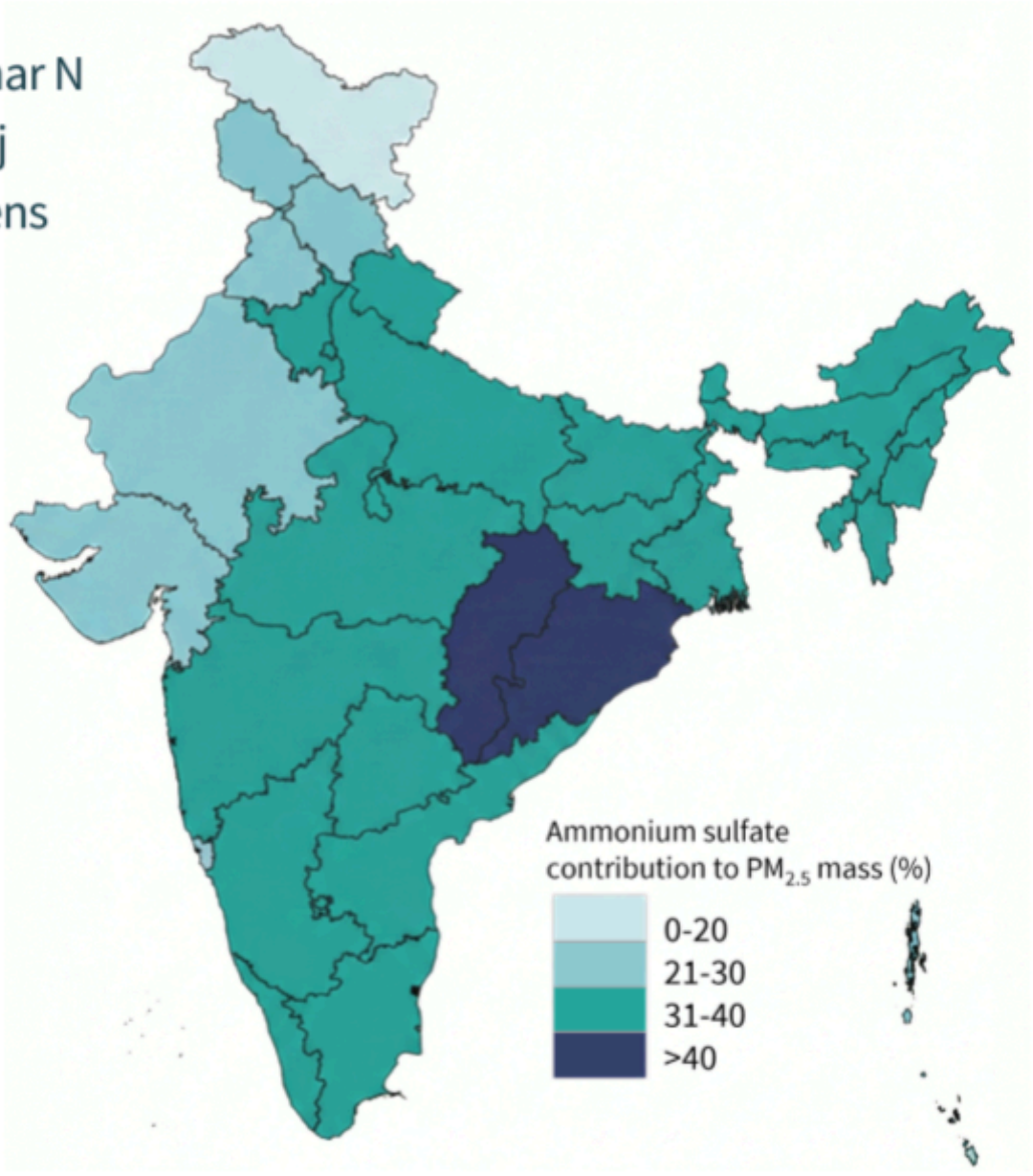
Secondary particulate matter is a core driver of dangerous PM2.5 in India

Manojkumar N
Monish Raj
Rosa Gierens

12/2025



CREA

CREA is an independent research organization focused on revealing the trends, causes, and health impacts, as well as the solutions to air pollution.

Secondary particulate matter is a core driver of dangerous $PM_{2.5}$ in India

December 2025

Authors

Manojkumar N

Monish Raj

Data Scientists

Rosa Gierens

Editor

Jonathan Seidman

Designer

Hannah Ekberg

About CREA

The Centre for Research on Energy and Clean Air (CREA) is an independent research organisation focused on revealing the trends, causes, and health impacts, as well as the solutions to air pollution. CREA uses scientific data, research, and evidence to support the efforts of governments, companies, and campaigning organisations worldwide in their efforts to move towards clean energy and clean air, believing that effective research and communication are the keys to successful policies, investment decisions, and advocacy efforts. CREA was founded in Helsinki and has staff in several Asian and European countries.

Disclaimer

CREA is politically independent. The designations employed and the presentation of the material in this report do not imply the expression of any opinion whatsoever concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

Secondary particulate matter is a core driver of dangerous $PM_{2.5}$ in India

Key findings

- Satellite reanalysis data shows that at the annual scale, ammonium sulfate accounts for a substantial share of $PM_{2.5}$ mass across all Indian states and Union Territories, confirming secondary particulate matter as a core driver of $PM_{2.5}$ in India.
- One third of annual $PM_{2.5}$ in 19 states comes from ammonium sulfate. Across all states, two exceed 40%, 23 fall in the 31-40% range, 10 in the 21-30% range, and only one state is below 20%.
- The highest annual ammonium sulfate contribution to $PM_{2.5}$ mass occurs in the coal-fired power plant dominant state of Chhattisgarh (42%), followed by Odisha (41%), and Jharkhand and Telangana (40% each).
- Seasonal contribution across Indian states reinforces the dominance of ammonium sulfate, peaking in both winter (31-52% of $PM_{2.5}$ mass) and post-monsoon (27-53%), compared with summer (11-36%) and monsoon (4-26%).
- Airshed analysis shows that ammonium sulfate contributes a disproportionately large share of $PM_{2.5}$ across most Indian airsheds, with winter and post-monsoon seasons showing widespread contributions above 40%, except for a few airsheds.
- Taken together with earlier assessment showing that India is the world's largest emitter of sulfur dioxide and among the top emitters of ammonia, CREA's analysis indicates that up to 42% of India's $PM_{2.5}$ burden is chemically formed in the atmosphere from precursor gases, reinforcing the central role of sulfur dioxide control in $PM_{2.5}$ mitigation.
- Despite this evidence, the current regulatory framework has exempted approximately 78% of coal-fired thermal power plants from installing flue gas desulfurisation systems, weakening sulfur dioxide control at source. Reinstating 2015 emission norms notification is therefore critical for mandatory installation of flue gas desulfurisation to reduce secondary ammonium sulfate formation and $PM_{2.5}$.

Introduction

India's air quality management has historically focused on PM_{10}, with limited attention to $PM_{2.5}$ and almost none to the secondary particulate fraction that forms through atmospheric chemical processes rather than being emitted directly. Yet, understanding how $PM_{2.5}$ is chemically constituted, especially the share arising from secondary formation, is essential for designing targeted, sector-specific interventions.

While ground monitoring networks provide high-resolution data on total $PM_{2.5}$ concentrations, they rarely offer consistent information on particle composition or precursor-driven secondary aerosols. Satellite-based reanalysis products such as NASA's MERRA-2 (Modern-Era Retrospective Analysis for Research and Applications, Version 2) help address this gap by providing spatially and temporally consistent estimates of both total $PM_{2.5}$ and its modeled chemical components.

This brief presents an assessment of $PM_{2.5}$ composition across India's states and airsheds, with a specific focus on secondary particulate matter, particularly ammonium sulfate [$(NH_4)_2SO_4$], using MERRA-2 reanalysis data.

Ammonium sulfate represents secondary $PM_{2.5}$ formed from interactions between sulfur dioxide and ammonia emissions, linking coal-based power generation, industrial activity, and agricultural ammonia to $PM_{2.5}$ pollution. The government had already diluted SO_2 emission norms for coal-fired power plants, and this approach delayed action, weakened compliance efforts, and underestimated the role of sulfur dioxide emissions in forming secondary $PM_{2.5}$.

The findings highlight the limitations of blanket PM control strategies and demonstrate the need for airshed and region-specific approaches that address precursor gases and secondary aerosol formation.

This evidence is directly relevant for the upcoming revision of the National Clean Air Programme (NCAP), supporting a stronger and more explicit focus on sulfur dioxide, ammonia, and combustion-related emissions to achieve sustained and structurally durable reductions in $PM_{2.5}$.

Ammonium sulfate

Ammonium sulfate is a secondary inorganic aerosol in $PM_{2.5}$ formed via oxidation of sulfur dioxide to sulfate and subsequent neutralization by ammonia in the gas and particle phases, with enhanced formation in humid conditions.

At the annual scale, ammonium sulfate accounts for a substantial share of $PM_{2.5}$ mass across all Indian states and Union Territories, confirming secondary particulate matter as a core driver of $PM_{2.5}$ in India. Annual mean contributions range from 17 to 42%, with most states clustering between 30 and 40% of total $PM_{2.5}$ mass.

The highest annual contributions are observed in Chhattisgarh (42%), Odisha (41%), Jharkhand and Telangana (40% each), Bihar (39%), Maharashtra, Andhra Pradesh, and West Bengal (38% each), and Uttar Pradesh and Madhya Pradesh (37% each). These states span eastern, central, southern, and western India, indicating that elevated secondary sulfate formation is not limited to a single region or airshed.

Several southern and northeastern states also exhibit consistently high annual contributions, including Karnataka (36%), Meghalaya (36%), Arunachal Pradesh (36%), Tripura (35%), Assam (34%), Sikkim (34%), Nagaland (33%), Mizoram (33%), Manipur (32%), and Tamil Nadu (32%). Even coastal and island regions such as Kerala (32%), Goa (30%), Puducherry (30%), Lakshadweep (27%), and Andaman and Nicobar Islands (21%) show a dominant secondary sulfate presence.

Lower annual contributions are observed in Ladakh (17%), Gujarat, Rajasthan, and Jammu and Kashmir (24% each), and Himachal Pradesh (25%), though even in these regions ammonium sulfate represents a non-trivial component of $PM_{2.5}$ mass.

Overall, the annual analysis demonstrates that secondary ammonium sulfate alone contributes roughly one-quarter to two-fifths of $PM_{2.5}$ mass across most Indian states, establishing it as one of the dominant $PM_{2.5}$ components nationwide. This annual baseline provides critical context for reinforcing the need for year-round control of sulfur dioxide and ammonia emissions within India's air quality management framework.

The seasonal data show a clear and consistent increase in the share of ammonium sulfate in $PM_{2.5}$ during winter and post-monsoon across nearly all Indian states. The post-monsoon season records the highest or near-highest ammonium sulfate contributions in most

states. Values frequently range between 27 and 53%, with many states approaching half of total $PM_{2.5}$ mass. This pattern is evident not only in the Indo-Gangetic Plain but also across southern, western, coastal, and northeastern states, showing that elevated post-monsoon contributions are widespread rather than regionally confined.

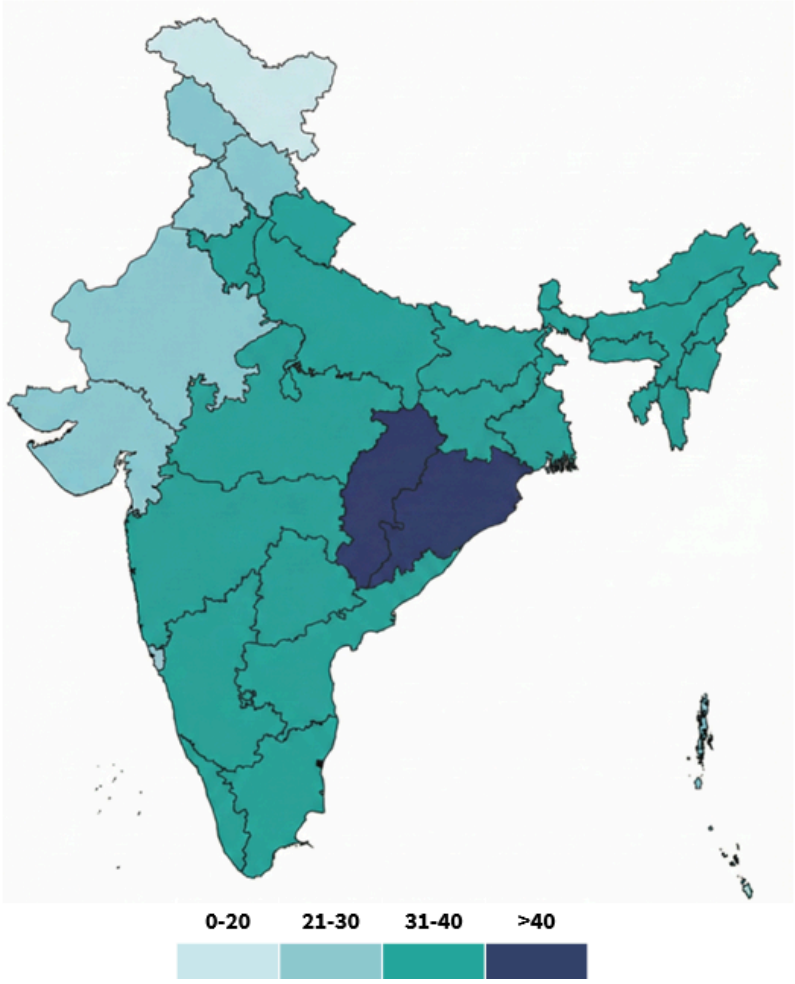


Figure 1. Annual ammonium sulfate contribution (%) to $PM_{2.5}$ mass across Indian states

In winter, ammonium sulfate typically contributes around 31-52% of $PM_{2.5}$ mass, with high values observed across northern, central, eastern, and southern states. Several states, including Andhra Pradesh, Bihar, Jharkhand, Odisha, Telangana, Maharashtra, Uttar Pradesh, and West Bengal, record winter contributions at or above 45%, indicating that secondary sulfate forms a dominant fraction of fine particulate matter during this season.

During summer, ammonium sulfate contributes a substantial share of $PM_{2.5}$, generally between 11% to 36% across states. Higher summer contributions are observed in several southern and central states, while northern regions tend to record lower shares. Despite this moderation, ammonium sulfate remains one of the major $PM_{2.5}$ components in most states during summer.

The monsoon season shows the lowest ammonium sulfate contributions nationwide. The sulfate fraction falls below 26% across all states. Although absolute $PM_{2.5}$ concentrations may vary, the monsoon consistently represents the seasonal minimum in ammonium sulfate's share of fine particulate matter.

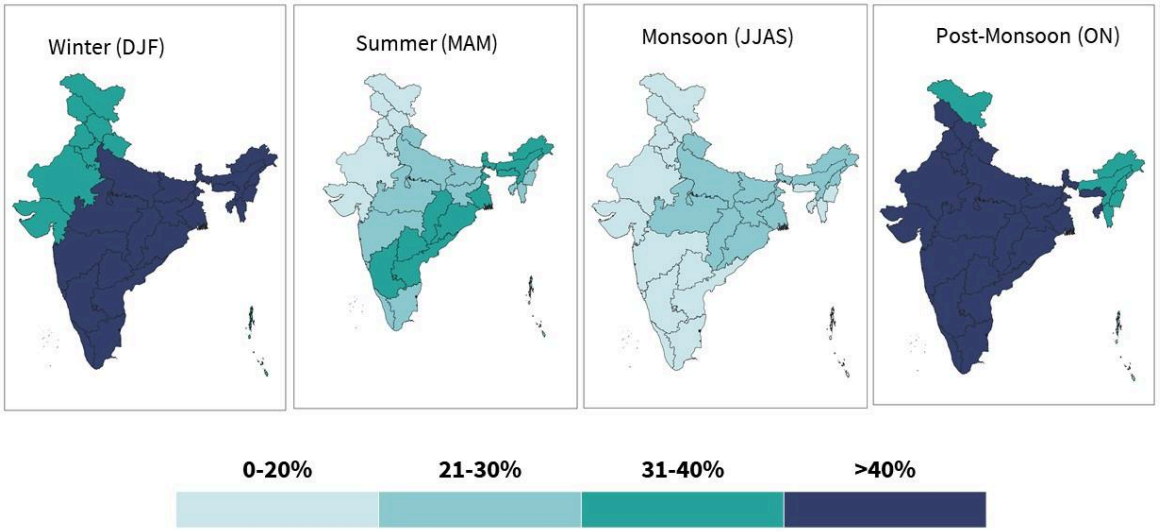


Figure 2. Seasonal ammonium sulfate contribution (%) to $PM_{2.5}$ mass across Indian states

Overall, the data demonstrate a strong seasonal pattern, with ammonium sulfate forming a much larger fraction of $PM_{2.5}$ in winter and post-monsoon than in summer and monsoon, and a broadly similar seasonal pattern observed across states and regions.

Figure 3 shows that ammonium sulfate contributes a very large share of $PM_{2.5}$ across most Indian airsheds, with a distinctly seasonal pattern. During winter and post-monsoon, nearly the entire country falls in the highest contribution band of more than 40%. The only exceptions in winter are the northern airsheds and one airshed in western India, which remain below this threshold. A similar pattern appears in the post-monsoon season, with

only one airshed in north India and all airsheds in north-eastern airsheds are in 31% to40% band.

During summer, most airsheds shift to intermediate contribution ranges (21-40%); however, northeastern airsheds stand out with the highest contributions, exceeding those observed in many other regions. A similar pattern is observed during the monsoon, when contributions decline across the country but remain comparatively higher in the northeastern airsheds, while most other regions fall into the lowest contribution category (0-20%).

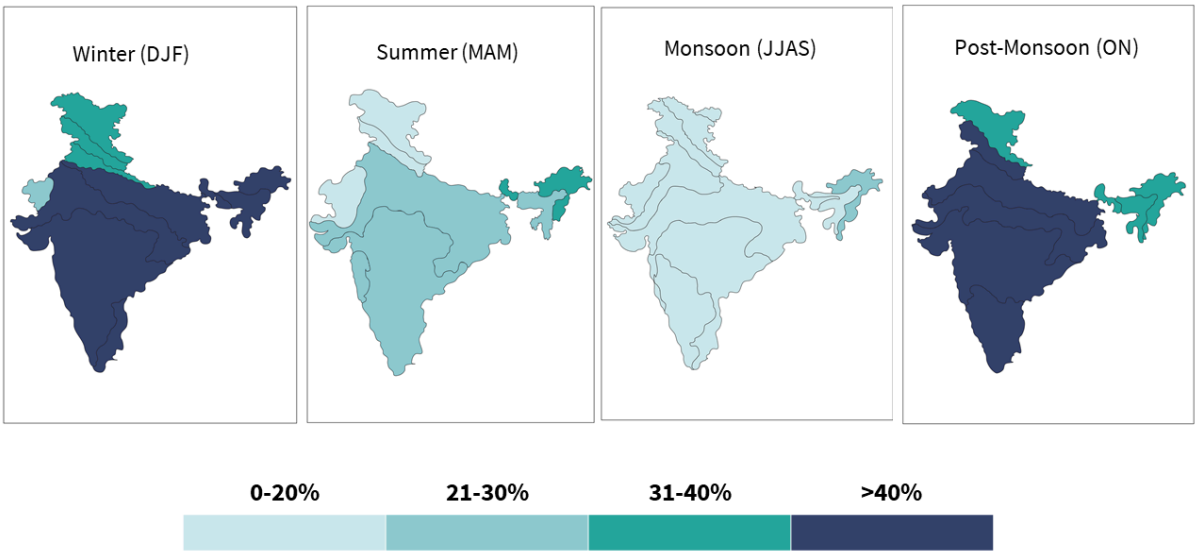


Figure 3. Seasonal ammonium sulfate contribution (%) to $PM_{2.5}$ mass across Indian airsheds

Overall, the airshed perspective highlights that ammonium sulfate exhibits synchronized seasonal behaviour across regions, reinforcing that its contribution to $PM_{2.5}$ is governed at regional scales and requires coordinated, multi-state management approaches.

The way forward

The evidence clearly establishes ammonium sulfate as a dominant and structurally embedded component of $PM_{2.5}$ across India, with consistently high annual contributions and pronounced seasonal amplification. This has direct implications for how air quality management priorities must evolve.

- First, air pollution control strategies need to move decisively beyond primary PM reduction. Given that ammonium sulfate alone accounts for roughly one-quarter to two-fifths of $PM_{2.5}$ mass across most states, effective $PM_{2.5}$ mitigation is not possible without explicitly targeting the precursor gases sulfur dioxide and ammonia.
- Second, the findings call for year-round control of sulfur dioxide emissions, particularly from coal-based power plants and large industrial sources. This makes a strong case for reinstating mandatory flue gas desulfurisation requirements, reversing recent dilutions in emission norms, and ensuring strict compliance across the power sector. Given the high contributions observed across multiple regions and airsheds, these measures must apply nationally rather than being restricted to a few priority cities.
- Third, ammonia emissions require explicit regulatory attention, which remains a major gap in India's air quality governance. Agricultural activities, fertilizer use, waste handling, and certain industrial processes contribute substantially to ammonia availability, enabling secondary sulfate formation.
- Fourth, the airshed-scale coherence observed in ammonium sulfate contribution highlights the need for regional and multi-state coordination. Since secondary sulfate formation and accumulation occurs across large airsheds, isolated city- or state-level actions will be insufficient. NCAP implementation should therefore prioritise airshed-based planning, shared accountability across states, and coordinated emission reduction strategies for precursor gases.
- Finally, strengthening $PM_{2.5}$ composition monitoring and evaluation is critical. Routine tracking of $PM_{2.5}$ chemical components and precursor gases will allow policymakers to distinguish between reductions driven by structural emission controls and short-term meteorological effects. This will help close the gap between emissions policies and observed air quality outcomes.

Overall, reducing India's $PM_{2.5}$ burden requires treating secondary ammonium sulfate not as a peripheral issue but as a central policy target. Embedding precursor gas control, airshed-level coordination, and composition-based assessment into the revision and implementation of the NCAP is essential to achieving durable, long-term improvements in air quality.

Methodology

To assess the contribution of ammonium sulfate to total $PM_{2.5}$, and how it varies across India, we use data from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2). The MERRA-2 reanalysis is created by merging modelling with observational data, especially satellite measurements, to get the best estimate of $PM_{2.5}$ properties at a given time and place. We used the tavg1_2d_aer_Nx collection, version 5.12.4, which contains the surface level concentrations for different PM species at a resolution of 0.625x0.5 degrees at hourly intervals. We calculated the mean for the year 2024 in each grid pixel for both total $PM_{2.5}$ and each type of particle, and used the averaged data to calculate the fraction of each particle type from the total $PM_{2.5}$ and to sample the concentrations at state and airshed levels.

Shapefiles delineating state and district administrative boundaries were sourced from Guttikunda (2024), while the airshed shapefile was obtained from Kumar et al. (2025). Seasonal airsheds varying between 9 and 11 across different seasons were also analysed to examine regional variations in $PM_{2.5}$ concentrations. In this analysis, seasons are defined as: winter (December 2024, January and February 2025), summer (March - May 2024), monsoon (June - September 2024), and post-monsoon (October - November 2024).

References

Global Modeling and Assimilation Office (GMAO) (2015), MERRA-2 tavg1_2d_aer_Nx: 2d,1-Hourly,Time-averaged,Single-Level,Assimilation,Aerosol Diagnostics 0.625 x 0.5 degree V5.12.4 (M2T1NXAER), Greenbelt, MD, USA: Goddard Space Flight Center Distributed Active Archive Center (GSFC DAAC), Accessed 3.6.2025 at doi: 10.5067/KLICLTZ8EM9D.

Guttikunda, S. (2024). GIS and Pollution Data: Designating Regional Airsheds for Air Quality Management in India [Data set]. *Zenodo*. https://doi.org/10.5281/zenodo.11332107

Kumar, A., Imam, F., Dixit, K., Chaudhary, E., Sharma, S., Singh, N., & Dey, S. (2025). Sectoral Contributions to Primary and Secondary $PM_{2.5}$ in Regional Airsheds of India. *ACS Earth and*

Space Chemistry, *9*(4), 806-816.
https://pubs.acs.org/doi/full/10.1021/acsearthspacechem.4c00332

Manojkumar N., & Rosa Gierens. (2025). Secondary particles contribute to one-third of India's PM2.5: A call to strengthen the NCAP by targeting precursor gases. Centre for Research on Energy and Clean Air (CREA).
https://energyandcleanair.org/publication/secondary-particles-contribute-to-one-third-of-indias-pm2-5/

Manojkumar N. (2025). Scientific evidence is clear: Enforcing SO2 norms in India's coal power plants is non-negotiable. Centre for Research on Energy and Clean Air (CREA). . Centre for Research on Energy and Clean Air (CREA).
https://energyandcleanair.org/publication/enforcing-so2-norms-in-indias-coal-power-plants-is-non-negotiable/

Press Information Bureau. (2023). National Clean Air Programme (NCAP) to improve air quality in 131 cities by engaging all stakeholders. Ministry of Environment, Forest and Climate Change.
https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=1909910&reg=3&lang=2