUR CITY

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ABSTRACT

This study quantifies emissions of particulate matter (PM10 and PM2.5) and gaseous pollutants (SOX, NOX, CO) in Lucknow district for 2022-23. A detailed source inventory across 13 sectors reveals road dust re-suspension as the primary source of particulate pollution, while the transport sector dominates emissions of NOX, and CO. Seasonal variations emphasize the residential sector's role and the prominence of secondary particulates. Receptor models, along with high-resolution emissions data, enhance estimation accuracy, offering insights for policy and mitigation strategies.

I. INTRODUCTION

India faces critical challenges with air pollution, exacerbated by rapid urbanization and fossil fuel consumption (Lawrence & Fatima, 2014; CPCB, 2011). The health risks associated with exposure to particulate matter (PM) and gaseous pollutants, including lung cancer, heart disease, and respiratory illnesses, are well documented (Health Effects of Air Pollution, 2004; Misra et al., 2012; Ramesh Bhat et al., 2012). As urban centers grow, understanding the sources and magnitude of emissions becomes crucial for developing effective air quality management strategies.

Lucknow, the capital of Uttar Pradesh, is an evolving urban center facing significant environmental challenges. The city's growing population and vehicular density, along with industrial emissions and inadequate waste management practices, contribute to the deterioration of air quality. Particulate matter (PM10 and PM2.5) and gaseous pollutants pose serious health risks, leading to conditions such as respiratory and cardiovascular diseases (Ramesh Bhat et al., 2012). Estimating the sources of these pollutants is key to understanding their contribution to overall air quality.

This research aims to develop a comprehensive emission inventory for Lucknow by applying methodologies consistent with previous emission inventory studies (Turn et al., 1997; Chow & Watson, 1998). The study takes a multi-sectoral approach, assessing emissions from transportation, industrial activities, road dust suspension, municipal solid waste burning, and other sources. Through detailed data collection, land-use analysis, and the application of emission calculation formulas, this paper seeks to quantify pollutant emissions and identify the most significant contributors to urban air pollution in Lucknow.

The methodology includes the estimation of vehicular emissions using Vehicle Kilometers Traveled (VKT) and emission factors derived from ARAI (2016), along with assessments of industrial emissions, waste management practices, and road dust suspension. Additionally, meteorological data is integrated to account for seasonal variations, such as rainy days, which influence emission levels. By constructing a comprehensive emission inventory, the study provides a foundation for targeted mitigation strategies aimed at improving air quality and protecting public health in Lucknow.

II. METHODOLOGY

2.1 Concept of Emission Inventory

An emission inventory is essential for improving regional air quality and mitigating adverse effects on human health and ecosystems. The methodology for creating an emission inventory involves categorizing emission sources as point, line, and area sources for organized tracking (see Figure 9).

Emission Calculation Formula:

$$\text{Emissions} = \text{Activity Data} \times \text{Emission Factor} \qquad \text{(Eq. 1)}$$

Where:

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- Activity Data: The scale of the activity generating emissions.
- Emission Factor (EF): The average rate of a specific pollutant per unit of activity.

For specific scenarios involving reduction measures, the equation is expanded as:

$$E = A \times EF \times (1 - ER/100) \quad \text{(Eq. 2)}$$

Where:

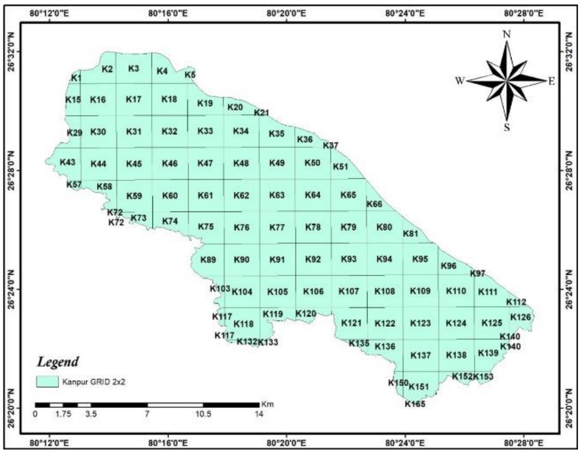
- ER: Overall emission reduction efficiency (%).

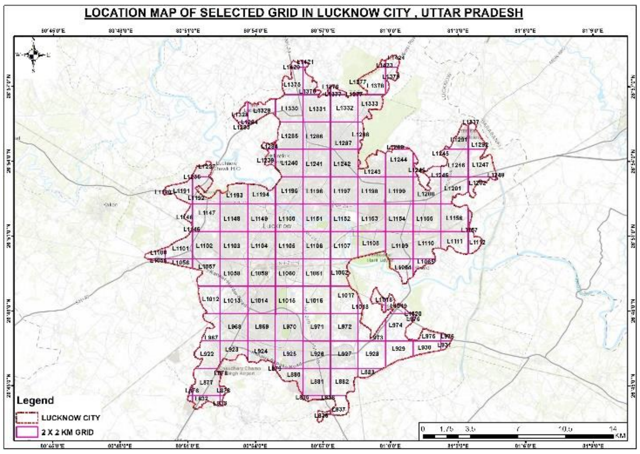
2.2. Data Collection Strategy

Primary Data: Field Surveys: Road dust sampling at 19 locations, construction activity data, and industrial area surveys.

Secondary Data: Sources include SPCB, CPCB, AAI, Indian Railways, CEA, transport department records, and toll plaza data. Supplemental data were accessed through published reports and online sources.

Digital Imagery: A land-use map was developed for the study area, segmented into 2 km × 2 km grids (Figures 1 & 2). Emission calculations were performed for each grid based on the collected data.





Figures 1 & 2

2.3. Study Area Profile

2.3.1. Location and Demographics

Lucknow (26.8467°N, 80.9462°E) spans 2,528 sq. km. The city is bordered by Barabanki, Raebareli, Sitapur, Hardoi, and Unnao, with the Gomti River flowing through it. The population is approximately 3.7 million with a density of 8,049 people per sq. km.

2.3.2. Climatic Conditions

Lucknow's climate includes cold winters, hot summers, and a monsoon season. Average annual rainfall is 1,000 mm, with temperatures ranging from 6.2°C to 41.9°C. Wind patterns predominantly originate from the WNW.

2.4. Land Use and Vehicular Impact

Urban development since 1999 has reduced agricultural and water body areas. Forest cover remains low at 4.66%, below the state average. The city has 3,387 km of road networks with increasing vehicle registrations.

Figures 4-5: Road network and vehicle registration data.

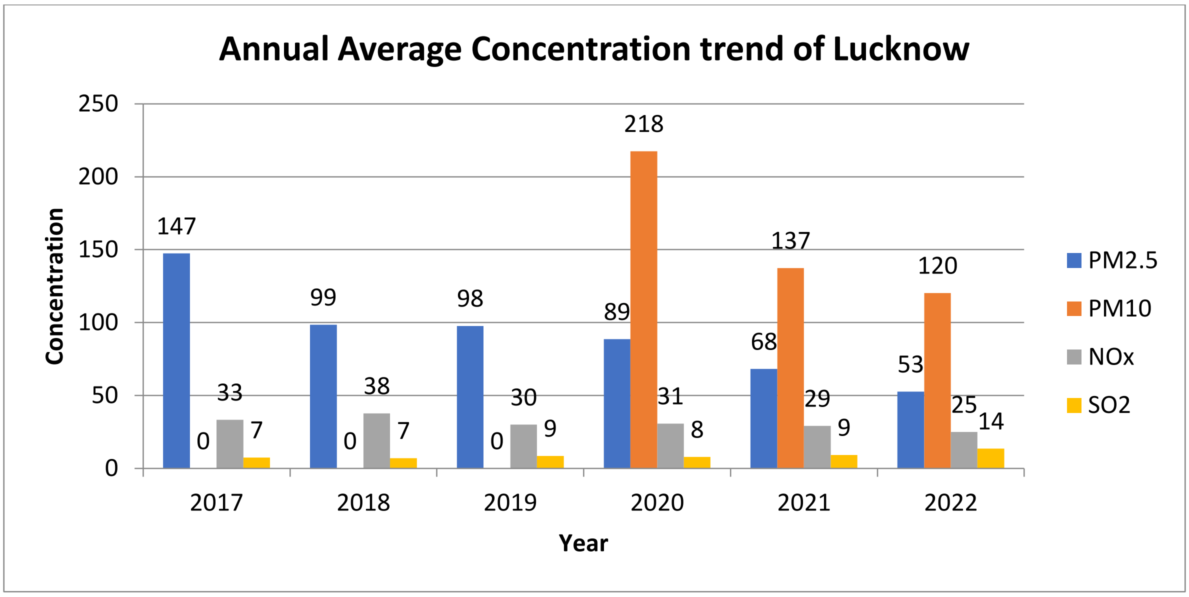
2.5. Industrial Emissions and Waste Management

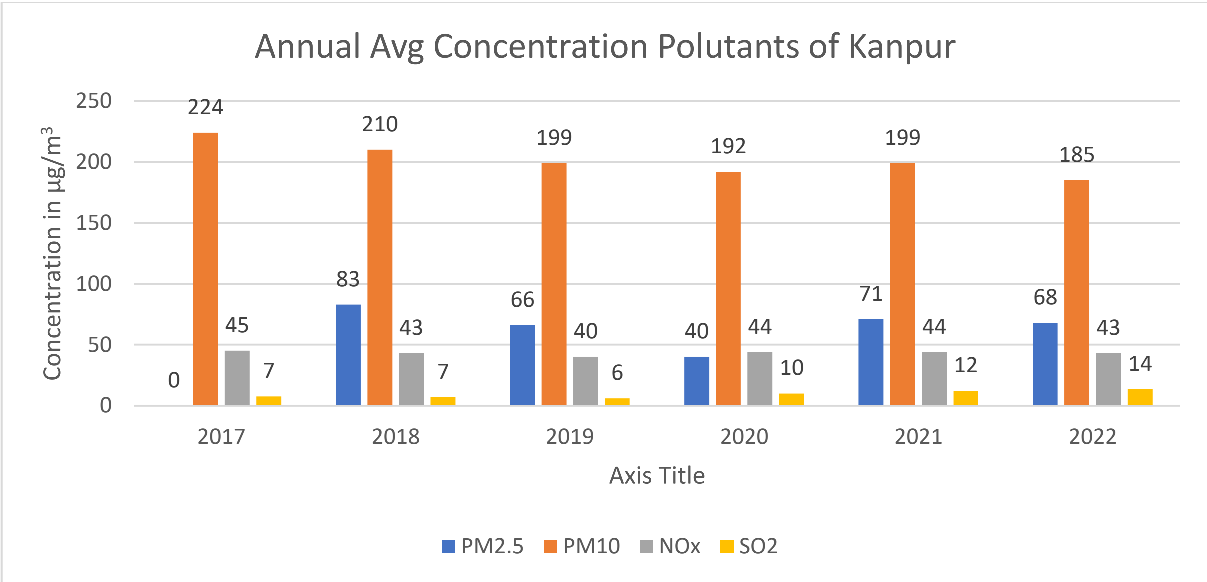
Prominent industrial zones include Talkatora and Chinhat, housing small- and medium-scale industries. The city's waste management system handles 114.7 tons/day with an 89% collection efficiency.

Figures 7a & 7b: Waste characterization and management processes.

2.6. Air Quality Trends

Annual air quality data highlight non-compliance with NAQS for PM10 levels, with occasional NO2 spikes and consistent SO2 compliance.





Figures 3 & 4: Annual air quality trends and monitoring data.

3. Sector-wise Emission Estimation

3.1. Industrial Emissions

To estimate emissions from the industrial sector, the general formula used is:

$$Ep=\sum i(Fc\times Ef\times \eta) \quad \text{(Eq. 2)}$$

Where:

- Ep = Industrial emission of pollutant ppp.
- Fc = Fuel consumption for a specific industry.
- Ef = Emission factor for a given pollutant and fuel type.
- η = Efficiency of installed air pollution control devices (APCDs).

The emissions from Diesel Generator Sets can be estimated using the following formula:

$$Ep=C\times t\times 36\times 105\times Ef \quad \text{(Eq. 3)}$$

Where:

- C = Capacity of the diesel generator.
- t = Operational hours of the generator.
- Ef = Emission factor for the specific pollutant.

3.2. Hotel and Restaurant Emissions

The emissions from hotels and restaurants were calculated using the following equation:

$$Ep = Cf \times Ef \quad \text{(Eq. 4)}$$

Where:

- Ep = Emission of the pollutant p.
- Cf = Fuel consumption.
- Ef = Emission factor.

The extrapolation of results from these surveyed grids is based on population density and land use patterns.

3.3. Municipal Solid Waste Burning Emissions

To calculate emissions from waste burning, the following formula is used:

$$E_{pol} = W_{ba} \times EF \quad \text{(Eq. 5)}$$

Where:

- W_{ba} = Quantity of waste burned in rural (a=1) or urban (a=2) areas.
- E_{pol} = Emissions of pollutant from burning of waste material.
- EF = Emission factor for a specific pollutant.

Additionally, for population-based estimation, the equation for the population in a block is:

$$Pop_a = Pop_{2011} \times (1+r)^t \quad \text{(Eq. 6)}$$

Where:

- Pop_a = Estimated population in rural (a=1) or urban (a=2) area.
- Pop_{2011} = Population in 2011.
- r = Annual population growth rate.
- t = Time period in years.

3.4. Road Dust Suspension Emissions

The equation for road dust suspension emissions is derived from AP-42:

$$E_p = VKT \times w \times Mo \times k \quad \text{(Eq. 7)}$$

Where:

- E_p = Fugitive emissions of pollutant p from transportation sector.
- VKT = Vehicle kilometers traveled.
- www = Average weight of vehicles.
- Mo= Silt loading on the road surface.
- k = Particle size-dependent factor (0.62 for PM_{10}, 0.15 for $PM_{2.5}$).

To adjust for wet days, the final fugitive emissions after considering rainy days are calculated as:

$$f[E_p] = E_p \times (1 - D_p/365) \quad \text{(Eq. 8)}$$

Where:

- D_p = Number of rainy days in a year.

3.5. Transport Sector Emissions

The transport sector emissions are computed using the Vehicle Kilometers Traveled (VKT) methodology, based on traffic count surveys and parking lot assessments:

$$E_p = \sum_c \sum_s (VKT_{c,s} \times EF_{p,c,s} \times \epsilon_{c,s} \times n_c) \quad \text{(Eq. 9)}$$

Where:

- E_p = Total emissions of pollutant p.
- c = Vehicle category (e.g., cars, buses, trucks).
- s = Emission control standard (e.g., BS-I, BS-II, BS-III, BS-IV, CNG).
- $VKT_{c,s}$ = Vehicle kilometers traveled for category ccc and standard s.

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- $EF_{p,c,s}$ = Emission factor for pollutant p.
- $\epsilon_{c,s}$= Percentage of vehicles with emission control standard s.
- n_c = Total number of vehicles in category c.

III. RESULTS AND DISCUSSION

4.1 Comparative Emission Inventory Analysis: Lucknow vs. Kanpur

This section highlights the major sources and contributions to emissions in Lucknow and Kanpur, providing a detailed comparison and discussion on their implications for air quality management.

4.1.1. Particulate Matter (PM10 and PM2.5):

- **Kanpur**: The estimated total PM10 emissions are 105,841 kg/day (approximately 106 t/day), with road dust being the dominant source (82%), followed by vehicles (6%), industries (4%), and construction activities (2%). PM2.5 emissions are around 34,411 kg/day (approximately 34 t/day), primarily from road dust (58%), vehicles (18%), and industries (12%).

- **Lucknow**: Total PM10 emissions are approximately 49,700 kg/day (50 t/day), with road dust contributing the majority (86%), followed by transport (16%). PM2.5 emissions are approximately 14,200 kg/day (14 t/day), with road dust accounting for 72% and vehicles 19%.

Both cities show that road dust is the leading source of PM10 and PM2.5, highlighting the need for robust dust control measures. However, the vehicle contribution to PM2.5 is relatively higher in Lucknow compared to Kanpur, emphasizing the impact of transport on urban air quality.

Table 1: Summary of Emission Contributions by Sector

Sector	PM10 (kg/day)	PM2.5 (kg/day)	SO2 (kg/day)	NOx (kg/day)	CO (kg/day)	Top Emission Contributors
Kanpur Total	105,841	34,411	9,962	76,581	145,022	Road dust, vehicles, industries
Lucknow Total	49,700	14,200	215	116,832	628,770	Road dust, transport, construction

4.2 Nitrogen Oxides (NOx) Emissions

- **Kanpur:** NOx emissions are estimated at 76,581 kg/day (77 t/day), with vehicular emissions being the main contributor (84%), followed by industrial emissions (7%) and DG sets (6%).

- **Lucknow:** NOx emissions are significantly higher at 116,832 kg/day (117 t/day), with transport being the dominant source (98%). The contributions from diesel generators and the residential sector are minimal.

The comparison highlights the prominence of transport as a key NOx emitter, particularly in Lucknow where it contributes nearly all NOx emissions. This underscores the importance of adopting cleaner vehicle technologies and enhancing public transportation.

4.3 Sulfur Dioxide (SO2) Emissions

- Kanpur: SO2 emissions total 9,962 kg/day (10 t/day), with the largest share from industries (71%), followed by vehicles (14%) and the hotel/restaurant sector (5%).

- Lucknow: SO2 emissions are much lower at 215 kg/day, primarily from industrial sources (58%) and transport (21%).

The industrial sector's role in SO2 emissions is notably significant in Kanpur, whereas in Lucknow, industrial and transport sectors both contribute moderately. This suggests a more localized emission control focus for SO2 in Kanpur.

4.4 Carbon Monoxide (CO) Emissions

- Kanpur: The estimated CO emissions are 145,022 kg/day (145 t/day), with vehicles contributing 82%, followed by domestic sources and MSW burning at 7% each.

- Lucknow: CO emissions are substantially higher, at 628,770 kg/day, with transport alone contributing 98%.

The overwhelming contribution of CO emissions from the transport sector in Lucknow indicates a pressing need for emission control strategies, including vehicle emission standards and traffic management policies.

4.5 Spatial Distribution of Pollutant Emissions in Lucknow

Spatial analysis using ArcGIS has revealed key areas of pollutant concentration. The 2 × 2 km grid-based mapping indicates:

- PM Emissions: Concentrated in densely populated urban areas with high vehicular movement and significant road dust resuspension.

- NOx Emissions: Primarily centered around major highways and urban hotspots, driven by transport activities.

- SO2 Emissions: Peaked in industrial zones with cement plants and metal processing industries using coal.

- CO Emissions: More distributed, with high concentrations in urban centers and residential areas where biomass combustion is prevalent.

4.6 Atmospheric Concentrations and CMAQ Modeling

Using the CMAQ model integrated with meteorological data from WRF 3.9.1, the research validated source contributions and pollutant dispersion. The model simulations align with observed data at four key monitoring stations, showcasing its reliability in representing atmospheric behavior.

Seasonal Analysis and Source Contributions:

- **Winter:** Residential emissions peak at 27% due to reduced wind speeds and shallow planetary boundary layers.

- **Summer:** Road dust contributes up to 26% due to dry conditions.

- **Monsoon/Post-Monsoon:** International sources contribute up to 20% due to long-range transport and high wind speeds.

Table 2: Sectoral Contributions of PM2.5 in Lucknow provides detailed seasonal and yearly averages, indicating the need for tailored interventions based on seasonal variations.

Sector	Winter	Summer	Post Monsoon	Monsoon	Yearly
Transport	17%	8%	13%	11%	12%
Residential	28%	21%	22%	22%	24%
Road dust	19%	26%	15%	32%	22%
Industry	9%	5%	7%	6%	%
International	12%	17%	11%	20%	14%

Primary vs. Secondary Particulate Matter Contributions:

The composition of PM2.5 includes primary particulate matter (PMPRIM), secondary inorganic aerosols (SIA), and secondary organic aerosols (SOA). Seasonal variations in meteorological and emission sources influence these contributions, guiding policymakers to target sources based on specific ambient PM2.5 compositions.

Particulate Matter (PM10 and PM2.5):

- **Kanpur**: Road dust (82%) and vehicles (6%) dominate PM10 emissions.
- **Lucknow**: Road dust contributes 86% to PM10 emissions.

Table 3

Sector	PM10 (kg/day)	PM2.5 (kg/day)	Top Sources
Kanpur	105,841	34,411	Road dust
Lucknow	49,700	14,200	Road dust

4.7 Nitrogen Oxides (NOx) Emissions

Transport emerges as the primary NOx source in both cities, with Kanpur's emissions at 76,581 kg/day and Lucknow's at 116,832 kg/day.

4.8 Sulfur Dioxide (SO2) Emissions

SO2 emissions are significantly higher in Kanpur due to industrial contributions, with 71% of emissions attributed to industrial sources.

4.9 Spatial Distribution of Emissions in Lucknow

Spatial analysis in ArcGIS, utilizing a 2 × 2 km grid, highlights hotspots of pollutant emissions. Road dust resuspension, vehicular NOx emissions, and industrial SO_2 emissions concentrate in urban areas and industrial zones.

4.10 Seasonal and Atmospheric Modeling

Using the CMAQ model integrated with WRF meteorological data, source contributions were validated. Key seasonal variations include:

- **Winter**: Residential emissions peak due to low wind speeds.
- **Summer**: Road dust increases due to dry conditions.
- **Monsoon**: High wind speeds facilitate pollutant dispersion.

Discussion

The results underscore the multifaceted nature of air pollution in Lucknow. Emission inventories combined with receptor models provide crucial insights into the impact of road dust, transport, and industrial activities. The analysis suggests a focus on road dust and vehicular emissions for effective air quality management.

IV. CONCLUSION

The comparative emission analysis of Kanpur and Lucknow reveals critical insights into the unique emission profiles of these cities, emphasizing the need for tailored air quality management strategies. Both cities exhibit significant contributions from road dust, transport, and, to a lesser extent, industrial activities, underscoring the necessity for sector-specific interventions.

Particulate Matter (PM10 and PM2.5): Road dust re-suspension is identified as the primary contributor to PM10 and PM2.5 emissions, with Kanpur and Lucknow showing over 80% and 86% contributions, respectively. Addressing this source through effective road maintenance, surface treatments, and dust suppression techniques is essential for managing particulate pollution.

Transport Sector: Transport emissions are particularly dominant in Lucknow, contributing 98% to both NOx and CO emissions, which highlights an urgent need for sustainable transport solutions. Kanpur shows a similar but slightly lower transport emission profile. Strengthening public transport, promoting electric vehicles, and enforcing stricter emission standards will be vital, especially in Lucknow.

Industrial Emissions: Kanpur experiences considerable industrial contributions to PM2.5 and SO2 emissions, positioning this sector as a primary target for emission control measures. While the industrial sector in Lucknow plays a smaller role compared to transport and road dust, targeted improvements can still yield significant air quality benefits.

Diesel Generator (DG) Sets: Emissions from DG sets contribute notably to NOx and SO2 levels in both cities. Initiatives that promote alternative power solutions, such as renewable energy and hybrid systems, can mitigate these emissions effectively.

Hotels and Restaurants: Although this sector contributes less to overall emissions, its impact on urban air quality, particularly for CO and PM, remains relevant. Kanpur's reliance on coal and wood in commercial establishments contrasts with Lucknow's higher use of cleaner fuels like LPG. Transitioning to cleaner and more efficient energy sources is a viable strategy for reducing emissions in the hospitality sector, particularly in Kanpur.

Way Forward

1. Road Dust Management: Proactive measures, such as regular road maintenance, surface sealing, and water spraying, should be implemented in both cities to reduce the re-suspension of particulate matter.
2. Transport Emission Controls: Investment in public transit infrastructure, incentives for electric vehicles, and the enforcement of strict vehicle emission standards are critical steps, particularly for managing NOx and CO emissions in Lucknow.

3. Industrial Regulations: In Kanpur, strengthening emission regulations and adopting cleaner technologies in industrial processes can significantly reduce PM2.5 and SO2 emissions.
4. Alternative Power Solutions: Reducing dependence on DG sets by promoting renewable energy sources or adopting hybrid power solutions can help lower NOx and SO2 emissions.
5. Cleaner Fuel Use in Commercial Sectors: Encouraging restaurants and hotels to shift towards cleaner fuels and more efficient cooking technologies can mitigate emissions, particularly in Kanpur, where coal and wood are frequently used.

In conclusion, targeted interventions focusing on road dust, transport emissions, industrial activities, and energy sources are pivotal for improving air quality in both cities. A comprehensive approach that integrates local, regional, and international collaboration, alongside policy and technology-driven solutions, will be essential to achieve sustained improvements in air quality and public health outcomes.

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