IN THE NATIONAL GREEEN TRIBUNAL

PRINCIPAL BENCH, NEW DELHI

ORIGINAL APPLICATION NO. OA 90/2025

In the matter of :-

Dr. Sanjay Kulshresthra MBBS, MS, MCh
Senior Consultant Pediatric Surgeon,
1/171, Delhi Gate, Gulab Rai Marg, AGRA -2

…… **Applicant in Person**

VERSUS

Union of India & another

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ADDITIONAL DOCUMENT IN SUPPORT OF PRAYER AS PER THE ORDER OF HONBLE COURT DATED 04.03.2025

MOST RESPECTFULLY SHOWETH :

[1]. Your Lordship, this original application [90/2025] was filed to share an alarming state of air pollution in most of the Indian cities with the prayer to define the road life of motorized vehicles in other states of India also like that of Delhi/NCR and pass directions to implement the ban on old diesel & petrol vehicles more than 10 years and 15 years respectively, in other Indian cities also in addition to Delhi/NCR.

Today the Air Pollution has become a serious health hazard at national level. Though Delhi is declared worst amongst all however, many other metro and smaller cities are also fast becoming cities with serious air pollution. Today the Air Pollution has become a serious health hazard at national level. Under article 21 it is statutory duty of govt to ensure a clean and safe environment to its citizens of all cities. Therefore the measures to control this air pollution also need to be implemented at national level and needs to be more aggressive. Therefore besides, Delhi/NCR, govt needs to pay equal attention for other effected cities also as fresh air is the birth right of every individual of the country.

[2] Honble tribunal in its order dated 04.03.2025 allowed the applicant to submit some additional information in support of prayer. The order was as follow:

"1. In this original application, applicant has prayed for a direction to implement the ban on old petrol and diesel vehicles of more than 15 years and 10 years respectively in other cities in addition to Delhi/NCR.

2. We find that applicant has not pin-pointedly disclosed the other cities which are facing the same issue with same severity as NCR Delhi concerning the air pollution and contribution of the vehicular pollution in overall air pollution in those cities. Hence, we permit the applicant to place on record the additional material in this regard.

3. Applicant has submitted that this original application be taken up along with OA No.687/2023 wherein Tribunal is considering the issue of air pollution in different cities on PAN India basis."

Therefore, applicant is submitting desired necessary information in compliance to that order with reasons why we need to define road life of vehicles in other parts of India. *This information is being submitted under following headings*:

[3] EVIDENCES FROM CPCB DATA REGARDING STATUS OF VARIOUS POLLUTANTS & AQI IN OTHER CITIES: These data shows that toxic air is an issue in most of the cites or a pan India phenomenon.

[a] Status of PM 10 across all the reporting cities: As per CPCB report on Ambient Air Quality Status of the Country during 2023 (Integrated data in microgram per cubic meter), the annual PM10 was high above permissible limit of 60 µg/m3 in 335 out of 500 cities i.e 67% or 2/3rd cities are facing high PM 10 exposure. Its further alarming that and in 106 or 21% Indian cities its level was found to be above120 µg/m3 or double the permissible level of PM 10. In India, the National Ambient Air Quality Standards (NAAQS) set by the Central Pollution Control Board define permissible levels for PM2.5 and PM10 in ambient air. For PM10, the annual average should not exceed 60 µg/m³, and the 24-hour average should not exceed 100 µg/m³. For PM2.5, the annual average concentration should not exceed 40 µg/m³, and the 24-hour average should not exceed 60 µg/mPM2.5. **[annexure 1, page 16-39]**

[b] Status of PM 2.5 across all the reporting cities Similarly out of out of 447 cities/towns, the PM2.5 in 194 cites was found above the permissible limit of 40 µg/m3 or 43% Indian cities are facing high PM 2.5 exposure [**Annexure 1, page 16-39]**. Its important that studies have proved that persistent high exposure to PM 2.5 is responsible for significant morbidity and mortality in India for example studies of cities where the PM2.5 levels remained within 10 µg/ m3 with that of major cities where PM2.5 data of major cities PM2.5 levels crossed the acceptable annual average limit of 40 µg/m3 found that mortality risk can be noticed in many big cities, such as Delhi, Mumbai, Nagpur, Kolkata, Patna, Ranchi and Ahmedabad, among others, where pollutant levels crossed the acceptable limits. It shows the highest over twofold increase (119%) in odds of mortality (risk) among kids in the 1-5 age group, followed by 104% rise in infants up to one year, 86% in newborns less than 30 days old and 13% in adults in the districts where the PM2.5 levels crossed the acceptable annual average limit of 40 µg/m3[as mentioned in annexure 1 of this OA]

[c] Status of Air Quality Index[AQI] across various cities:

As per report of All India monthly average AQI**,** it's a matter of concern that during the year 2022 & 2023, except the months of July, august and September, in rest of the year average AQI remained in the moderate cate gory or above 100 [between 100 to 200]. CPCB, WHO and other health agencies warned that this moderate exposure to pollutants significantly effects body systems especially to vulnerable categories like breathing discomfort to people with lung, heart disease, children and older adults. **[annexure 2, page 40-47]**

[d] Factors effecting health damage: It is important to mention that damage occurring to general population due to exposure to these pollutant doesn't exactly matches with 'average' parameters of AQI, PM, etc, rather a significant factor is how much Variation is occurring during the year i.e seasonal variation during the months and variation during the day. In other words adverse effects on health not only depend on yearly average but also on the peak levels of various pollutants and their duration of exposure of this high level e.g:

- *Seasonal:* The winter months (December to February) continue to be worse than the summer/monsoon months (June to September).
- *Geographical:* Northern cities have strong seasonality in their AQI values like winter months are worse than the summer/monsoon months.
- *Diurnal or 24-hour Average*: Represents the average concentration of pollutants over a 24-hour period, indicating short-term exposure. During peak pollutants exposure for more than 8 hrs is risky.
- *Short term vs long term health risk*: some pollutants can lead to an immediate response like carbon monoxide (CO) and Ozone (O3) as compared to other pollutants that can lead to chronic impacts. Therefore there are different temporal standards based on their respective importance for short-term and chronic exposure impacts.
- *More Risk to vulnerable class*: Exposure to same concentration may have different effect in normal and diseased/children/senior citizens.

[e] Report of 1 Oct 2024 shows Meghalaya, Bihar beat Delhi in air pollution Byrnihat, in NE India, was the country's most polluted place last year and through most of this year. And several cities and small towns are more polluted than the national capital. Similarly on 27 May 2023 Bose Institute-IIT Kanpur study and IIT Kanpur showed Darjeeling air high in PM10, turning toxic darjeeling air high in PM10, turning toxic. Published in the scientific journal 'Atmospheric Environment', the study analysed PM10 levels in Darjeeling from 2009 to 2021. Researchers found that in summer and winter, the concentration of PM10 particles exceeded the Indian standard of 60μg/m3. The primary cause of this pollution was ultrafine components of PM10, specifically PM1 particles. It also identified the major sources of ultrafine particulate matter pollution, like vehicular emissions from tourism activities, biomass burning from roadside eateries and dust transport from the Indo-Gangetic Plain. [as mentioned in annexure 6 of this OA, page 38]

[f] Recent report on Oct 13, 2024 showed even coastal cities like Mumbai had the worst air quality, the city saw in decades. By Dec that year, the AQI in many areas touched 300 and crossed 250 in parts of south Mumbai where the sea breeze usually reduces the density of pollutants. In recent years, winter has not brought relief from the sweltering heat but rather heralded the return of thick, choking smog. "Things weren't this bad until a few years ago," To provide context, a study published in The Lancet Planetary Health in July reported that between 2009 and 2019, Mumbai's average level of particulate matter (PM2.5) was 41.7 μg/m3. Even at that lower concentration, these fine particles were linked to an average of 30,544 deaths in Mumbai annually [as mentioned in annexure 7 of this OA, page 38]

the National Air Quality Index that month recorded Mulund's AQI at 247—a level considered 'poor' due to PM2.5 concentrations between 90 and 120 microgram per cubic meter (μg/m3). It was the worst air quality the city saw in decades. By Dec that year, the AQI in Shivaji Nagar, Govandi, touched 300, and crossed 250 in parts of south Mumbai where the sea breeze usually reduces the density of pollutants. His recent study showed that PM2.5 particles in Mumbai were more toxic than in any other SAFAR cities. "Even low magnitudes of PM2.5 carry higher toxic elements in Mumbai compared to, say, Delhi. Moreover, due to humidity, they remain longer in the at mosphere," he added.

[g] 4 FEB 2023: Surprisingly as per Swiss air tracking index IQAir (a realtime international air quality monitor), within a week between January 29 and February 8, Mumbai was the second most polluted city in the world. On January 29, Mumbai was ranked 10th in IQAir rankings again to second position on February 8. . On February 13, it was the third most unhealthy cityworldwide for air quality, overtaking even Delhi which was India's most polluted metro till recently. IQAir partners with UNEP and Greenpeace and uses Central Pollution Control Board data (CPCB) in India to assess airquality. Categorization into 'healthy', unhealthy' and 'hazardous' is as per US air quality index (AQI) standards, which are more stringent than in India. According to a 2020 study by NEERI and IIT-B, road or construction dust is the source of over 71% of the particulate matter (PM) load in Mumbai's air. The remaining comes from industrial and power units, airport, and garbage dumps.

Even according to CPCB data, Poor and Very Poor days in Mumbai in November-January this winter was more than double over three previous winters. The deterioration, say experts, is mainly because of dust and smoke constantly emanating from vehicles, roads and construction activities. Two decades ago, cardiac surgeon Dr O H Jaiswal would occasionally spot black lung patches. Today, he says it's alarmingly common. "During heart surgeries, we routinely encounter lungs visibly affected by air pollution— we often see black lungs or lungs with patches, even in non-smokers," Jaiswal said. [as mentioned in annexure 8 of this OA, page 41]

[h] 08 FEB 2024: Press Information Bureau Government of India, Ministry of Environment released the top 5 most polluted cities. Ambient Air Quality monitoring is carried out in 518 cities/towns of the country. Details of Ambient Air Quality data in 5 cities/towns having highest PM_{10} levels measured during the year

2022 are; Jharia, Jharkhand, Brynihat, Assam, Saharsa, Katihar, Samastipur, Bihar

[i] 08 MAR 2023: a CSE study revealed air pollution is on the rise in most mega cities, besides Delhi. During 2022-23 winter, Kolkata and Mumbai were the most polluted after the national capital while Bengaluru and Chennai saw the fastest worsening of hazardous pollutant levels, said the Centre for Science and Environment in its analysis of real time particulate matter (PM2. 5) data of six cities for October-February [mentioned in annexure 10 of this OA, page 43]

Many people when thought of shifting from polluted cities like Delhi to shift to smaller, cleaner cities in search of clean air but found another city doesn't necessarily mean a respite from pollution. Nor does a coastal city, as Mumbai and Chennai residents will attest. AQI levels in these two cities peaked at 315 and 311 respectively last week which was worse than Delhi. Kolkata, which is near the coast, breached the 300-mark in November and is still in the poor category while Bengaluru's air quality in the same month saw a 40% deterioration as compared to the same period last year**. "When there is focus on pollution levels in some cities, it brings a false sense of complacency that some parts of India are safer to live in than others,"**

[4] SCIENTIFIC STUDIES SHOWING DIRECT RELATION OF RISING AIR POLLUTION WITH SERIOUS HEALTH HAZARDS IN OTHER CITIES

[a] On 4th July, 2024; A study published in The Lancet Planetary Health journal [www.thelancet.com/planetary-health[July 2024, Vol 8, page 433-440], reveals that high levels of PM2.5 air pollution takes 33,000 lives each year in major Indian cities like Delhi and Bengaluru, Mumbai. Other cities included in the analysis were Ahmedabad, Hyderabad, Kolkata, Pune, Shimla and Varanasi. On average, 7.2% of daily deaths in these cities were attributable to PM2.5 levels exceeding WHO guidelines. Delhi showed the highest fraction of deaths associated with PM2.5 pollution. The research, conducted by experts from BHU and the Centre for Chronic Disease Control, New Delhi, analyzed data from ten major cities spanning over a decade. The study challenges India's current air quality standards, which allow up to 60 micrograms per cubic metre of PM2.5 over a 24-hour period four times higher than WHO guidelines of 15 micrograms/cubic metre. The research analyzed data from approximately 3.6 million deaths recorded between 2008 and 2019 across the ten cities. [**Annexure 3, page 48-57** **]**

[b] As per report on Aug 27, 2024, a study conducted by International Institute for Population Sciences [IIPS] shows air pollution in India poses a significant threat to human health, leading to a substantial rise in mortality observed for all age groups in districts where PM2.5 levels exceed the acceptable limit under National Ambient Air Quality Standard. The study compared the govt mortality and socio-demographic data from National Family and Health Survey 2019-2021, of cities where the PM2.5 levels remained within 10 µg/ m3 with that of major cities where PM2.5 data of major cities PM2.5 levels crossed the acceptable annual average limit of 40 µg/m3. Study found that mortality risk can be noticed in many big cities, such as Delhi, Mumbai, Nagpur, Kolkata, Patna, Ranchi and Ahmedabad, among others, where pollutant levels crossed the acceptable limits. It shows the highest over twofold increase (119%) in odds of mortality (risk) among kids in the 1-5 age group, followed by 104% rise in infants up to one year, 86% in newborns less than 30 days old and 13% in adults in the districts where the PM2.5 levels crossed the acceptable annual average limit of 40 µg/m3. [as mentioned in annexure 1 of this OA, page 32]

[c] As per report Jun 19, 2024 of 'State of Global Air (SoGA) 2024' brought out by an US-based research organisation, Health Effects Institute (HEI), children are most vulnerable from air pollution in India. As Every day, on average, 464 children aged under 5 die in India due to foul air Across all age groups, while the all-India toll stood at 2.1 million in 2021, it said. The findings show air pollution is now second to hypertension as a death risk factor, beating tobacco and diabetes. "Around 40% of deaths due to heart disease, 33% of lung cancer deaths, 20% of type 2 diabetes deaths, 41% of stroke deaths and 70% of chronic obstructive pulmonary disease deaths were linked to air pollution in 2021," As per the report, 8.1 million died across the globe in 2021 due to air pollution-related diseases/conditions— meaning one in four such deaths occurred in India. India (2.1 million deaths) and China (2.3 million deaths) accounted for 55% of the global air pollution burden that year. The biggest culprit is the microscopic PM2.5, which accounts for six of every 10 air pollution-linked deaths in the world [i.e 60%]; the other pollutants ; household air pollution and ozone—account for 38% and 6% of deaths, respectively.

[d] a study by Energy Policy Institute at University of Chicago (EPIC) on 30 AUG 2023 on the basis of Air Quality Life Index (AQLI) revealed that in the most polluted Northern Plains region of the Delhi/NCR, 18 million residents are on track to lose 11.9 years of life expectancy on average relative to the WHO guideline if current pollution levels persist," . EPIC releases the impact of air pollution on life expectancy every year. The latest report takes 2021 as the base year. The report said Delhi was among the seven states and UTs comprising the majority of Northern Plains - others being Bihar, Chandigarh, Haryana, Punjab, UP and West Bengal – that face the greatest health burden due to particulate pollution in the country[as mentioned in annexure 4 of this OA, page 35]

[e] 30th AUG 2023; according to an updated Air Quality Life Index (AQLI) released by the Energy Policy Institute at the University of Chicago (EPIC), fine particulate air pollution (PM2.5) is estimated to shorten an average Indian's life span by 5.3 years and in Delhi, often labelled the most polluted city in the world, by as much as 11.9 years when compared to the WHO standards of 5micrograms per cubic metre (μg/m3),. However, an average Indian could lose 1.8 years of life expectancy and a Delhi resident up to 8.5 years if the country's national ambient air quality standards (40 µg/m3) are not met, says the report.

[f] March 01, 2022; according to a new report by the Centre for Science and Environment, the green think-tank of india, deaths attributable to PM2. 5 pollution in India have increased by 2.5 times over the last two decades. The report released by Union environment minister Bhupender Yadav on Tuesday said India accounted for one out of every four deaths due to air pollution in 2019. Data collated by green think tank Centre for Science and Environment, and represented in its "State of India's Environment Report", showed that 6. 6 million people died due to air pollution in the world. Of these, 1. 6 million deaths occurred in India. China saw 1.8 million deaths due to air pollution. It said 4,76,000 infants died globally in their first month of life from health effects associated with air pollution exposure in 2019. Of these, 1,16,000 deaths occurred in India. "Over the last two decades, deaths attributable to PM2. 5 in India has increased from 2,79,500 in 1990 to 9,79,900 in 2019," the report read. [as mentioned in annexure 5 of this OA, page 32]

[g] Today we have not only established that air pollution causes birth defects in newborns & fetuses. Studies on pregnant women have shown that chances of birth defects, fetal growth retardation and premature delivery are more in those cases where residence is close to busy roads. The higher the level of exposure to nitrogen dioxide, carbon monoxide and particulate matter (PM2.5 and PM10), the greater is the risk of having low-weight babies. Approximately 25% of babies delivered in India suffer prematurity and fetal growth failure that would mean every year out of 2.6 crore babies delivered every year in India, 65 lakhs suffer this problem. Similarly if we believe the reported incidence of birth defects occurring due to air pollution as 10% of total, that would mean out of total 17 lakhs babies of birth defects delivered every year in

India, 1.7 lakhs babies develop such defects due to air pollution. [Environmental Health volume 18, 09 July 2019]

[5] VEHICULAR POLLUTION: A MAJOR CONTRIBUTOR

[a] 7.11.24: as per the study of CSE in New Delhi 'Wheels Are To Blame For Half Of Bad Air' as despite technical measures to curb emissions, vehicular pollution is the top pollutant in the city, accounting for 51.1% of pollution from all local emission sources. The CSE analysis points out that over the years there is sharp rise in the private vehicle fleet and these account for a high contribution to pollution in the winter, so much so that even when harvest stubble burning has been low, Delhi's air quality has remained at the 'poor' or 'very poor' level. CSE held urban transport to be the main source of local emissions. "The emission inventory studies for Delhi done by IIT Kanpur in 2015, TERI-ARAI in 2018 and Safar, also in 2018, have determined the transport sector's contribution to PM2.5 to be, respectively, 20%, 39% and 41%. Among combustion sources, it is the highest source and annually, it is the second biggest source behind dust." As per the Economic Survey Delhi 2023-24, the capital has 79 lakh vehicles and 6.5 lakh new vehicles were added in 2023-24 itself (6.1 lakh annual addition in the pre-pandemic years). In addition, 1.1 million vehicles entered and exited the city daily. Two wheelers and cars are growing at the same annual pace of 15%, adding that transport accounts for 81% of nitrogen oxide emissions. [as mentioned in annexure 11 of this OA, page 44]

[b] Nov 15, 2023: Delhi government's real-time source apportionment study by IIT Kanpur shows vehicles continue to be the top contributors in Delhi's PM2.5 levels and the recent share of vehicle pollution was 44-45%. The contribution of secondary inorganic aerosols is currently second highest and its share in Delhi's PM2.5 level on Wednesday was 33%. Biomass burning is the third highest contributor to the national capital's foul air with a share of 27%.

[c] Ministry of Earth Sciences accepted that vehicular pollution is responsible for 40% of air The first-ever high resolution emission inventory of major pollutants in Delhi-NCR, done by the Indian Institute of Tropical Meteorology (IITM), Pune, under ministry of earth sciences (MoES) [4th Nov., 2019], showed the episodic sources such as stubble burning and firecrackers might have added to Delhi's air pollution woes but the capital cannot afford to overlook the constant sources of pollution — primarily transport, industry and dust — whose contributions put the entire National Capital Region in high risk for most of the year. It also showed that the share of vehicular emissions increased not only in Delhi but also in the entire NCR in 2018 as compared to 2010. It showed increase in share of transport sector in overall PM2.5 emissions from 25.4% in 2010 to 41% in 2018 in the capital, and from 32.1% in 2010 to 39.1% in 2018 in the NCR.

[6] SUMMARY OF FACTS & GROUNDS

[a] In the recent years it has been found that important markers of air pollution are persistently high significantly for many months in a year. For example as per CPCB report on Ambient Air Quality Status of the Country during 2023, the annual PM10 was high above permissible limit of 60 μg/m3 in 335 out of 500 cities i.e 67% or 2/3rd cities are facing high PM 10 exposure. Its further alarming that and in 106 or 21% Indian cities its level was found to be above120 μg/m3 or double the permissible level of PM 10. Similarly out of 447 cities/towns, the PM2.5 in 194 cites was found above the permissible limit of 40 μg/m3 or 43% Indian cities are facing high PM 2.5 exposure. As far as All India monthly average AQI is concerned, it's a matter of concern that during the year 2022 & 2023, except the months of July, august and September, in rest of the year average AQI remained in the moderate category or above 100.

[b] Now scientific studies in India have proved beyond doubt that that besides, Delhi-NCR, there are direct relation of rising air pollution with serious health hazards in other Indian cities as well! Most important study being published in The Lancet Planetary Health journal [July 2024, Vol 8, page 433-440], reveals that high levels of PM2.5 air pollution takes 33,000 lives each year in major Indian cities like Delhi and Bengaluru, Mumbai. Other cities included in the analysis were Ahmedabad, Hyderabad, Kolkata, Pune, Shimla and Varanasi. On average, 7.2% of daily deaths in these cities were attributable to PM2.5 levels exceeding WHO guidelines. Delhi showed the highest fraction of deaths associated with PM2.5 pollution. The study challenges India's current air quality standards, which allow up to 60 micrograms per cubic metre of PM2.5 over a 24-hour period four times higher than WHO guidelines of 15 micrograms/cubic metre. The research analyzed data from approximately 3.6 million deaths recorded between 2008 and 2019 across the ten cities.

[c] It is important to mention that damage occurring to general population due to exposure to these pollutant doesn't exactly matches with 'average' parameters of AQI, PM, etc, rather a significant factor is how much Variation is occurring during the year i.e seasonal variation during the months and variation during the day. In other words adverse effects on health, not only depends on yearly average but also on the peak levels of various pollutants and their duration of exposure of this high level. **More Risk to vulnerable class** i.e exposure to same concentration may have different effect in normal and diseased/children/senior citizens. The winter months continue to be worse than the summer/monsoon months. Some pollutants can cause an immediate toxic effect like carbon monoxide(CO) & Ozone(O3) as compared to other pollutants that can lead to chronic impacts. During high peak pollutants exposure more than 8 hrs is risky.

[d] For initiating aggressive actions against air pollution in severely affected cities**,** Govt should not wait for pollutants to achieve levels similar to that of Delhi; rather it should consider such actions much before that. Reason being, studies have shown that adverse effects on health starts at much lower levels of pollutants. This is especially true in context of Indian parameters that are much higher that the WHO or in India, pollutants are allowed to achieve much higher levels before to be blamed a health risk.

PRAYER

It is therefore, most respectfully prayed that in order to provide relief in alarming air pollution in some selected heavily polluted Indian cities, Hon'ble court may kindly be pleased:-

[1] Considering the air pollution a Pan India health hazard, kindly Pass direction to define the road life of motorized vehicles in other Indian cities also and pass directions to implement the ban on old diesel & petrol vehicles more than 10 years and 15 years respectively, to some selected heavily polluted Indian cities also in addition to Delhi/NCR.

[2] Pass such other order or orders as this Hon'ble Court may deem fit and proper in the facts and circumstances of the present case.

And for this act of kindness the applicant shall ever pray and duty-bound

Deponent

[Dr Sanjay Kulshrestha]

Applicant in Person

MBBS, MS, MCh, FIAPS

Senior Consultant Pediatric Surgeon

Annexure A/1

Ambient Air Quality Status of the Country during 2023

(Integrated data in microgram per cubic meter) …. 500 cities/towns [pm 2.5 in 194 above 40 out of out of 447 cities] [pm 10 is high above 60 in 335 out of 500 cities and in 106 its above 120

Ambient air quality is being monitored in the country with the help of Manual & Continuous Ambient Air Quality monitoring stations. The monitoring of air pollutants is being carried out with the help of State Pollution Control Boards (SPCB), Pollution Control Committees (PCC) and other reputed institutes. CPCB co-ordinates with these agencies to ensure uniformity, consistency of air quality data and provides technical and financial assistance. The data generated through manual & continuous monitoring is integrated for the year 2023 and presented in following table.

Ambient Air Quality Status of the Country during 2023 (Integrated data in microgram per cubic meter)

State / Union Territory	City / town	SO2 Annual Average	NO2 Annual Average	PM10 Annual Average	PM2.5 Annual Average
Andaman & Nicobar (UT)	Port Blair	NM	NM	22	-
Andhra Pradesh	Amaravati	14	11	71	34
Andhra Pradesh	Anantapur	10	20	58	24
Andhra Pradesh	Chittoor	5	11	57	33
Andhra Pradesh	Kadapa	4	22	53	34
Andhra Pradesh	Kakinada	8	16	76	-
Andhra Pradesh	Kurnool	7	17	60	30

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Andhra Pradesh	Rajahmundry/ Rajamahendravaram	10	16	78	38
Andhra Pradesh	Srikakulam	9	20	72	-
Andhra Pradesh	Tirupati	5	30	61	32
Andhra Pradesh	Vijayawada	6	19	71	38
Andhra Pradesh	Visakhapatnam	11	34	129	50
Andhra Pradesh	Vizianagaram	9	20	74	28
Arunachal Pradesh	Naharlagun	-	-	45	24
Assam	Bongaigaon	5	12	51	24
Assam	Brynihat	33	28	289	146
Assam	Guwahati	13	10	120	57
Assam	Nagaon	11	15	113	51
Assam	Nalbari	6	17	132	61
Assam	Silcher	6	11	33	17
Assam	Sivasagar	4	12	40	18
Assam	Tinsukia	6	12	52	24
Bihar	Araria	15	26	167	73
Bihar	Arrah	10	36	168	84
Bihar	Aurangabad	12	8	139	61
Bihar	Begusarai	18	39	264	147

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Bihar	Bettiah	9	24	187	85
Bihar	Bhagalpur	17	33	167	82
Bihar	Bihar Sharif	10	7	121	42
Bihar	Chhapra	17	20	210	82
Bihar	Gaya	12	21	119	59
Bihar	Hajipur	6	28	173	57
Bihar	Katihar	14	50	193	89
Bihar	Kishanganj	12	35	148	57
Bihar	Manguraha	5	31	91	47
Bihar	Motihari	7	49	142	47
Bihar	Munger	20	28	193	73
Bihar	Muzaffarpur	13	21	179	83
Bihar	Patna	8	32	183	90
Bihar	Purnia	9	28	154	89
Bihar	Rajgir	5	18	141	73
Bihar	Saharsa	16	7	183	89
Bihar	Samastipur	14	18	184	82
Bihar	Sasaram	18	26	99	57
Bihar	Siwan	13	47	176	88

Chandigarh (UT)	Chandigarh	6	25	113	58
Chattisgarh	Bilaspur	10	10	71	31
Chattisgarh	Chhal	15	16	64	28
Chattisgarh	Durg Bhillainagar	11	14	66	31
Chattisgarh	Korba	8	26	65	31
Chattisgarh	Kunjemura	9	32	96	19
Chattisgarh	Milupara	9	19	50	22
Chattisgarh	Raigarh	NM	NM	93	38
Chattisgarh	Raipur	9	33	77	31
Chattisgarh	Tumidh	9	21	88	35
Delhi (UT)	Delhi	8	38	205	105
Goa	Mapusa	3	12	62	-
Goa	Panaji	3	13	71	21
Gujarat	Ahmedabad	12	18	100	39
Gujarat	Ankleshwar	31	30	91	47
Gujarat	Gandhinagar	7	8	87	48
Gujarat	Nandesari	-	8	25	18
Gujarat	Rajkot	14	19	94	25
Gujarat	Surat	16	14	121	50

Gujarat	Vadodara	14	19	96	26
Gujarat	Vapi	25	24	105	60
Gujarat	Vatva	8	-	118	54
Haryana	Ambala	10	23	81	42
Haryana	Bahadurgarh	9	28	149	76
Haryana	Ballabgarh	11	8	137	65
Haryana	Bhiwani	11	21	126	67
Haryana	Charkhi Dadri	9	14	135	77
Haryana	Dharuhera	7	32	185	80
Haryana	Faridabad	15	19	196	86
Haryana	Fatehabad	7	-	139	65
Haryana	Gurgaon	12	25	176	90
Haryana	Hissar	14	22	136	66
Haryana	Jind	8	34	103	65
Haryana	Kaithal	14	-	126	69
Haryana	Karnal	22	8	92	50
Haryana	Kurukshetra	10	21	110	63
Haryana	Mandikhera	19	15	101	22
Haryana	Manesar	10	20	138	77

Haryana	Narnaul	13	25	129	62
Haryana	Palwal	9	15	89	30
Haryana	Panchukula Urban Estate	10	-	NM	51
Haryana	Panipat	11	24	132	42
Haryana	Rohtak	9	30	NM	70
Haryana	Sirsa	13	25	106	43
Haryana	Sonipat	17	31	178	64
Haryana	Yamuna Nagar	16	13	129	62
Himachal Pradesh	Baddi	24	18	119	53
Himachal Pradesh	Damtal	2	5	53	23
Himachal Pradesh	Dharamshala	2	5	43	22
Himachal Pradesh	Kala Amb	4	12	95	49
Himachal Pradesh	Manali	2	7	37	12
Himachal Pradesh	Nalagarh	2	12	64	25
Himachal Pradesh	Parwanoo	2	5	41	11
Himachal Pradesh	Poanta Sahib	4	12	89	38
Himachal Pradesh	Shimla	2	7	34	14
Himachal Pradesh	Sunder Nagar	2	5	43	22
Himachal Pradesh	Una	2	6	65	25

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Himachal Pradesh	Vashisht	2	5	42	NM
Jammu & Kashmir (UT)	Jammu	3	16	108	23
Jammu & Kashmir (UT)	Ramban (J)	NM	NM	54	NM
Jammu & Kashmir (UT)	Srinagar (K)	11	14	90	30
Jharkhand	Dhanbad	25	62	148	68
Jharkhand	Jamshedpur	34	43	127	NM
Jharkhand	Jorapokhar	23	12	154	NM
Jharkhand	Ranchi	17	35	107	NM
Karnataka	Bagalkote	12	11	47	23
Karnataka	Bangalore	6	21	68	33
Karnataka	Belgaum	15	18	74	28
Karnataka	Bidar	17	7	58	-
Karnataka	Bijapur / Vijayapura	4	16	47	20
Karnataka	Chamarajanagar	3	19	43	18
Karnataka	Chikkaballapur	14	17	64	31
Karnataka	Chikkamagaluru	4	12	46	18
Karnataka	Devanagere	4	8	72	28
Karnataka	Gadag	24	6	54	21
Karnataka	Gulbarga / Kalaburgi	11	11	63	29

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Karnataka	Hassan	17	13	66	27
Karnataka	Haveri	12	17	62	30
Karnataka	Hubli Dharwad	5	12	82	28
Karnataka	Kolar	61	13	82	28
Karnataka	Koppal	20	11	49	19
Karnataka	Madikeri	8	4	33	19
Karnataka	Mandya	2	14	40	-
Karnataka	Mangalore	16	15	76	33
Karnataka	Mysore	4	17	51	22
Karnataka	Raichur	34	18	84	19
Karnataka	Ramanagara	21	22	57	27
Karnataka	Shimaga / Shivamogga	4	12	44	20
Karnataka	Tumkuru	6	20	103	37
Karnataka	Udupi	26	12	31	-
Karnataka	Yadgir	14	10	61	32
Kerala	Alappuzha	2	5	44	NM
Kerala	Eloor	5	11	64	29
Kerala	Kannur	7	12	68	35
Kerala	Kochi	16	9	75	34

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Kerala	Kollam	6	11	73	34
Kerala	Kottayam	2	5	51	NM
Kerala	Kozhikode	5	6	46	-
Kerala	Mallappuram	2	14	31	24
Kerala	Palakkad	2	5	49	-
Kerala	Pathanamthitta	2	5	30	NM
Kerala	Thiruvanantapuram	5	10	42	23
Kerala	Thrissur	4	10	73	37
Kerala	Wayanad	2	5	40	-
Madhya Pradesh	Amlai	12	14	67	24
Madhya Pradesh	Bhopal	13	22	111	47
Madhya Pradesh	Chindwara	4	16	74	31
Madhya Pradesh	Damoh	NM	6	40	16
Madhya Pradesh	Dewas	20	15	99	41
Madhya Pradesh	Gwalior	20	22	139	66
Madhya Pradesh	Indore	13	38	107	43
Madhya Pradesh	Jabalpur	8	24	103	40
Madhya Pradesh	Katni	12	29	127	45
Madhya Pradesh	Maihar	10	11	50	25

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Madhya Pradesh	Mandideep	29	36	122	44
Madhya Pradesh	Pithampur	12	12	108	42
Madhya Pradesh	Ratlam	17	32	100	40
Madhya Pradesh	Sagar	5	13	73	29
Madhya Pradesh	Satna	5	17	104	27
Madhya Pradesh	Singrauli	34	56	143	54
Madhya Pradesh	Ujjain	9	14	92	47
Maharashtra	Ahmednagar	11	31	96	34
Maharashtra	Akola	11	15	76	46
Maharashtra	Amravati	12	15	79	38
Maharashtra	Aurangabad	14	27	107	51
Maharashtra	Badlapur	15	38	143	45
Maharashtra	Belapur	3	23	81	30
Maharashtra	Bhiwandi	22	39	81	50
Maharashtra	Boisar	18	15	97	50
Maharashtra	Chandrapur	14	22	106	51
Maharashtra	Dhule	10	12	105	48
Maharashtra	Dombivali / Kalyan	19	42	133	41
Maharashtra	Jalgaon	11	21	88	48

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Maharashtra	Jalna	7	37	91	38
Maharashtra	Kolhapur	9	24	80	30
Maharashtra	Latur	7	15	58	35
Maharashtra	Mahad	26	21	76	38
Maharashtra	Malegao	7	11	105	36
Maharashtra	Mira Bhayander	5	17	97	46
Maharashtra	Mumbai	18	29	108	47
Maharashtra	Nagpur	13	31	94	52
Maharashtra	Nanded	16	30	75	34
Maharashtra	Nashik	5	20	68	38
Maharashtra	Navi Mumbai	19	49	106	59
Maharashtra	Parbhani	20	17	87	39
Maharashtra	Pimpri Chinchwad	11	47	93	49
Maharashtra	Pune	40	54	99	52
Maharashtra	Roha	-	14	97	NM
Maharashtra	Sangli	8	30	73	31
Maharashtra	Solapur	22	29	96	37
Maharashtra	Tarapur	20	53	110	NM
Maharashtra	Thane	21	29	112	34

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Maharashtra	Ulhas Nagar	17	42	137	59
Maharashtra	Vasai virar	7	17	119	44
Manipur	Imphal	48	10	75	41
Meghalaya	Byraihat	16	18	100	49
Meghalaya	Dawki	7	11	41	24
Meghalaya	Khlihriat	6	11	50	27
Meghalaya	Nongstoin	6	11	45	23
Meghalaya	Shillong	18	8	58	31
Meghalaya	Tura	3	7	45	21
Meghalaya	Umsning	7	9	90	35
Mizoram	Aizwal	2	4	52	12
Mizoram	Champhai	2	5	29	-
Mizoram	Kolasib	2	4	19	8
Mizoram	Lawngtlai	2	5	47	-
Mizoram	Lunglei	2	5	12	-
Mizoram	Mamit	2	5	36	-
Mizoram	Siaha	2	5	32	-
Mizoram	Serchhip	2	5	22	-
Nagaland	Dimapur	2	8	97	NM

Nagaland	Kohima	27	3	69	33
Odisha	Angul	24	20	142	72
Odisha	Balasore	7	11	106	61
Odisha	Baripada	5	6	101	47
Odisha	Bhubaneshwar	4	18	111	46
Odisha	Bileipada	18	8	165	63
Odisha	Brajrajnagar	21	19	78	34
Odisha	Cuttack	7	23	129	55
Odisha	Jharsuguda	9	14	112	55
Odisha	Keonjhar	6	19	100	55
Odisha	Konark	2	12	64	-
Odisha	Nayagarh	3	27	129	56
Odisha	Paradeep	15	11	90	44
Odisha	Puri	2	13	98	26
Odisha	Rairangpur	9	19	99	60
Odisha	Rourkela	8	17	127	56
Odisha	Sambalpur	8	25	111	44
Odisha	Suakati	11	16	112	54
Odisha	Talcher	25	31	110	54

Odisha	Tensa	11	36	85	43
Pondicherry (UT)	Karaikal	2	5	40	-
Pondicherry (UT)	Pondicherry	7	12	50	24
Punjab	Amritsar	15	25	117	59
Punjab	Aspal Khurd (Tapa)	6	14	87	NM
Punjab	Barnala	6	15	92	NM
Punjab	Batala	7	15	71	NM
Punjab	Bhatinda	12	21	124	51
Punjab	Changal (Sangrur)	5	13	85	NM
Punjab	Dera Baba Nanak	5	13	55	NM
Punjab	Dera Bassi	7	16	105	NM
Punjab	Faridkot	6	16	89	NM
Punjab	Fatehpur (Samana)	5	13	85	NM
Punjab	Fazilka	6	16	94	NM
Punjab	Mandi Gobindgarh	15	26	125	68
Punjab	Gurdaspur	6	15	81	NM
Punjab	Guru Ki Dhab (Kotkapura)	6	14	79	NM
Punjab	Jaito Sarja (Batala)	7	14	68	NM
Punjab	Jalandhar	10	21	116	52

Punjab	Khanna	12	24	98	41
Punjab	Kharaori (Sirhind)	6	15	86	NM
Punjab	Kotladoom (Ajnala)	6	16	102	NM
Punjab	Lakho ke Behram (Ferozpur)	-	14	81	NM
Punjab	Ludhiana	11	23	169	61
Punjab	Malerkota	6	16	92	NM
Punjab	Moga	6	16	88	NM
Punjab	Mohali	6	15	100	NM
Punjab	Mrar Kalan (Muktsar)	5	14	82	NM
Punjab	Mukandpur (Nawashahar)	6	15	65	NM
Punjab	Mureedke (Batala)	6	15	77	NM
Punjab	Naudhrani (Malerkotla)	6	14	82	NM
Punjab	Naya Nangal	5	11	60	NM
Punjab	Patiala	8	20	92	43
Punjab	Peer Mohammad (Jalalabad)	-	14	84	NM
Punjab	Poohli (Bhatinda)	6	14	86	NM

Punjab	Qila Bharian (Sangrur)	6	14	85	NM
Punjab	Rakhra (Patiala)	5	13	85	NM
Punjab	Rohila (Samrala)	7	16	84	NM
Punjab	Rupnagar	5	21	142	50
Punjab	SBS nagar	6	16	92	NM
Punjab	Sirhind	6	17	93	NM
Punjab	Taran-Tarn	6	15	92	NM
Punjab	Tirathpur (Amritsar I)	7	15	104	NM
Rajasthan	Ajmer	14	23	101	46
Rajasthan	Alwar	15	36	128	42
Rajasthan	Banswara	6	15	110	45
Rajasthan	Baran	6	16	111	52
Rajasthan	Barmer	5	10	102	28
Rajasthan	Bharatpur	8	32	168	65
Rajasthan	Bhilwara	7	20	121	55
Rajasthan	Bhiwadi	14	35	226	77
Rajasthan	Bikaner	4	26	174	53
Rajasthan	Bundi	3	16	136	46

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Rajasthan	Chittorgargh	8	22	114	55
Rajasthan	Churu	5	25	116	47
Rajasthan	Dausa	4	34	163	54
Rajasthan	Dholpur	7	13	127	68
Rajasthan	Dungarpur	4	16	99	52
Rajasthan	Hanumangarh	6	20	211	81
Rajasthan	Jaipur	9	32	143	55
Rajasthan	Jaisalmer	4	20	139	39
Rajasthan	Jalore	5	32	163	56
Rajasthan	Jhalawar	5	16	98	40
Rajasthan	Jhunjhunu	4	23	127	55
Rajasthan	Jodhpur	7	25	127	45
Rajasthan	Karauli	7	19	60	31
Rajasthan	Kota	9	32	122	60
Rajasthan	Nagaur	4	17	135	43
Rajasthan	Pali	10	22	110	54
Rajasthan	Pratapgarh	3	13	100	36
Rajasthan	Rajasmand	3	11	93	38
Rajasthan	Sawai Madhopur	9	16	108	45

Rajasthan	Sikar	3	16	147	44
Rajasthan	Sirohi	5	19	88	30
Rajasthan	Sri Ganganagar	3	36	216	69
Rajasthan	Tonk	4	17	170	56
Rajasthan	Udaipur	8	29	122	48
Sikkim	Gangtok	30	4	34	16
Sikkim	Mangan	3	5	41	-
Sikkim	Namchi	5	5	-	NM
Sikkim	Pelling	6	5	-	NM
Sikkim	Ravangla	4	5	-	-
Sikkim	Singtam	5	10	63	-
Tamilnadu	Ariyalura	18	27	43	24
Tamilnadu	Chengalpattu	-	24	-	35
Tamilnadu	Chennai	10	21	63	28
Tamilnadu	Coimbatore	7	11	83	-
Tamilnadu	Cuddalore	15	40	42	21
Tamilnadu	Dharmapuri	8	22	42	21
Tamilnadu	Dindigul	-	-	52	29
Tamilnadu	Gummidipoondi	11	10	119	60

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Tamilnadu	Hosur	17	10	77	40
Tamilnadu	Kanchipuram	10	4	51	25
Tamilnadu	Madurai	19	24	69	30
Tamilnadu	Mettur	8	21	43	20
Tamilnadu	Nagercoil	11	15	55	20
Tamilnadu	Ooty	29	9	55	28
Tamilnadu	Palkalaiperur	37	3	37	18
Tamilnadu	Perambalur	10	14	34	13
Tamilnadu	Ramanathapuram	9	3	43	17
Tamilnadu	Sivagangai	15	19	51	27
Tamilnadu	Theni	12	17	54	23
Tamilnadu	Tirupur	19	18	59	-
Tamilnadu	Tiruvannamalai	7	14	51	21
Tamilnadu	Tiruvarur	14	16	42	16
Tamilnadu	Trichy	11	15	45	19
Tamilnadu	Tuticorin	9	14	56	16
Tamilnadu	Vellore	22	10	76	41
Tamilnadu	Villupuram	14	16	43	18
Telangana	Choutupal	18	36	89	NM

Telangana	Hyderabad	8	16	86	38
Telangana	Khammam	-	31	76	-
Telangana	Sangareddy	11	32	84	41
Tripura	Agartala	28	12	117	76
Uttar Pradesh	Agra	9	-	112	57
Uttar Pradesh	Aligarh	-	24	-	NM
Uttar Pradesh	Allahabad	21	17	123	42
Uttar Pradesh	Anpara	18	-	165	NM
Uttar Pradesh	Ayodhya	-	22	-	NM
Uttar Pradesh	Baghpat	19	29	160	79
Uttar Pradesh	Bareilly	21	25	85	35
Uttar Pradesh	Bulandshahr	15	34	132	58
Uttar Pradesh	Firozabad	12	22	109	39
Uttar Pradesh	Gajroula	22	23	170	NM
Uttar Pradesh	Ghaziabad	14	46	176	72
Uttar Pradesh	Gorakhpur	37	5	115	48
Uttar Pradesh	Greater Noida	13	50	228	88
Uttar Pradesh	Hapur	23	27	127	63
Uttar Pradesh	Jhansi	22	21	99	37

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Uttar Pradesh	Kanpur	13	42	128	49
Uttar Pradesh	Khurja	36	23	118	59
Uttar Pradesh	Lucknow	10	25	141	56
Uttar Pradesh	Mathura	12	28	168	NM
Uttar Pradesh	Meerut	11	32	166	81
Uttar Pradesh	Moradabad	20	16	111	50
Uttar Pradesh	Muzaffarnagar	16	29	159	83
Uttar Pradesh	Noida	16	53	183	81
Uttar Pradesh	Raibareli	6	12	93	NM
Uttar Pradesh	Unnao	7	26	118	NM
Uttar Pradesh	Varanasi	22	19	79	27
Uttar Pradesh	Vrindavan	28	5	120	34
Uttarakhand	Dehradun	5	7	105	48
Uttarakhand	Kashipur	6	23	97	40
Uttarakhand	Rishikesh	8	11	77	37
West Bengal	Amtala	4	28	83	41
West Bengal	Asansol+Raniganj	11	29	115	60

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West Bengal	Baharampur	3	19	70	39
West Bengal	Balurghat	3	19	70	42
West Bengal	Bankura	2	14	66	41
West Bengal	Bansberia (Tribeni)	3	22	75	44
West Bengal	Barasat	5	24	79	47
West Bengal	Bardhaman	3	14	67	40
West Bengal	Barrckpore	4	23	81	48
West Bengal	Baruipur	4	29	83	40
West Bengal	Birpara	3	19	69	41
West Bengal	Bolpur	2	12	63	37
West Bengal	Chinsura	3	21	73	43
West Bengal	Coochbihar	2	17	66	37
West Bengal	Dankuni	4	23	77	46
West Bengal	Darjeeling	2	12	52	28
West Bengal	Durgapur	19	28	110	52
West Bengal	English Bazaar/Malda	3	20	72	43
West Bengal	Ghatal	3	19	68	40

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West Bengal	Haldia	13	19	86	37
West Bengal	Howrah	8	30	115	58
West Bengal	Jaigaon	4	22	76	45
West Bengal	Jalpaiguri	3	19	68	40
West Bengal	Jhargram	3	20	73	43
West Bengal	Kalimpong	2	12	52	28
West Bengal	Kalyani	3	21	73	42
West Bengal	Kharagpur	6	25	86	52
West Bengal	Kolkata	8	26	94	48
West Bengal	Krishnanagar	3	19	69	40
West Bengal	Madhyamgram	4	23	75	46
West Bengal	Makhrapara /Alipurduar	3	17	65	37
West Bengal	Medinipur	3	22	75	44
West Bengal	Purulia	2	12	63	37
West Bengal	Raigunj	3	20	72	40
West Bengal	Rampurhat	2	13	66	40
West Bengal	Ranaghat	3	20	72	41
West Bengal	Rishra	4	24	80	48

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West Bengal	Sankrail	6	33	105	53
West Bengal	Siliguri	7	26	80	40
West Bengal	Suri	2	13	66	39
West Bengal	Tamluk	4	23	77	46
West Bengal	Uluberia	6	33	102	51
West Bengal	Uttarpara	3	20	70	40

Annexure A/2

Seasonality in AQI Values: Air Quality Index Analysis for Indian Cities 2015-2023
Dr Sarath Guttikunda Mr Saikrishna Dammalapati SIM-air working paper series # 47-2024

City-wise summaries of these values as downloadable CSV's of all the available data are @ www.urbanemissions.info & www.github.com/urbanemissions. All the data and analysis presented in this working paper is extracted from the official daily air quality index (AQI) bulletins issued by the Central Pollution Control Board (CPCB), New Delhi, India, between 2015 and 2023.

While AQI is not a measure of absolute pollution nor represents one pollutant, the changes in its value can represent the efforts (or lack-off) in addressing the air pollution problems in the city

National Air Quality Index AQI
Good (0–50) Minimal Impact
Satisfactory (51–100) Minor breathing discomfort to sensitive people
Moderate (101–200) Breathing discomfort to people with lung, heart disease, children and older adults
Poor (201–300) Breathing discomfort to people on prolonged exposure
Very Poor (301–400) Respiratory illness to the people on prolonged exposure
Severe (>400) Respiratory effects even on healthy people

Table: All India monthly average AQI across all the reporting cities

Avg. AQI	J	F	M	A	M	J	J	A	S	O	N	D
in 2015					147	114	87	85	110	178	239	242
in 2016	252	190	149	162	139	118	84	72	82	152	225	234
in 2017	208	188	148	147	144	111	85	82	99	164	215	204
in 2018	209	177	159	141	143	126	77	79	87	157	202	211
in 2019	203	155	134	143	149	122	86	68	70	139	186	183
in 2020	157	145	98	85	93	77	61	53	78	147	179	180
in 2021	173	157	142	126	91	86	69	67	57	109	185	179
in 2022	155	138	144	141	122	106	61	65	70	111	164	174
in 2023	172	145	115	114	103	88	65	77	71	114	167	153

Table: Agra (all stations) monthly average AQI across all the reporting cities

Avg. AQI	J	F	M	A	M	J	J	A	S	O	N	D
in 2015					109	66	63	73	91	206	330	342
in 2016	377	233	143	168	134	129	134	79	89	229	378	377
in 2017	331	248	176	143	136	96	56	58	111	274	340	340
in 2018	354	236	183	146	162	109	66	56	61	216	317	363
in 2019	309	216	151	141	129	115	63	71	47	104	173	135
in 2020	222	186	100	94	97	99	81	76	139	258	296	303
in 2021	285	212	190	190	87	92	70	68	50	153	298	217
in 2022	178	172	133	143	176	102	37	40	45	106	120	104
in 2023	66	55	57	72	73	76	50	70	74	100	143	106

Table: Delhi (all stations) monthly average AQI across all the reporting cities

Avg. AQI	J	F	M	A	M	J	J	A	S	O	N	D
in 2015					242	192	138	147	194	264	358	301
in 2016	370	293	238	271	246	208	146	105	163	271	374	365
in 2017	304	267	211	227	249	174	98	103	139	285	361	316
in 2018	328	243	203	222	217	202	104	111	112	269	335	360
in 2019	328	242	184	211	221	189	134	86	98	234	312	337
in 2020	286	241	128	110	144	123	84	64	118	265	328	332
in 2021	324	288	223	202	144	147	110	107	78	173	377	336
in 2022	279	225	217	255	212	190	87	93	104	210	321	319
in 2023	311	237	170	180	171	130	84	116	108	219	373	348

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Table: Hyderabad (all stations) monthly average AQI across all the reporting cities

Avg. AQI	J	F	M	A	M	J	J	A	S	O	N	D
in 2015					91	64	45	64	146	173	118	103
in 2016	138	116	103	93	71	69	57	35	40	91	129	138
in 2017	163	173	146	160	127	59	54	56	67	107	110	138
in 2018	148	111	110	89	90	63	53	57	78	107	111	134
in 2019	134	114	104	90	111	59	41	48	43	76	138	132
in 2020	105	94	78	62	76	45	37	34	49	96	114	145
in 2021	129	125	121	102	61	49	40	49	43	99	97	140
in 2022	113	118	121	102	100	75	51	54	55	68	103	98
in 2023	100	105	91	88	83	72	56	74	65	91	92	96

Table: Chennai (all stations) monthly average AQI across all the reporting cities

Avg. AQI	J	F	M	A	M	J	J	A	S	O	N	D
in 2015					156	131	129	100	80	92	99	128
in 2016	135	147	145	126	121	88	65	69	66	122	154	147
in 2017	105	108	89	118	116	94	96	63	68	87	87	108
in 2018	142	110	98	67	80	98	98	86	80	94	109	126
in 2019	115	86	89	70	96	99	72	65	82	83	116	80
in 2020	82	76	62	47	59	82	77	61	64	63	74	76
in 2021	80	78	67	58	62	66	57	60	59	63	58	87
in 2022	64	80	78	43	69	65	60	59	68	88	86	99
in 2023	107	102	72	66	74	71	74	73	61	81	72	85

Table: Jaipur (all stations) monthly average AQI across all the reporting cities

Avg. AQI	J	F	M	A	M	J	J	A	S	O	N	D
in 2015											282	290
in 2016	296	221	186	234	224	205	178	196	112	162	240	259
in 2017	181	170	155	154	143	111	76	110	156	223	229	164
in 2018	182	162	116	145	165	164	99	100	94	143	168	151
in 2019	141	113	101	139	137	115	79	60	69	129	155	126
in 2020	105	120	94	82	106	88	67	52	81	137	175	142
in 2021	154	130	134	139	102	111	75	79	52	110	213	168
in 2022	142	132	136	162	190	135	56	66	76	117	153	144
in 2023	152	151	95	119	114	99	88	108	80	138	240	200

Table: Jodhpur (all stations) monthly average AQI across all the reporting cities

Avg. AQI	J	F	M	A	M	J	J	A	S	O	N	D
in 2015												294
in 2016	269	186	171	174	229	255	106	74	138	180	270	225
in 2017	197	165	181	222	208	170	108	87	100	196	278	223
in 2018	270	250	228	268	301	241	129	135	115	226	256	222
in 2019	203	145	141	208	231	183	187	116	112	168	147	169
in 2020	155	176	137	99	133	111	102	86	88	161	222	182
in 2021	185	178	207	188	141	124	106	115	79	142	224	182
in 2022	165	180	175	181	215	158	74	91	93	144	171	146
in 2023	143	173	147	136	117	91	90	101	77	122	186	158

Table: Ahmedabad (all stations) monthly average AQI across all the reporting cities

Avg. AQI	J	F	M	A	M	J	J	A	S	O	N	D
in 2015					140	87	87	71	89	237		
in 2016						61	87	91	69	188	287	251
in 2017	182	253	188								227	151
in 2018	187	221	201	175	105	109	108	89	108	218	204	181
in 2019	179	129	142	190	129	183	137	128	134	184	164	129
in 2020	119	152	103	99	170	76	73	69	89	133	167	154
in 2021	164	165	178	150	132	95	73	71	65	111	141	134
in 2022	124	152	154	129	154	90	73	72	71	137	132	123
in 2023	130	158	129	115	112	82	81	74	77	123	135	109

Table: Bengaluru (all stations) monthly average AQI across all the reporting cities

Avg. AQI	J	F	M	A	M	J	J	A	S	O	N	D
in 2015					81	51	50	62	70	98	62	89
in 2016	132	145	145	130	74	38	38	53	53	88	89	83
in 2017	82	85	76	84	57	49	61	54	51	73	72	83
in 2018	97	78	97	90	78	60	54	54	68	83	91	112
in 2019	111	103	121	115	94	59	55	48	58	64	83	72
in 2020	87	88	85	56	60	47	39	48	49	64	70	83
in 2021	81	85	82	87	51	55	53	58	57	71	67	89
in 2022	82	95	102	87	72	60	64	57	60	82	93	84
in 2023	93	98	79	80	62	52	49	66	48	84	75	87

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Table: Moradabad (all stations) monthly average AQI across all the reporting cities

Avg. AQI	J	F	M	A	M	J	J	A	S	O	N	D
in 2015												
in 2016												
in 2017									152	316	390	266
in 2018	248	259	203	224	196	210	93	97	121	249	265	326
in 2019	301	231	182	214	238	169	95	83	88	245	262	328
in 2020	313	309			64	98	69	64	117	280	315	318
in 2021	287	324	247	209	116	123	89	101	96	186	286	220
in 2022	163	136	140	149	119	138	63	75	65	118	136	130
in 2023	112	100	115	114	106	96	73	95	79	118	166	145

Table: Lucknow (all stations) monthly average AQI across all the reporting cities

Avg. AQI	J	F	M	A	M	J	J	A	S	O	N	D
in 2015					106	140	109	96	124	212	371	353
in 2016	347	307	179	250	196	137	111	89	82	236	375	385
in 2017	293	297	245	250	239	158	68	95	98	237	363	357
in 2018	361	279	209	186	208	172	85	76	120	247	337	332
in 2019	295	229	202	204	172	156	81	74	67	195	314	280
in 2020	255	206	128	104	112	95	78	74	129	249	291	343
in 2021	315	252	212	172	105	80	71	61	62	129	252	213
in 2022	173	141	161	202	133	143	67	54	65	128	204	209
in 2023	189	155	114	124	122	105	56	81	74	119	219	172

Table: Mumbai (all stations) monthly average AQI across all the reporting cities

Avg. AQI	J	F	M	A	M	J	J	A	S	O	N	D
in 2015								67	72	134	119	134
in 2016	172	100	106	75	66	52	56	53	55	81	108	168
in 2017	186	168	126	97	66	55	78	51	71	107	136	152
in 2018	160	149	130	90	74	71	67	70	76	115	138	151
in 2019	169	148	120	93	86	69	52	57	45	85	133	179
in 2020	163	156	100	70	55	38	39	36	58	96	154	173
in 2021	215	161	150	99	72	60	59	56	56	96	148	176
in 2022	176	159	165	107	122	62	64	62	60	97	173	202
in 2023	203	194	147	105	80	80	72	63	66	146	141	144

Table: Pune (all stations) monthly average AQI across all the reporting cities

Avg. AQI	J	F	M	A	M	J	J	A	S	O	N	D
in 2015								88	107	154	211	210
in 2016	194	173	158	119	106	101	111	99	113	135	228	155
in 2017	132	106	99	84	72	71	76	81	81	106	105	108
in 2018	79	117	113	101	95	64	57	55	64	105	143	170
in 2019	180	130	124	92	84	65	66	74	78	98	143	159
in 2020	155	124	86	54	67	61	57	50	52	64	91	130
in 2021	120	123	115	90	62	72	72	67	67	79	127	156
in 2022	139	126	140	119	128	84	68		77	88	120	167
in 2023	161	158	126	122	121	106	97	89	83	143	143	162

Table: Patna (all stations) monthly average AQI across all the reporting cities

Avg. AQI	J	F	M	A	M	J	J	A	S	O	N	D
in 2015									139	223	364	373
in 2016	401	290	198	161	137	104	76	78	85	247	355	379
in 2017	322	335	240	194	135	130	80	88	140	207	242	327
in 2018	328	299	252	197	185	147	91	101	124	233	353	392
in 2019	372	271	209	163	187	141	73	78	94	209	352	357
in 2020	251	184	141	109	103	69	54	50	67	151	228	309
in 2021	254	243	234	198	96	78	70	72	69	115	255	269
in 2022	260	224	238	240	143	133	93	84	81	148	287	368
in 2023	337	274	210	209	163	160	83	94	82	134	274	268

Table: Kolkata (all stations) monthly average AQI across all the reporting cities

Avg. AQI	J	F	M	A	M	J	J	A	S	O	N	D
in 2015												
in 2016							31	37	33	60	153	208
in 2017	193	170	96	76	74	87	91	73	85	110		
in 2018				55	73	83	46	63	78	156	259	327
in 2019	345	251	151	61	64	68	57	46	38	115	196	201
in 2020	204	188	122	56	44	39	41	45	46	76	176	264
in 2021	268	227	160	59	59	51	52	56	49	103	166	202
in 2022	210	153	137	71	72	59	40	47	50	76	169	254
in 2023	225	129	96	55	65	58	32	67	45	102	165	176

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ANNEXURE 3

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Ambient air pollution and daily mortality in ten cities of India: a causal modelling study

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Summary

Background: The evidence for acute effects of air pollution on mortality in India is scarce, despite the extreme concentrations of air pollution observed. This is the first multi-city study in India that examines the association between short-term exposure to $PM_{2·5}$ and daily mortality using causal methods that highlight the importance of locally generated air pollution.

Methods: We applied a time-series analysis to ten cities in India between 2008 and 2019. We assessed city-wide daily $PM_{2·5}$ concentrations using a novel hybrid nationwide spatiotemporal model and estimated city-specific effects of $PM_{2·5}$ using a generalised additive Poisson regression model. City-specific results were then meta-analysed. We applied an instrumental variable causal approach (including planetary boundary layer height, wind speed, and atmospheric pressure) to evaluate the causal effect of locally generated air pollution on mortality. We obtained an integrated exposure–response curve through a multivariate meta-regression of the city-specific exposure–response curve and calculated the fraction of deaths attributable to air pollution concentrations exceeding the current WHO 24 h ambient $PM_{2·5}$ guideline of 15 μg/m^3. To explore the shape of the exposure–response curve at lower exposures, we further limited the analyses to days with concentrations lower than the current Indian standard (60 μg/m^3).

Findings : We observed that a 10 μg/m^3 increase in 2-day moving average of $PM_{2·5}$ was associated with 1·4% (95% CI 0·7–2·2) higher daily mortality. In our causal instrumental variable analyses representing the effect of locally generated air pollution, we observed a stronger association with daily mortality (3·6% [2·1–5·0]) than our overall estimate. Our integrated exposure–response curve suggested steeper slopes at lower levels of exposure and an attenuation of the slope at high exposure levels. We observed two times higher risk of death per 10 μg/m^3 increase when restricting our analyses to observations below the Indian air quality standard (2·7% [1·7–3·6]). Using the integrated exposure–response curve, we observed that 7·2% (4·2%–10·1%) of all daily deaths were attributed to $PM_{2·5}$ concentrations higher than the WHO guidelines.

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Interpretation :Short-term $PM_{2·5}$ exposure was associated with a high risk of death in India, even at concentrations well below the current Indian $PM_{2·5}$ standard. These associations were stronger for locally generated air pollutants quantified through causal modelling methods than conventional time-series analysis, further supporting a plausible causal link.
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Introduction

Exposure to air pollution is a global public health hazard, with a considerable body of evidence linking short-term and long-term exposures to a range of health outcomes, including all-cause and cause-specific mortality, respiratory and cardiovascular conditions, neurodevelopmental deficiencies, and adverse pregnancy and birth outcomes.[1–6] Evidence of these health harms has led to sustained reductions in air pollution exposures globally, yet many low-income and-middle income countries, including India, continue to experience high concentrations of air pollution.

Air pollution levels in many parts of India routinely exceed the WHO guidelines for safe exposure (24 h ambient $PM_{2·5}$ standard of 15 μg/m^3 not to be exceeded more than three to four times per year), and even exceed India's own less stringent ambient air quality standards for 24 h ambient exposure (60 μg/m^3).[7,8] Annual average exposure to $PM_{2·5}$ in the nation's capital Delhi exceeded 100 μg/m^3 in 2021 (WHO guideline value 5 μg/m^3; Indian standard 40 μg/m^3), with similar concentrations faced across much of the Indo-Gangetic Plain airshed.[9] Meteorological factors and seasonal high combustion events, such as festivals or crop residue burning, often push short-term exposures to concentrations as high as 700–1000 μg/m^3.[10] These hyperlocal pollution episodes that trigger greater exposures, especially to ambient air pollution, can cause increased vulnerability and burden of disease. The 2019 subnational burden of disease study estimated that more than 10·4% of total deaths (approximately 980 000) and 6·7% of total disability-adjusted life years (approximately 31·1 million) are associated with exposure to ambient $PM_{2·5}$.[10] These estimates are treated with relative scepticism by policy makers because they are not based on studies from India. However, a growing body of local evidence has begun to fill the gaps in knowledge on both long-term and short-term exposures.[11–14]

Research in context

Evidence before this study

We carried out two PubMed searches without language restrictions from database inception to March 14, 2024. We used the search terms “air pollution”, “particulate matter”, “short-term”, and “mortality” and then added “India”. Our search identified that numerous studies globally have found effects of short-term ambient air pollution on daily mortality. However, we observed no multi-city studies conducted in India and no global multi-city, multi-country analyses that featured Indian cities. Further, no study has applied causal inference methods to capture the role of locally generated pollutants in a low-income and-middle income setting. In addition, previous studies from India have not investigated exposure–response curves across such broad range of exposures, including evaluating the effect of air pollution at lower thresholds, even below the Indian recommended air quality guidelines. Finally, policy makers are reluctant to set standards based solely on studies conducted in other continents.

Added value of this study

We observed an important effect of short-term exposure to $PM_{2·5}$ on daily mortality in the first multi-city study including data from some of the largest and most polluted cities in India. These associations were observed to be stronger when using causal modelling methods accounting for locally generated pollutants. We were able to generate an integrated exposure–response curve for India that indicates increased risk of mortality even at lower concentrations of $PM_{2·5}$ exposure. We did not observe any evidence of a safe threshold nor lower incremental effects on mortality at lower concentrations of $PM_{2·5}$.

Implications of all the available evidence

This study adds to the vast body of research globally showing increased effects of $PM_{2·5}$ on daily mortality and provides strong evidence for such an association in India. Accounting for locally generated air pollutants by using causal methods might indicate a previous underestimation of the effect of air pollution. In line with previous studies regarding the exposure–response curve, no safe threshold for air pollution exposure exists. Our findings support the current evidence that approximately 7·2% of all deaths in India are attributable to daily $PM_{2·5}$ exposure.

Many studies elsewhere have evaluated the effect of short-term ambient air pollution on daily mortality. Although many of these studies are focused on specific geographical areas, some have conducted multi-city analyses in the USA, Latin America, Europe, China, and globally.[15–19] To the best of our knowledge, there have been no multi-city studies conducted in India, and neither have any Indian cities featured in global multi-city, multi-country analyses. Previous studies on the effect of short-term $PM_{2·5}$ exposures on daily mortality in India are scarce—they have focused only on one or two cities and have not investigated exposure–response curves across a broader range of exposures.[11,20] Further, there are only a few studies that have evaluated the possible effect of locally generated air pollution on mortality through causal modelling techniques such as instrumental variable analysis.[21,22] The instrumental variable approach relies on the selection of a variable (the instrument) that can cause a build-up of locally generated pollution but does not have other plausible links with daily changes in mortality, except through air pollution itself.[21,22] In effect, the instrument allows local pollutants to vary independently in relation to both measured and unmeasured confounders, thus eliminating any effects that might influence the relationship between exposure and outcome. This approach allows us to provide causal estimates of the effect of changes in local air pollution levels.

Using a national spatiotemporal exposure model and daily mortality data from ten cities, we aimed to conduct the first multi-city analysis for India, including the use of causal modelling methods. The ultimate goal of our study was to provide a first national causal exposure–response function directly relevant to policy. Furthermore, the inclusion of cities with different exposure levels aimed to increase statistical power and capture a broader range of daily exposure to $PM_{2·5}$.

Methods

Daily mortality

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We obtained daily counts of all-cause mortality from the death registries of ten municipal corporations in India (Ahmedabad, Bangalore, Chennai, Delhi, Hyderabad, Kolkata, Mumbai, Pune, Shimla, and Varanasi), covering each of the five climate zone classifications (appendix p 2). The data covered the period from 2008 to 2019, with 3–7 years of data available for each city (appendix p 2). We acquired de-identified mortality records from each municipal corporation, and we cleaned and aggregated the data to compile daily deaths for use in our analyses. International Classification of Diseases codes were not available for most cities, leaving us unable to conduct analyses of cause-specific mortality. The city-specific populations varied from 170 000 in Shimla to approximately 16·8 million in Delhi.[23]

Exposure assessment: daily ambient air pollution

We generated daily average $PM_{2·5}$ concentrations at 1 km^2 spatial resolution across India using a hybrid ensemble averaging approach from 2008 to 2020.[8] Briefly, we collected ground monitoring-based observations of daily average $PM_{2·5}$ and PM_{10} across 1056 locations and an extensive set of predictors encompassing satellite-based observations, meteorology, land-use patterns, emissions inventories, and reanalysis-based data. Using a cross-validation approach by leaving out 20% of the monitors, we trained four machine learning methods (deep learning, random forests, gradient boosting, and extreme gradient boosting) on the training data. The optimised models were implemented on the left-out validation data to obtain learner-specific predictions and combined using a Gaussian process regression to obtain the final predictions. The ensemble averaging was done to borrow strength across the different machine learning algorithms. We observed that certain algorithms performed better in specific areas and used a Gaussian process-based model (including elevation and land-use features) to combine the predictions from the four different algorithms into one final prediction for each grid-day combination. This method allowed us to obtain $PM_{2·5}$ exposures in regions with no monitoring data across time. The daily ensemble averaged predictions had a cross-validated R^2 of 86% and mean absolute error ranging between 14·4 $\mu g/m^3$ and 25·4 $\mu g/m^3$ across India. In this study, we estimated daily population weighted $PM_{2·5}$ concentrations of all 1 km^2 grid cells contained within the municipal boundaries of each of the ten cities included in the study throughout our study period. Population-weighted averages were used to provide a more accurate representation of the actual exposure experienced by the population.

Analytical strategy

We applied a two-stage analysis approach to evaluate the effects of $PM_{2·5}$ on daily mortality counts. In the first stage, we used quasi-Poisson generalised additive models (GAMs) to estimate city-specific associations. The models were adjusted for a penalised spline smooth function of calendar day with nine degrees of freedom (df) per year to account for underlying long-term and seasonal time trends, an indicator of day-of-week to account for weekly variations, and a natural spline function with four df for daily mean air temperature (lag 0–4). We used the 2-day moving average of current and previous day $PM_{2·5}$ concentration (lag 0–1) to estimate the effect on daily mortality, in line with the current literature.[15,16] We explored different lag patterns including single lags of same day (lag 0), previous day (lag 1), 2 days preceding level (lag 2), and 4-day moving average (lag 0–3). We modelled $PM_{2·5}$ as a linear term, and expressed the effect estimates as percentage change in daily mortality, with 95% CIs per 10 μg/m^3 increase in $PM_{2\cdot5}$ (lag 0–1). In the second stage, we applied a random-effects meta-analytical model to pool the city-specific estimates of associations of $PM_{2\cdot5}$ with mortality. We calculated I^2 statistics and Cochran's Q-test to evaluate the between-city heterogeneity.

Effect of locally generated pollutants using instrumental variable analysis

We used an instrumental variable approach to estimate the causal effect of locally generated air pollution in India. A more comprehensive overview of this approach can be found elsewhere;[21,22] briefly, the authors identified three instruments: planetary boundary layer height (PBLH), wind speed, and atmospheric pressure. PBLH is the elevation height at which vertical mixing of local emission occurs in the atmosphere. The mean PBLH varies day to day through dynamic interplay of various atmospheric processes. Wind speed affects horizontal transport of pollutants, with lower speeds increasing local influence and higher speeds promoting turbulent mixing and reduced concentrations. High atmospheric pressure typically induces weather conditions such as lower vertical temperature gradients, which impede both vertical and horizontal mixing of pollutants. Although each variable can individually capture distinct aspects of air pollution variation, the daily variability of each instrument is unlikely to be associated with daily deaths except through air pollution changes. Therefore, these three instruments serve as the most appropriate options for an instrumental variable in our study.[21,22] If these variables are not predictors of mortality except through air pollution, then they should not be associated with any confounders. If these instruments produce variations in air pollution that are randomised with respect to measured and unmeasured confounders, and if that fraction of variation in air pollution is associated with daily mortality, the effect estimates should be causal.

We obtained daily mean levels of PBLH, wind speed, and atmospheric pressure from the European Centre for Medium-Range Weather Forecasts.[21,22] Similar to $PM_{2\cdot5}$, we used the 2-day moving average of current and previous day PBLH, atmospheric pressure, and wind speed. We regressed our $PM_{2\cdot5}$ values (lag 0–1) on time trends, air temperature (lag 0–4), and day of the week, then extracted the residuals. To obtain a single final instrumental variable, the three instruments were combined to derive one single pollution-calibrated instrumental variable by applying a support vector regression (SVM) with a radial kernel to account for non-linear interaction between the predictors and the residuals of local pollution. We used the SVM function in the R package e1071. The obtained fitted values represent the remaining variation in $PM_{2\cdot5}$ that was explained by the three instrumental variables, and are independent of season, time trend, and temperature.[21,22] Then, we used the instrument as our exposure in the quasi-Poisson regression in each city as specified previously. The effect estimates obtained from this model are on the same scale as $PM_{2\cdot5}$.

Meta-analytic regression and attributable fraction

We assessed the shape of the exposure–response curve for each city using our main GAM. To account for possible non-linearity, we applied a quadratic B-spline with one single knot located at the 50th percentile of the city-specific air pollution distribution (2-day moving average of $PM_{2\cdot5}$). Then we applied a multivariate meta-regression of the city-specific predictions of the exposure–response curve to obtain an integrated exposure–response curve.[24] As we observed a supralinear relationship, we used the integrated exposure–response curve to calculate the fraction of deaths attributable to air pollution concentrations exceeding the WHO 24 h ambient $PM_{2·5}$ guideline of 15 μg/m^3.[25] To do so, for each day in each city, we used the overall integrated relative risk comparing each day's air pollution with WHO guidelines to calculate the attributable deaths and attributable fraction, using a previously described method.[25] Then, we obtained the total deaths attributable to $PM_{2·5}$ above the WHO guidelines by summing all the daily attributable deaths series, and estimated the total attributable fraction by dividing the total number of attributable deaths by the total deaths. 95% CIs were derived through 1000 Monte Carlo simulations. Finally, we investigated if associations persisted at successively lower concentrations of air pollution (<250 μg/m^3, <125 μg/m^3, <100 μg/m^3, <75 μg/m^3, and <60 μg/m^3, the last being the Indian standard of 24 h ambient $PM_{2·5}$ concentration).

Sensitivity analysis

To assess the robustness of our results we performed several sensitivity analyses. We applied different df (between six and ten df per year) to account for time trends, and we applied different adjustments for temperature (at lag 1 and 3 and using three and six df in the smoothing variables). Relative humidity is used as a confounder in previous studies, but these data were not available for all cities or all time periods.[9,23] Thus, as a sensitivity analysis, we adjusted for relative humidity from meteorological stations for those cities when data were available (Ahmedabad, Bangalore, and Hyderabad). Finally, we estimated the integrated exposure–response curve and attributable fraction using different knot points for $PM_{2·5}$, with equidistant knots (at 25th, 50th, and 75th percentiles) and at specific percentiles (10th, 50th, and 90th). We also estimated fractions of deaths attributable to air pollution concentrations exceeding the Indian 24 h ambient $PM_{2·5}$ standard.

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

This time series analysis included more than 3·6 million deaths in India from 2008 to 2019 (appendix p 2). The long-term average of daily means of $PM_{2·5}$ over this period ranged from 28·4 μg/m^3 in Shimla to 113·0 μg/m^3 in Delhi (figure 1). The maximum daily $PM_{2·5}$ concentration was registered in Delhi at 617·6 μg/m^3, and in 99·8% of all days across all cities (27 091 of 27 146 days) the daily $PM_{2·5}$ concentrations exceeded the 2021 WHO recommended 24 h air quality guidelines of 15 μg/m^3 (figure 1).

Figure 1 Daily $PM_{2·5}$ concentrations across ten Indian cities (dashed line shows the WHO recommended air quality guidelines [24 h of 15 μg/m^3])

Show full caption

From our main analyses, we observed a 1·42% (95% CI 0·67–2·19, I^2 95·7%) increase in daily mortality per a 10 μg/m^3 increase of $PM_{2·5}$ (lag 1; figure 2). The city-specific estimates showed large variations, ranging from 0·31% (0·21–0·41) in Delhi to 3·06% (1·54–4·59) in Bangalore. In our instrumental variable analysis, we observed an increase in daily mortality of 3·57% (2·11–5·04, 96·3%) per 10 μg/m^3, which was higher than in the conventional time-series analyses (figure 2). The causal effects were especially strong in cities with lower concentrations of air pollution, such as Bangalore, Chennai, and Shimla.

Figure 2 City-specific and pooled estimates using conventional time-series analyses (A) and instrumental variables causal analyses (B) of the association between short-term exposure to $PM_{2·5}$ and daily mortality per 10μg /m^3

Estimates are provided as percentage change in mortality and 95% CIs per 10 μg/m^3 increase in $PM_{2·5}$ (lag 1). Models were adjusted for a penalised spline smooth function of calendar day with nine df, an indicator of day-of-week, temperature (lag 4), and relative humidity (lag 4).

We observed a supralinear relationship in our integrated exposure–response curve, with steeper slopes at lower levels of exposure and an attenuation of the slope at higher levels of exposure (figure 3). We looked at the relative risk of air pollution against the minimum air pollution concentration at which an effect was observed in our study (17·1 μg/m^3), as selecting the WHO 24 h ambient $PM_{2·5}$ guideline of 15 μg/m^3 was not feasible as there were not enough days in which such concentrations were observed in our dataset (figure 3). Using the estimated integrated exposure–response curve, we estimated that 7·2% (95 % CI 4·2–10·1) of all deaths were attributable to $PM_{2·5}$ concentrations higher than the WHO recommended 15 μg/m^3, corresponding to 33 627 (19 443–47 426) annual deaths across our ten cities (table). Delhi had the largest attributable fraction and highest attributable yearly deaths. The steeper slope at lower levels of exposure was supported when we restricted our analyses at different thresholds as we observed an increase in the effect estimates as we lowered the thresholds. When we restricted our analyses to days that observed $PM_{2·5}$ concentrations below the recommended Indian guidelines (<60 μg/m^3 recommended daily $PM_{2·5}$ concentrations), we observed two times higher risk estimates compared with our main analyses without restriction (percent change [<60 μg/m^3] of 2·65 [95%CI 1·68–3·63] per 10 μg/m^3; figure 4).

Figure 3 Integrated exposure–response curve (2-day moving average) between air pollution and mortality, with 95% CIs

Figure 4 The effect of air pollution on daily mortality at lower thresholds of $PM_{2·5}$

	$PM_{2·5}$, mg/m^3 mean (SD)	**Attributable fraction (95% CI)**	**Attributable deaths (95% CI)**	**Attributable deaths per year (95% CI)**
Ahmedabad	37·9 (9·7)	5·6% (2·8–8·1)	28 680 (13 859–40 632)	2495 (1230–3588)
Bangalore	33·0 (6·5)	4·8% (2·2–7·2)	10 509 (5323–15 652)	2102 (969–3167)

	$PM_{2\cdot5}$, mg/m^3 mean (SD)	Attributable fraction (95% CI)	Attributable deaths (95% CI)	Attributable deaths per year (95% CI)
Chennai	33·7 (9)	4·9% (2·2–7·3)	28 674 (12 883–43 266)	2870 (1329–4298)
Delhi	113·0 (64·5)	11·5% (5·2–16·4)	95 715 (45 449–13 5217)	11 964 (5399–16 983)
Hyderabad	38·9 (10·4)	5·6% (2·8–8·3)	5552 (2972–8274)	1597 (805–2363)
Kolkata	55·2 (35·3)	7·3% (4·0–10·5)	45 458 (26 227–63 911)	4678 (2573–6735)
Mumbai	41·7 (18·5)	5·6% (3·0–8·0)	30 544 (15 507–43 843)	5091 (2761–7340)
Pune	45·3 (22·6)	5·9% (3·3–8·6)	7169 (3866–10 328)	1367 (761–1999)
Shimla	28·4 (6·9)	3·7% (1·9–5·6)	281 (132–415)	59 (30–90)
Varanasi	82·1 (35·3)	10·2% (6·2–14·4)	8263 (4973–11 517)	831 (506–1178)
Total	53·6 (39·5)	7·2% (4·2–10·1)	26 0845 (151 397–367 490)	33 627 (19 443–47 426)

Table

Attributable fraction (%) and deaths (N) to daily $PM_{2\cdot5}$ exposure with 95% CIs during the follow-up period, by city

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Exploring different lag patterns, we observed similar associations for single lags of 0 and 1 days and lag 0–3 on daily mortality, but we observed a smaller effect on lag 0–2 days (appendix p 5). In the sensitivity analyses, we observed almost identical effect estimates adjusting for different df per year for time trend (six to ten df), and similar effect estimates were observed by adjusting for different degrees of smoothness for temperature (appendix p 6). The effect estimates of $PM_{2\cdot5}$ and mortality did not change after adjusting for relative humidity (appendix p 7). Finally, when using different knot points for $PM_{2\cdot5}$, we observed similar integrated exposure–response curves, but slightly higher attributable fractions and total attributable deaths (appendix p 8). Using the Indian standard, we observed lower deaths attributed to $PM_{2\cdot5}$ concentrations higher than 60 μg/m^3 compared with the WHO guidelines (appendix p 3).

Discussion

Our study analysed the association between $PM_{2\cdot5}$ exposure and approximately 3·6 million daily deaths in ten Indian cities between 2008 and 2019. As such, it is the first multi-city study to examine the association between short-term exposures to air pollution and daily mortality in India. We observed a clear association between daily $PM_{2\cdot5}$ exposure and increased risk of mortality. These associations were stronger when using causal modelling methods incorporating instrumental variables that isolated the effect of locally generated air pollution, indicating that previous studies probably underestimated the effect of short-term exposure to air pollution on daily mortality. Exposure–response curves generated as part of this study show the risk of mortality escalated rapidly at lower levels of exposure and tapered off at higher levels.

Overall, we found an increase of 1·42% (95% CI 0·67–2·19) in daily mortality associated with each 10 $\mu g/m^3$ $PM_{2·5}$ exposure. This effect estimate is higher than those reported by previous studies conducted in India[11,12,26] and is higher than a recently published multi-city meta-analysis (499 cities) that reported a pooled estimate of 0·68% increase in daily mortality per 10 $\mu g/m^3$ increase in $PM_{2·5}$.[15] When compared with regions that experience similar concentrations of $PM_{2·5}$ exposure as India, our estimate remained higher, with a 272-city study in China reporting a 0·22% increase, and an 11-city east Asian study reporting a 0·38% increase in daily mortality per 10 $\mu g/m^3$ increase in $PM_{2·5}$.[16] However, our effect estimate was lower than some country-specific effect estimates from Greece (2·54%), Japan (1·42%), and Spain (1·96%).[15] Several factors could explain the stronger effects of $PM_{2·5}$ observed in our study, including the differential composition and toxicity of $PM_{2·5}$, varied age structures and susceptibility patterns, and climatological differences. We also found substantial heterogeneity in effect estimates across the cities studied, indicating the need for further research on local $PM_{2·5}$ mortality associations, particularly since different cities have different pollutant source profiles.

Our integrated exposure–response curve showed a plateauing of risk at higher concentrations of $PM_{2·5}$ exposure, similar to other city-specific studies from India and multi-city studies published elsewhere.[11,12,26] For instance, the Chinese study of 272 cities had similar annual concentrations of $PM_{2·5}$, but our exposure–response curve plateaus at higher concentrations of $PM_{2·5}$.[16] In addition, we observed stronger effects in lower polluted areas, such as Shimla and Bangalore, than higher polluted areas such as Delhi. This effect is probably related to the supralinear exposure–response curve, since Shimla and Bangalore had considerably lower concentrations. This sharp increase in risk at lower levels of exposure, which plateaus at higher levels, was reported by other studies in the region and studies in Europe.[12,14,25]

Analysis of the same relationship using an instrumental variable yielded a much higher effect estimate than the conventional time-series analysis. This difference could be due to several factors. First, the instrumental variable might be better at capturing the effect of locally generated air pollution because the instruments (planetary boundary layer height, wind speed, and atmospheric pressure) are directly related to higher contributions to ambient $PM_{2·5}$ from local sources since they cannot be easily dispersed, and since when the boundary layer is low, transported pollution from elsewhere is generally not mixed downwards to the surface. It is likely that given the plurality of local sources observed in most Indian cities (including waste burning, local transport, and diesel generator sets), the air pollution generated from these sources might be more toxic than transported particles. However, this hypothesis requires further study. Second, it is possible that our model using the instrumental variable might capture the effect of other local air pollutants—such as NO_2—and not just $PM_{2·5}$. Since our model does not generate estimates of local NO_2, we were unable to study the so-called cocktail effect[27] of both pollutants, and we highlight the need for further study of this complex area.

As the first multi-city, time series analysis of short-term exposure to $PM_{2·5}$ and daily mortality in India, our study has several strengths. First, the large dataset comprising approximately 3·6 million deaths provided us with more than adequate statistical power to estimate the observed effects. Second, we developed and used an innovative spatiotemporal exposure model to estimate $PM_{2·5}$ concentrations. This model allowed us to move beyond the use of fixed site monitors and to generate population-weighted exposure metrics for each of the cities we studied. Third, through the use of instrumental variables, we have been able to generate causal estimates for the association between $PM_{2·5}$ and mortality, providing deeper insight on the role of local sources of $PM_{2·5}$ in this relationship.

Our study also had some limitations. First, although we were able to use our spatiotemporal exposure model to generate 1 km^2 gridded predictions of $PM_{2·5}$, the exposure metrics used in this study were daily city-level average $PM_{2·5}$. This limitation is likely to have resulted in some non-differential misclassification of exposure, thereby lowering our effect estimates. Second, there is heterogeneity in the strength of death registration across the various states and cities in India, resulting in a proportion of deaths being missed by the civil registration system each year. We expect that these deaths are probably missed at random in relation to daily variations in air pollution concentrations and unlikely to bias our effect estimates.[28,29] Third, we were unable to obtain data for more cities and larger time periods, and on age, sex, and other individual-level effect modifiers, the analysis of which could have yielded information relevant to policy. For instance, analysis of effect modification of the $PM_{2·5}$ mortality relationship in Delhi revealed a larger effect among elderly and male populations.[11] As additional health data and contextual information become increasingly accessible in India, we anticipate that forthcoming studies will have the opportunity to address these limitations. Finally, the minimum $PM_{2·5}$ concentration observed across all cities in our study was 17·1 mg/m^3, and this therefore served as the counterfactual for our analyses. Research from other settings has shown considerable health harms observed well below these concentrations, and the high minimum concentrations of $PM_{2·5}$ in our study presents a challenge in understanding these risks locally.[30,31] In the absence of such local data, policy makers must rely on evidence from other settings in defining appropriate health-based thresholds.

The results of our study have direct relevance to policy in several ways. First, India is currently conducting its decadal process of reviewing its national ambient air quality standards (NAAQS). The NAAQS are substantially more relaxed than the WHO guidelines for acceptable exposure for all pollutants (eg 60 μg/m^3 *vs* 15 μg/m^3 for 24 h $PM_{2·5}$ exposure). This study could serve as a strong addition to the growing local evidence base that the review could include in developing new standards for India. Second, the effect of $PM_{2·5}$ at lower concentrations and the associated steep risk gradient means ambient $PM_{2·5}$ must be reduced substantially from current concentrations to garner concomitant health benefits. Although India launched the National Clean Air Program in 2019, its target of reducing air pollution by 25–30% from 2017 concentrations will fall short in protecting health and preventing possible deaths from exposure to poor air quality. Furthermore, several cities have or are currently formulating Graded Response Action Plans to tackle high exposure events. These action plans kick in at high concentrations of air pollution (often above 150 μg/m^3), which, based on our results, would only yield marginal benefits with respect to daily mortality, and negative health effects could continue to accrue even at lower pollution concentrations.[9,32,33] Third, the estimates generated from our instrumental variable analysis have shown the substantial effect of local sources of air pollution, which are numerous in most Indian cities. Action plans to tackle air pollution must therefore direct as much attention to these dispersed sources of air pollution as they do to traditional point or line sources. Finally, the large fraction of deaths attributable to short-term $PM_{2·5}$ exposures across all the cities we studied indicate that the emphasis on policy and action, which has gradually expanded to regions of India besides the Indo-Gangetic Plain, must intensify in coming years.

Short-term $PM_{2·5}$ exposure increased the risk of daily mortality in multiple Indian cities of varying size and location. Our results generally show stronger associations than other studies, and highlighted the more pronounced associations for locally generated $PM_{2·5}$. The plurality of study sites allowed us to extend analysis to lower ambient $PM_{2·5}$ concentrations than previously studied in India, and the results revealed a steep increase in risk well below the current Indian $PM_{2·5}$ standard. Daily deaths attributable to short-term $PM_{2·5}$ exposure over the course of the study period amounted to approximately 30 000 (7·2%) deaths each year in the ten included cities. As efforts to develop and strengthen air pollution action plans at state, district, and city levels continue, the results of this study show the growing need to address dispersed local sources of air pollution in addition to traditional fixed and line sources. This work also provides important insights on harmful health outcomes even at lower pollution concentrations in India and reinforces the message that there is no safe level of exposure to air pollution, even in highly polluted regions.

Contributors

JdB contributed to conceptualisation, investigation, methodology, data curation, formal analysis, validation, visualisation, writing the original draft, and review and editing. BK contributed to conceptualisation, investigation, methodology, data curation, validation, writing the original draft, and review and editing. MS contributed to conceptualisation, validation, methodology, and review and editing. TB, HD, AG, and VI contributed to investigation, data curation, and review and editing. SJ contributed to conceptualisation, data curation, and review and editing. IK, KL, AN-S, and GAW contributed to conceptualisation and review and editing. RKM, AST, and YW contributed to investigation, data curation, and review and editing. SM and AR contributed to conceptualisation, investigation, resources, and review and editing. DP contributed to conceptualisation, funding acquisition, and review and editing. JS contributed to conceptualisation, methodology, validation, and review and editing. PP contributed to conceptualisation, methodology, supervision, project administration, funding acquisition, resources, and review and editing. PL contributed to conceptualisation, methodology, supervision, project administration, funding acquisition, resources, writing the original draft, and review and editing.

Data sharing

All the data in this study are routinely collected and contain no information about specific people. Our data are available upon request to the corresponding author, subject to the agreement of the CHAIR-India steering group.

Declaration of interests

PP reports working as a consultant for World Bank for climate change and health outcomes. GAW reports receiving consulting income from the Health Efects Institute and Google. PL has received air travel and hotel accommodation paid by Fondazione Menarini to attend and hold a presentation at the Respirami meeting in Milan. He is the Scientific Secretary of the Swedish Society of Cardiology and co-chair of the European Chapter of International Society of Environmental Epidemiology (both unpaid). He was a paid member of the ethical committee board for the Swedish Ethical Authority 2022–23. All other authors declare no competing interests.