



A comparative study of air quality between pre and post COVID-19 periods in India

Sarbendu Bikash Dhar¹

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Abstract

Since late 2019, SARS-CoV-2 has taken a scourge form worldwide, and to prevent the spread of this virus, a partial or complete lockdown was started. In India, the lockdown has been implemented in four phases starting from 25th March 2020. These circumstances restricted the operations of human movement, vehicles and industries, which began to improve the air quality. The aim of the present work is to enquire about air quality during the lockdown period at the national level in India and specifically in four metropolitan cities—Delhi, Mumbai, Chennai and Kolkata. The air quality data of critical air pollutants—PM_{2.5}, PM₁₀, SO₂, NO₂ and CO of pre-COVID-19 (May & June 2019; and January 2020) and COVID-19 periods (May & June 2020; and January 2021) have been analyzed based on Sentinel 5P satellite image and Indian Central Pollution Control Board data. After a thorough study, it is found that the air quality is improved during the lockdown phase but again it degrades rapidly after the lockdown. Results show that among the four selected metropolitan cities, air pollution in Kolkata is the least whereas Delhi is the most polluted city in India. But the concentration of SO₂ is reduced to 20 µg/m³ in the lockdown period from 45 µg/m³ in pre-lockdown periods. Similarly, NO₂ was reduced from 52 µg/m³ to 20 µg/m³; CO from 32 µg/m³ to 29 µg/m³ and aerosol concentration from 168 µg/m³ to 125 µg/m³ between pre-lockdown to lockdown periods. For other places and cities in India such air pollution reduction has been noticed. It is to be accomplished that the findings of this study could also be helpful for the policymakers and stakeholders to require some effective future initiatives to manage air quality through the partial lockdown process.

Keywords COVID-19 pandemic; Lockdown; Sulphur dioxide · Nitrogen dioxide · Carbon monoxide · Particulate matter 10 and 2.5 · Sentinel data · Google Earth Engine · Central Pollution Control Board of India

✉ Sarbendu Bikash Dhar
sbdhar@tdbcollege.ac.in

¹ Trivenidevi Bhalotia College, Raniganj, West Bengal, India

1 Introduction

In the recent past, the novel Coronavirus (SARS-CoV-2) had taken a pandemic form throughout the world which had affected the global economy and human health at its worst. The first case of COVID-19 was identified in December 2019 near Wuhan City, Hubei Province, China. On 30th January 2020 considering the growing case of COVID-19, the World Health Organisation (WHO) declared it as a global health emergency (Singh & Subedi, 2020). Coronavirus spreads through physical contact and close interaction between people (Fong et al., 2020) and attacks our respiratory system which causes colds, sneezing, coughing, etc. Social distancing is the only way to break the transmission chain of COVID-19 (Kumar et al., 2020) and for that reason many countries have imposed complete lockdowns to stop the interaction between infected and non-infected people. It has been reported that countries and their provinces with more exposure to commercial trade seem to be good indicators of virus spread (Bontempi, 2022).

In India, the first case of COVID-19 was identified on 30th January 2020 when a 20 years old female reached Kerala from Wuhan, China. By 30th March 2020, 1251 confirmed cases and 32 deaths were reported (Chatterjee et al., 2020). To control this situation a nationwide lockdown in four phases was called, 24th March to 14th April 2020; 15th April to 3rd May 2020; 4th to 17th May 2020 and 18th to 31st May 2020 (Pai et al., 2020). Nations or regions with high population density have more potential in spreading the disease (Chowdhury et al., 2022). Being a highly populated country, India took every potential precaution to prevent the spreading of COVID cases. The nationwide lockdown was one of those measures in this regard. During those days all kinds of vehicular, industrial and social activities were prohibited which creates different types of socio-economic glitches. Still, at the same time, it helped to improve the quality of air in the atmosphere. Due to reduced human activities, the reduction in pollutants at significant levels in the atmosphere has been noticed worldwide. A study based in Jaipur city in India reveals a significant difference in air pollution concentration between pre-COVID and post-COVID periods (Dangayach et al., 2023). The grey spatiotemporal model suggests that in Wuhan, China during the lockdown from 23rd January to 8th April 2020, the concentration of PM_{2.5} was remarkably reduced (Gao et al., 2022). In the West Bengal state of India, it has been noticed that Air Quality Index (AQI) was improved in the lockdown phase. But the authors suspected that the improvement was not only the result of nationwide restrictions on anthropogenic activities, but it also had the effect of some natural influences like monsoon rain showers in the study area (Ghosh et al., 2023). In a study on patient records from the Greater Manchester Care of United Kingdom, it was stated that long-term exposure to air pollution is associated with developing severe COVID-19 infection. It also increases the chance of hospitalisation or death of the patient. It again signifies the severity of air pollutants like PM_{2.5}, PM₁₀, NO₂, SO₂, benzene, etc. (Hyman et al., 2023). In such another study in Southern California, USA, authors suspect that air pollution exposure increases the risk of COVID-19 death and prevention of air pollution is important for controlling future pandemics like this (Jerrett et al., 2023). In a case study on China using the MODIS instruments on Terra and Aqua, and TROPOMI on Sentinel-5P data showed lower concentrations of PM_{2.5} and NO₂ resulting in reducing both the number of premature deaths by approximately 97,390 and welfare costs by over USD 74 billion across the regions of Beijing, Hebei, Shandong, Henan, Xi'an, Shanghai and Hubei in 2020 (Liou et al., 2023). A study of Shaanxi Province, China reveals that during 2015–2019

almost 61% of the total number of individuals were exposed to unhealthy air, whereas this proportion decreased to 16% during the phase of lockdown in 2020–2021 (Ma et al., 2023). Indian cities with poor air quality experience higher COVID-19 cases and associated deaths (Naqvi et al., 2021). Another study on predictive modelling of air quality analysis shows that the reduced economic activities during the lockdown period led to the drop in concentration of PM_{10} and $PM_{2.5}$ by 27% and 50% on average (Persis & Ben Amar, 2023). A research work covering 47 European cities exhibits that, hundreds of people were able to avoid deaths across Europe during that period due to a decrease in air pollution, (Schneider et al., 2022). Studies suggest that ambient $PM_{2.5}$ exposure increases the risk of COVID-19 and other such diseases (Sheppard et al., 2023). In Nanjing, China it has been noticed that the COVID-19 lockdown has a greater impact on the concentrations of $PM_{2.5}$ and PM_{10} emitted by the industrial sector, and also on the concentration of NO_2 emitted by the transportation sector. In both the cases, the level of pollution has decreased significantly (Yao et al., 2023). These studies highlight the need for constant monitoring of air quality and its management, which may be helpful to combat such pandemics in the future.

In recent years, poor air quality has emerged as a global health concern. Air pollution occurs due to the presence of various hazardous substances like particulate matter ($PM_{2.5}$ and PM_{10}), Nitrogen Dioxide (NO_2), Carbon Dioxide (CO_2), Carbon monoxide (CO), Sulphur Dioxide (SO_2), volatile organic compounds, etc., in the air. These substances create an environmental health threat. It causes different types of airborne diseases, respiratory problems, premature mortality, animal death, global warming, etc. $PM_{2.5}$ is the most dangerous air pollutant which is responsible for most pulmonary and cardiac diseases (Rathore et al., 2021). According to Global Burden of Diseases, worldwide 4.1 million people died prematurely in the year 2016 due to $PM_{2.5}$. High concentration of PM_{10} causes coughing, wheezing, asthma, bronchitis, high blood pressure, etc. Also, high NO_2 concentration may contribute to developing health risks for children (EPA, 2016a) and SO_2 affects the respiratory system, particularly lung function, irritation in the eyes, etc. (Queensland, 2021). According to the World Health Organisation, about 4.2 million people die worldwide per year due to air pollution. In India, about 30.7% of deaths can occur per year (Sreedhar, 2021). In the year 2019, 1.7 premature deaths occurred in India due to air pollution (DTE, 2020). The main reason for air pollution is vehicular emissions, industrial activities, combustion of fossil fuel, etc. Though, several studies have been done worldwide to address the issue of improved air quality due to lockdown; very few have addressed the spatial variation of pollutants as well as city-based observations simultaneously. The present study highlights this aspect. Along with that, it also suggests some measures to control air pollution in the country based on the experiences received during the lockdown period.

As seen in different studies so far, the lockdown has a significant impact on air quality. The present study is an attempt to explore the impact of the COVID-19 lockdown on air quality and variation in the concentration of pollutants during the pre-lockdown, lockdown and post-lockdown periods in India. It is an endeavour to explore the impact of the lockdown on air quality at the national level in India. It is conducted both at spatial (for the entire India) and point (for four metropolitan cities in the country – Delhi, Mumbai, Chennai and Kolkata) scales using the Copernicus Sentinel 5P TROPOMI daily satellite image data and daily air quality data from Central Pollution Control Board, India respectively. Along with that, such pollution data analysis for pre, during and post-lockdown periods helps to understand the importance of controlled anthropogenic activities over the air quality nationwide, which is very noteworthy and may be useful in the future policy development in air pollution prevention in the country.

1.1 Objectives

On the basis of the above discussions, the present paper aims to achieve the following objectives:

- To analyze the spatial pattern of air quality for the pre, during and post-COVID lockdown period in India.
- To make a comparative analysis of air quality among four metropolitan cities in the country.
- To suggest some future initiatives to control air pollution.

1.2 Study area

This study is focused on the air quality of India. For this, four metropolitan cities—Delhi (Northern India), Mumbai (Western India), Kolkata (Eastern India) and Chennai (Southern India) have been selected. Delhi is the national capital of India with 16.3 million urban population and 29 planned industrial areas (Census, 2011). Mumbai is the industrial capital of this country. These are the highly populated cities with high vehicular movement (Table 1).

After an in-depth literature study about the air quality of India, it is found that, Delhi is the most polluted city and Mumbai has the highest PM_{2.5} concentration in the country (DTE Staff, 2023). Kolkata is the third most populous metropolitan and the second largest CO₂-producing city in India (Chakraborti, 2017). These cities are located in four different geographical regions comprising 58 air quality stations monitored by the Central Pollution Control Board of India.

2 Methodology and data source

To analyze the changing nature of air quality in pre, during and post-lockdown periods; four air quality monitoring stations – Alipur (Delhi), Bandra (Mumbai), Alandur Bus Depot (Chennai) and Rabindra Bharati University area (Kolkata) of India have been selected.

Table 1 Location and key information of the study points

City	Coordinates ¹	Climate ²	Population (2011) ³	Air quality Index (µg/m ³) (September, 2021) ⁴
Delhi	28.7041° N & 77.1025° E	Humid subtropical and Semi-arid	11 million	157
Mumbai	19.0760°N & 72.8777°E	Tropical wet-and-dry	12.5 million	105
Chennai	13.0827°N & 80.2707°E	Tropical wet-and-dry	4.3 million	104
Kolkata	22.5726°N & 88.3639°E	Tropical wet-and-dry	4.5 million	106

Source: compiled by the authors from <https://www.mapsofindia.com/>¹, <https://en.climate-data.org/>², <https://censusindia.gov.in/>³, <https://www.aqi.in/in/dashboard/india>⁴

To describe the status of air quality, five key air pollutants -Particulate Matter with a diameter of fewer than 2.5 microns ($PM_{2.5}$), Particulate Matter with a diameter of less than 10 microns (PM_{10}), Nitrogen Dioxide (NO_2), Sulphur Dioxide (SO_2) and Carbon Monoxide (CO) have been considered for the present study.

The official lockdown in India was declared on 24th March 2020. Therefore, the hourly data of key air pollutants are collected in three phases- pre-monsoon (May 2019), monsoon (June 2019) and post-monsoon (January 2020) data for pre COVID-19 lockdown period; pre-monsoon (May 2020) and monsoon (June 2020) data for lockdown phase and post-monsoon (January 2021) data for post lockdown period for these selected stations. The monsoon period is the prime rainy season in India occurring from June to mid-September every year. As air pollution significantly increases in the dry season and drops in the monsoon period, the current study has collected the air pollutant data for the pre, during and post-monsoon seasons to examine the seasonal variations also. Daily air quality data is obtained from Central Pollution Control Board (CPCB, 2021). The concerned pollution control boards usually record the data at 12 noon daily. Here it should be mentioned that the data on PM_{10} concentration in Chennai is not available for the above-mentioned study period.

Copernicus Sentinel 5P TROPOMI daily satellite image data, developed by the European Space Agency (ESA) have been used in the present study to evaluate the spatial/regional air quality of India. These data possess a spatial resolution of 1113.2 m. Images have been processed in Google Earth Engine (GEE) platform and the final maps of the study area at various levels are prepared in QGIS 3.16 software (Google for Developers, 2021). All data have been collected within the time span of January 2020 to January 2021. Sentinel 5P data are processed using the required codes for the relevant location and time. The scripts used for processing Aerosol Index for the study area in the GEE platform have been presented here (Box 1). All necessary satellite images have been processed in the same way for the respective pollutants and time for India.

3 Discussions

SO_2 , NO_2 , CO, $PM_{2.5}$ and PM_{10} -have been selected to analyze the changing nature of air quality during pre-lockdown (May and June 2019, January 2020); lockdown (May and June 2019) and post-lockdown (January 2021) period, which is already mentioned. To evaluate the concentration of these five pollutants, four metro cities (Delhi, Mumbai, Chennai and Kolkata) in India have been selected. Their status and changing behaviours are discussed here.

3.1 Status of Sulphur Dioxide (SO_2)

It is a colourless, bad-smelling, toxic gas that belongs to the Sulphur Oxide group of chemicals. Burning of fossil fuels (coal, petrol, diesel) in power plants, metal processing, and vehicular emissions are the main reasons behind SO_2 emissions. Secondary pollutants like aerosols, particulate matter, etc., are also responsible for its existence. It can cause acid rain (damage plant tissues and reduce their natural growth rate), respiratory problems for children and affect the heart and lungs. SO_2 and other Sulphuric Oxide compounds react with each other and create haze and fog which reduce visibility(US

Box 1 GEE script for processing Aerosol Index for the study area prepared by the authors

GEE CODE (Aerosol Index of India)

```

var geometry =
  ee.Geometry.Polygon(
    [[[67.37156250000001, 37.42294345886498],
      [67.37156250000001, 6.64330510497895],
      [98.30906250000001, 6.64330510497895],
      [98.30906250000001, 37.42294345886498]]], null, false)
Map.addLayer(geometry, {}, 'India');
Map.setCenter(78.27, 23.06, 4);

var band_viz = {min:0, max:0.0005,
  palette:['black', 'blue', 'purple', 'cyan', 'green', 'yellow', 'red']};

var image = ee.ImageCollection('COPERNICUS/S5P/OFFL/L3_AER_AI')
  .select('absorbing_aerosol_index')
  .filterDate('2021-01-01', '2021-01-06')
  .max();

// print(image)

// image = ee.ImageCollection('COPERNICUS/S5P/OFFL/L3_AER_AI')
// .select('absorbing_aerosol_index')
// .filterDate('2021-01-01', '2021-01-06');

Map.addLayer(image.clip(geometry), band_viz, 'S5P AI Post-Lockdown');

//export the image, specifying scale and region.
Export.image.toDrive({
  image: image,
  description: "India_AI_Post-lockdown",
  folder: "GEE data for paper (New)",
  scale: 1113.2,
  region: geometry
});

```

EPA, 2016b). An increase of $10 \mu\text{g}/\text{m}^3$ of 2-day moving average in the concentration of SO_2 increases by 1% total death (Kan et al., 2010).

Due to the lockdown, a significant variation has been observed in the accumulation of Sulphur Dioxide (SO_2) in the atmosphere in India. These figures show the spatial distribution of SO_2 in selected metro cities of India in the three time-span.

3.1.1 Pre-lockdown period

The air quality of the pre-lockdown period (May and June 2020) in India (Fig. 1) has been studied. In the month of May, the SO₂ level is very high in Delhi (> 45 μ/m³) whereas it is moderate in Mumbai (< 20 μ/m³) and very low in Chennai (< 7 μ/m³) and Kolkata (< 4 μ/m³). But in June, the concentration of SO₂ was almost moderate (> 20 μ/m³) in both Delhi and Mumbai and also very low (≤ 6 μ/m³) in Chennai and Kolkata.

The all-India scenario of SO₂ concentration in the pre-lockdown period has been represented here (Fig. 2) for the month of January 2020. From the map, it is quite clear that the northern mountains, parts of northeast India, north Indian plains and some parts of the eastern coast are less polluted. Most of the northern and north-western states including Delhi, Punjab and Haryana; some urban centres of Bihar, and Uttar Pradesh exhibit a considerable amount of SO₂ concentration in the air. The Central Pollution Control Board data of SO₂ concentration for Delhi and Mumbai depicts a relatively high polluted condition in the latter one.

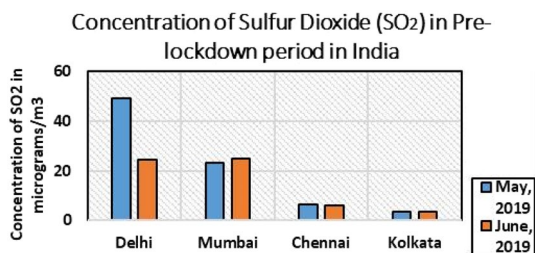
3.1.2 Lockdown period

The lockdown period (May and June 2020) denotes a very high absorption (> 50 μ/m³) of SO₂ (Fig. 3) in Mumbai in May whereas it is moderate (≥ 20 μ/m³) in Delhi and very low (≤ 9 μ/m³) in Chennai and Kolkata. On the contrary, accumulation is low (< 14 μ/m³) in all the selected cities in June, which is the rainy season.

3.1.3 Post Lockdown period

In the post-lockdown period, a diversified scenario of SO₂ concentration is identified (Fig. 4) in January 2021, in the context of the National level. The density of SO₂ is relatively moderate in nature in the northern mountains, north Indian plains, north-eastern and north-western parts of India. But the pollution level is high in some parts of Assam and Nagaland (North-East India) and some parts of Gujarat and Rajasthan (Western India) than the other places. Proportionately it is more dominant in Chhattisgarh; some parts of Odisha and Jharkhand; Northern and Southern parts of West Bengal and some parts of Bihar. Almost no concentration has been found in Ladakh, Madhyapradesh and Southern Parts of India. On the other hand, CPCB has marked an extreme absorption of SO₂ in Mumbai.

Fig. 1 In pre-lockdown period concentration of SO₂ remained high in Delhi and Mumbai. It also decreases in the rainy monsoon season (Data source: CPCB)



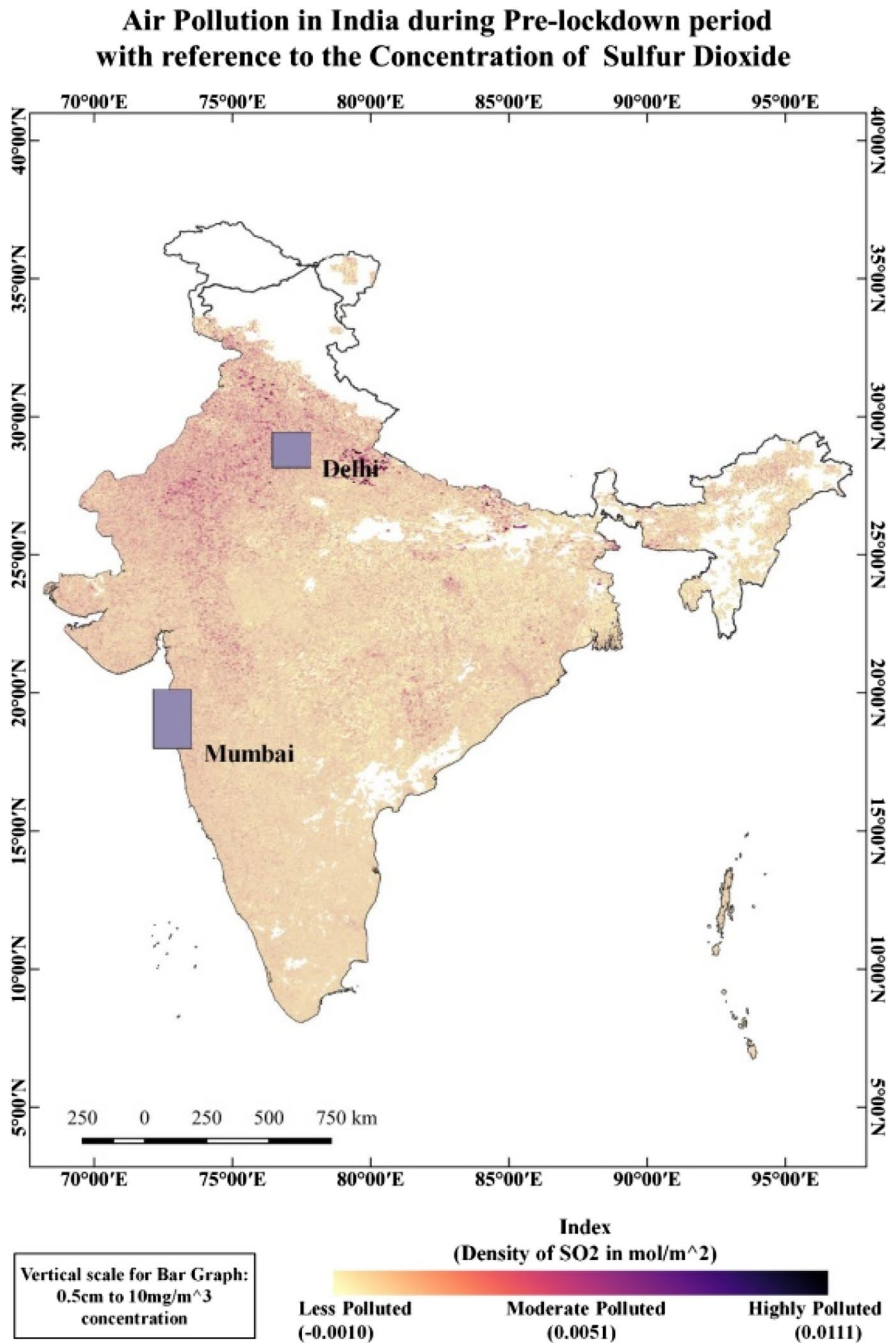
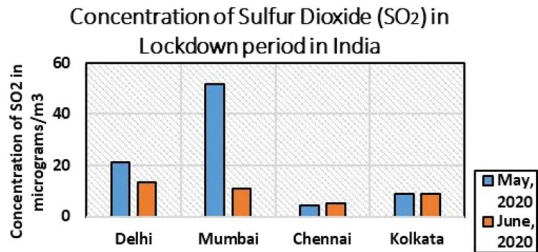


Fig. 2 National level distribution of SO₂ during pre-lockdown period in India, along with its concentration in Delhi and Mumbai (Data source: CPCB, India, and Sentinel 5P)

Fig. 3 In lockdown period, concentration of SO₂ remained high in Delhi and Mumbai. It also decreases in the rainy monsoon season (Data source: CPCB)



3.2 Status of nitrogen dioxide (NO₂)

Nitrogen Dioxide is a gaseous air pollutant which is the composition of Nitrogen and Oxygen and a group of gasses related to it called Nitrogen Oxide. This is formed due to the burning of coal, petrol, diesel in vehicles, movable engines; industrial boilers, etc., are an important source of NO₂. It causes inflammation of the airways, sneezing, coughing, lung problems, asthma among children, premature death, etc. Also, there are various environmental problems like acid rain, low visibility, smog and nutrient pollution in coastal water (Purelogic Labs India Pvt Ltd, 2021). Even a 10 µg/m³ increase in daily NO₂ concentration increases 0.40 per cent cardiovascular mortality and 0.38 per cent of respiratory mortality (Samoli et al., 2006).

The spatial distribution of NO₂ in the selected cities of India is analyzed here. There is a significant variation that has been identified across the three periods which are discussed below.

3.2.1 Pre-lockdown period

The air quality of the Pre-lockdown period has been examined (Fig. 5). An extreme concentration (> 52 µg/m³) has been notified in Delhi in both May and June 2019. It is moderate in nature (≥ 23 µg/m³) in Kolkata (May and June 2019) and Chennai (June 2019). Conversely, the pollution level is comparatively lower (≤ 19 µg/m³) in Mumbai and Chennai (May 2019) than in Delhi and Kolkata. The Indian scenario of NO₂ concentration in the pre-lockdown period (January 2020) has been represented here (Fig. 6). It is quite clear that some parts of the Northern plains including Delhi, Punjab, Haryana and parts of Uttar Pradesh are moderately polluted. Besides, parts of Rajasthan (North-West India), some urban centres of western India, a small portion of Bihar, and West Bengal (in eastern India) also represent average concentration. Tolerable conditions have been observed in the western states. The intensity of NO₂ is quite higher in some parts of Jharkhand and Odisha than the others. The states of northern mountains (Jammu, Kashmir and Eastern states) and Southern states exhibit very small amounts of air pollution. On the other hand, CPCB records show an extreme amount of NO₂ absorption in the air of Delhi and Mumbai.

3.2.2 Lockdown period

The lockdown period reflects the considerable amount of less polluted condition of air quality in all the selected cities (Fig. 7). Concentration is a little higher (≥ 20 µg/m³) in May 2020 in Delhi and Mumbai; it is low (≤ 16 µg/m³) in Chennai in this month. Contrarily, it

Air Pollution in India during Post lockdown period with reference to the Concentration of Sulfur Dioxide

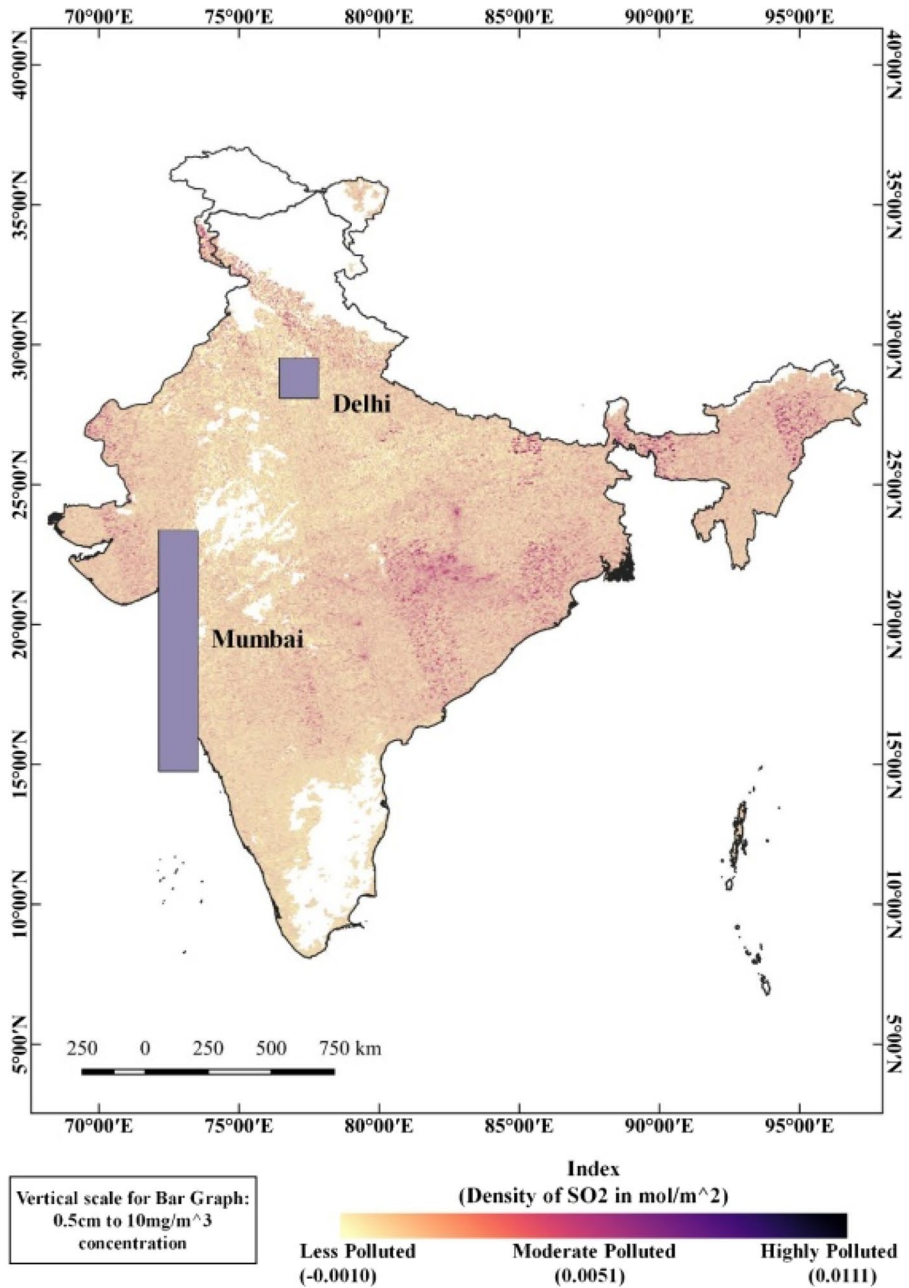
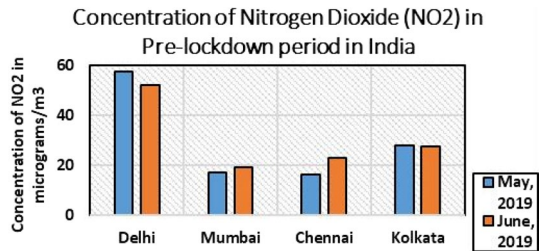


Fig. 4 National level distribution of SO₂ during post-lockdown period in India, along with its concentration in Delhi and Mumbai city. (Data source: CPCB, India, and Sentinel 5P)

Fig. 5 In pre- lockdown period concentration of NO₂ remained high in Delhi and Kolkata (Data source: CPCB)



is slightly higher ($\geq 23 \mu\text{g}/\text{m}^3$) in Chennai in June 2020 than in the other cities. In Mumbai, less amount of pollution ($\leq 8 \mu\text{g}/\text{m}^3$) has been recorded in May; it is almost none ($1 \mu\text{g}/\text{m}^3$) in June.

3.2.3 Post lockdown period

The scenario of NO₂ absorption across India in the post-lockdown period (January 2021) has expressed here (Fig. 8). A severe concentration has been observed in Chhattisgarh, Jharkhand, West Bengal and some parts of Odisha. Also, some parts of the Northern Plains like Punjab and Haryana, some urban centres of Uttar Pradesh and Bihar and some urban areas of Gujarat exhibit considerable amounts of NO₂ in the air. Other states of northern (Jammu and Kashmir); north-western (Rajasthan); and western (Maharashtra and parts of Gujarat) India; and all states of north-eastern India are less polluted. Pollution is almost not recorded in most of the south Indian states including Tamilnadu, Kerala, etc. The CPCB data of NO₂ concentration also indicates comparatively high pollution in Delhi and it is very less in Mumbai.

3.3 Status of carbon monoxide (CO)

Carbon Monoxide (CO) is a colourless, odourless and tasteless gas which is very toxic and flammable. It consists of both carbon and oxygen atoms and it is less dense than the air. The main source of CO is thermal combustion and also incomplete combustion of various fuels like wood, coal, oil, natural gas, etc. Besides this, different kinds of Environmental and biological sources also help to generate CO. It contributes a spatial role in Ground-level Ozone (O₃) formation and also helps in climate change. Besides this, it causes various health issues like headache, weakness, dizziness, weak pulse, respiratory problems, etc. (Britannica, 2023). In India, about 80% of death cases due to CO poisoning have occurred in the winter season (Sikary et al., 2017). Like other pollutants, a significant variation has been observed in the concentration of CO in the three periods.

3.3.1 Pre-lockdown period

The national level air quality of the pre-lockdown period has been studied for the months of May and June 2019 (Fig. 9). An extreme intensity of CO ($\geq 84 \mu\text{g}/\text{m}^3$) has been identified in Mumbai in both months.

In Chennai, the concentration of CO is moderate in nature ($\geq 52 \mu\text{g}/\text{m}^3$) and it is moderate ($\leq 32 \mu\text{g}/\text{m}^3$) in Delhi. Kolkata is relatively less polluted ($\leq 12 \mu\text{g}/\text{m}^3$) than the others. The all-Indian scenario of CO in the Pre-lockdown period (January 2020) has represented

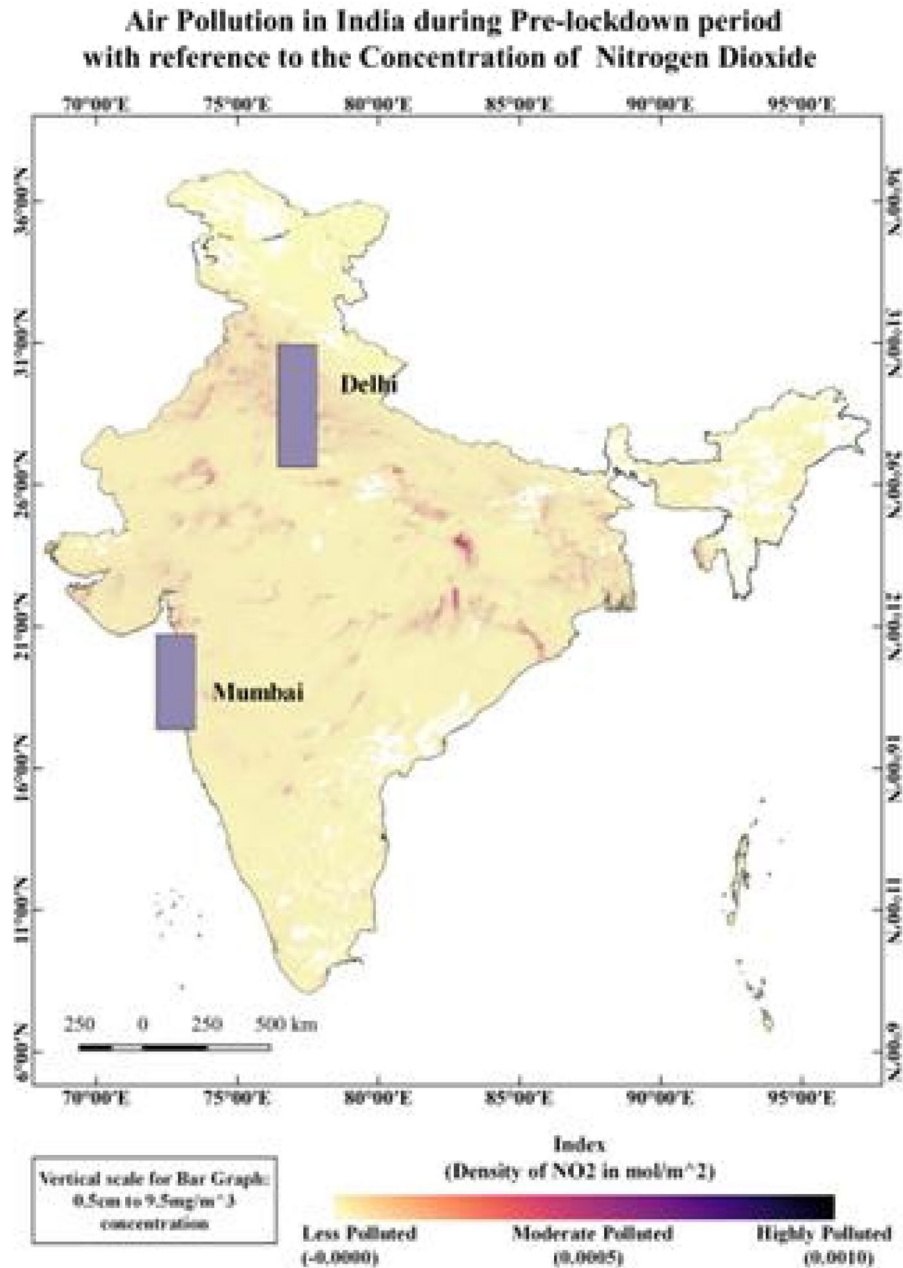
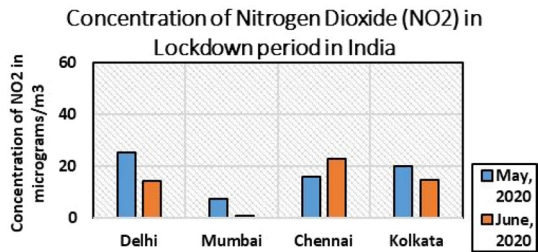


Fig. 6 National level distribution of NO₂ during pre-lockdown period in India, along with its concentration in Delhi and Mumbai city (Data source: CPCB, India, and Sentinel 5P)

here (Fig. 10). From the map it is quite clear that most of the parts of India including the northern mountain, northern plain, East and West coast and South Bengal exhibit an extreme amount of CO concentration. The highest intensity has been observed in Gujarat

Fig. 7 In lockdown period, concentration of NO_2 decreased in all cities (Data source: CPCB)



and some portions of Rajasthan. But a few divisions of Jammu, Kashmir, and Uttar Pradesh and a little segment of North Indian states indicate slightly lower absorption than the rest. Conversely, Ladakh and Some parts of Himachal Pradesh are less polluted. The data collected from CPCB depicts an excessive amount of CO accumulation in Mumbai and it is also high in Delhi.

3.3.2 Lockdown period

The lockdown period reflects a considerable condition of CO concentration in most of the cities (Fig. 11). In May 2020, the density is almost the same ($\leq 41 \mu\text{g}/\text{m}^3$) in Delhi and Mumbai in June 2020, whereas it is low ($\leq 24 \mu\text{g}/\text{m}^3$) in Chennai. On the other hand, the pollution level is average ($\leq 51 \mu\text{g}/\text{m}^3$) in Mumbai, although it is tolerable ($\leq 29 \mu\text{g}/\text{m}^3$) in Delhi and Chennai in June 2020. Kolkata is less polluted ($\leq 12 \mu\text{g}/\text{m}^3$) in both months.

3.3.3 Post lockdown period

After analysing the scenario of CO concentration across the country (Fig. 12) it is understood that the pollution level is also very high in most of the parts of India including Northern Mountain, Northern Plain, East and West Coast and South India. Severe conditions have been observed in Gujarat, Rajasthan, Bihar, Jharkhand, Odisha and West Bengal. Very low concentration has been found in a few portions of Punjab, Uttar Pradesh and Madhya Pradesh and also some parts of South India. Concentration is tolerable in Ladakh and it is average in nature in Jammu, Kashmir and some Northern-Eastern states. On the other hand, CPCB data on air quality exhibits comparatively high pollution in Delhi whereas Mumbai is less polluted in this period.

3.4 status of aerosol index ($\text{PM}_{2.5}$, PM_{10})

Particulate matter (with a diameter of 2.5 μm and 10 μm) is a mixture of solid and liquid particles which are suspended in the atmosphere. Dust, spores, pollen, etc., are examples. The source of these particles is both natural (Volcanic eruption, forest fires, chemical reactions taking place in the atmosphere, etc.) and anthropogenic (dust from roads, vehicular and industrial activities, combustion of fossil fuel, etc.) factors. These particles are small enough, so it penetrates easily our throat and lungs and causes cough, nose run, eye sting, etc. (short term) and asthma, chronic bronchitis and heart disease, etc. (long term). This is more harmful to children and elderly people. The prescribed standard of $\text{PM}_{2.5}$ is $60 \mu\text{g}/\text{m}^3$ and The national ambient air quality standard of PM_{10} is $60 \mu\text{g}/\text{m}^3$ in India (annual average) (US EPA, 2016c). Every $10 \mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$ results in a 3–26 per cent increase

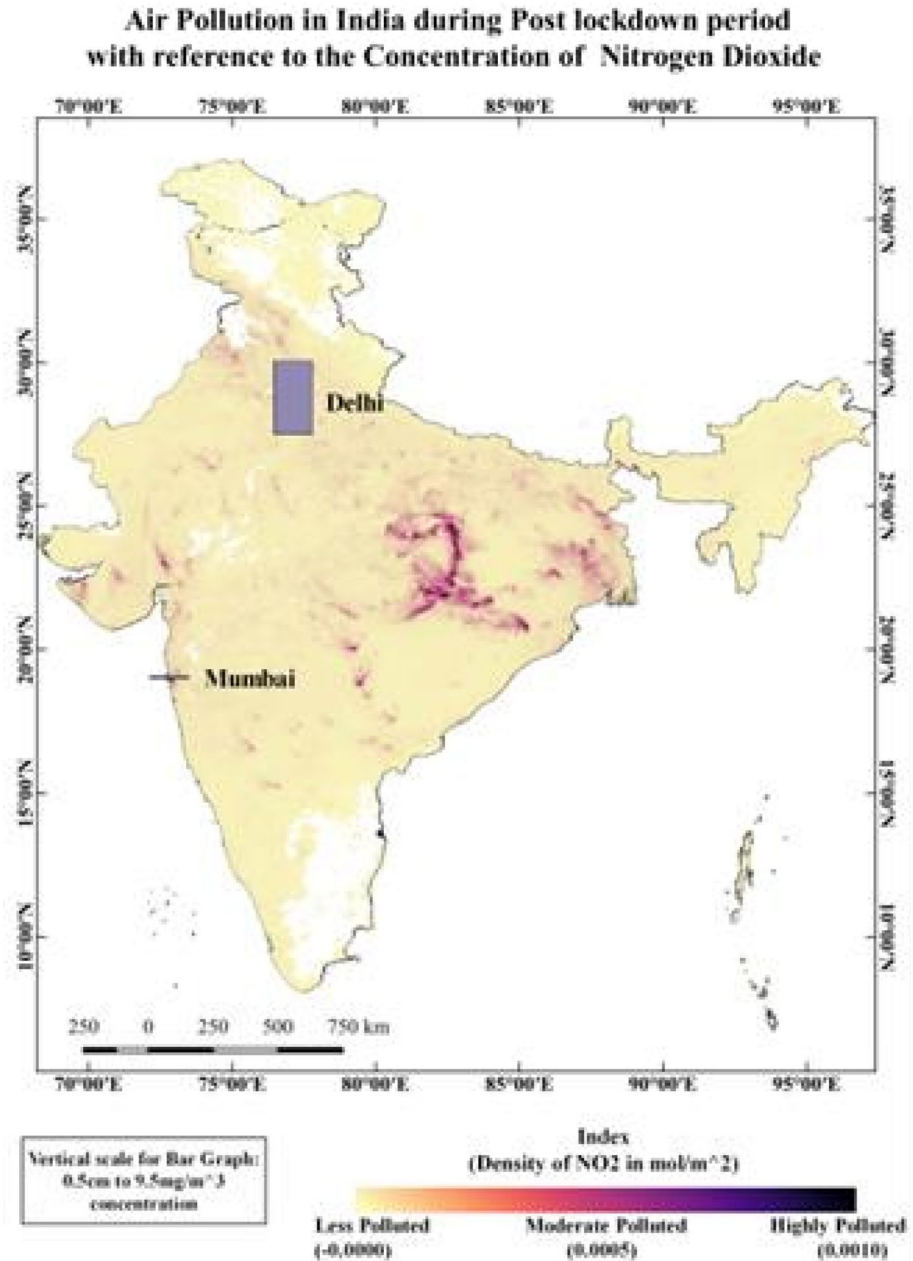
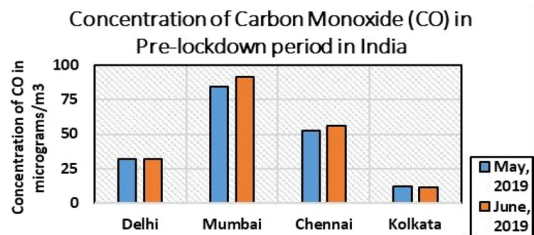


Fig. 8 National level distribution of NO₂ during post-lockdown period in India, along with its concentration in Delhi and Mumbai city (Data source: CPCB, India, and Sentinel 5P)

Fig. 9 In pre-lockdown period concentration of CO was quite high in the cities, except Kolkata (Data source: CPCB)



in mortality (Airveda, 2017). The spatial distribution of aerosol index ($PM_{2.5}$ and PM_{10}) during pre-COVID to COVID period has been represented below.

3.4.1 Pre-lockdown period

After analysing (Figs. 13 and 14) the pollution level of the pre-lockdown period (May and June 2019), it is realised that the concentration of $PM_{2.5}$ and PM_{10} are very extreme ($\geq 168 \mu\text{g}/\text{m}^3$) in Delhi (Slightly low in June). As well as the concentration of each contaminant is significant ($\geq 80 \mu\text{g}/\text{m}^3$) in Kolkata. The amount of PM_{10} is comparatively low ($\leq 65 \mu\text{g}/\text{m}^3$) in Mumbai and the density of $PM_{2.5}$ is very less ($\leq 26 \mu\text{g}/\text{m}^3$). Also, Chennai reflects low accumulation ($\leq 50 \mu\text{g}/\text{m}^3$) of $PM_{2.5}$ (data on PM_{10} is not available).

The spatial distribution of the aerosol index across India in the pre-lockdown period (January 2020) has been analyzed (Fig. 15). From this it is quite clear that the concentration of aerosol is very high all over the country. Most of the parts including North India, Northern Mountain, Northern plains, North-Eastern states, East coast and Middle India exhibit an extreme amount of pollution. Although the density of aerosol is slightly lower in Gujarat, Maharashtra and some portions of Rajasthan than the rest. The South Indian states including Karnataka, Kerala, and Tamil Nadu also reflect sufficient concentrations of aerosol. On the other hand, the CPCB data illustrates an excessive amount of $PM_{2.5}$ in Delhi and the intensity of PM_{10} is also very high. It is comparatively low in Mumbai.

3.4.2 Lockdown period

After a brief study it is identified that the concentration of aerosols is comparatively low during the lockdown period (May and June 2019). The highest concentration has been observed in Delhi where the accumulation of each pollutant is extremely high ($\geq 125 \mu\text{g}/\text{m}^3$) in May but it is slightly low ($\geq 87 \mu\text{g}/\text{m}^3$) in June. In Mumbai, the contamination of aerosol is sufficient ($\geq 67 \mu\text{g}/\text{m}^3$) in May but it is very less ($\leq 37 \mu\text{g}/\text{m}^3$) in June. On the other hand, Chennai (data of PM_{10} is not available) and Kolkata are less polluted ($\leq 45 \mu\text{g}/\text{m}^3$) in both months (Figs. 16 and 17).

3.4.3 Post lockdown period

The all-Indian scenario of the aerosol index in the pre-lockdown period for the month of January 2021 has been represented here (Fig. 18). After analysing this map, it is quite clear that most of the parts including North India (Jammu, Kashmir, Ladakh, Punjab, Haryana, Uttar Pradesh, etc.), North-West India (Rajasthan), Middle India (Madhya Pradesh, Chhattisgarh), and South India (Kerala, Tamil Nadu, half of Andhra Pradesh, etc.) contain an

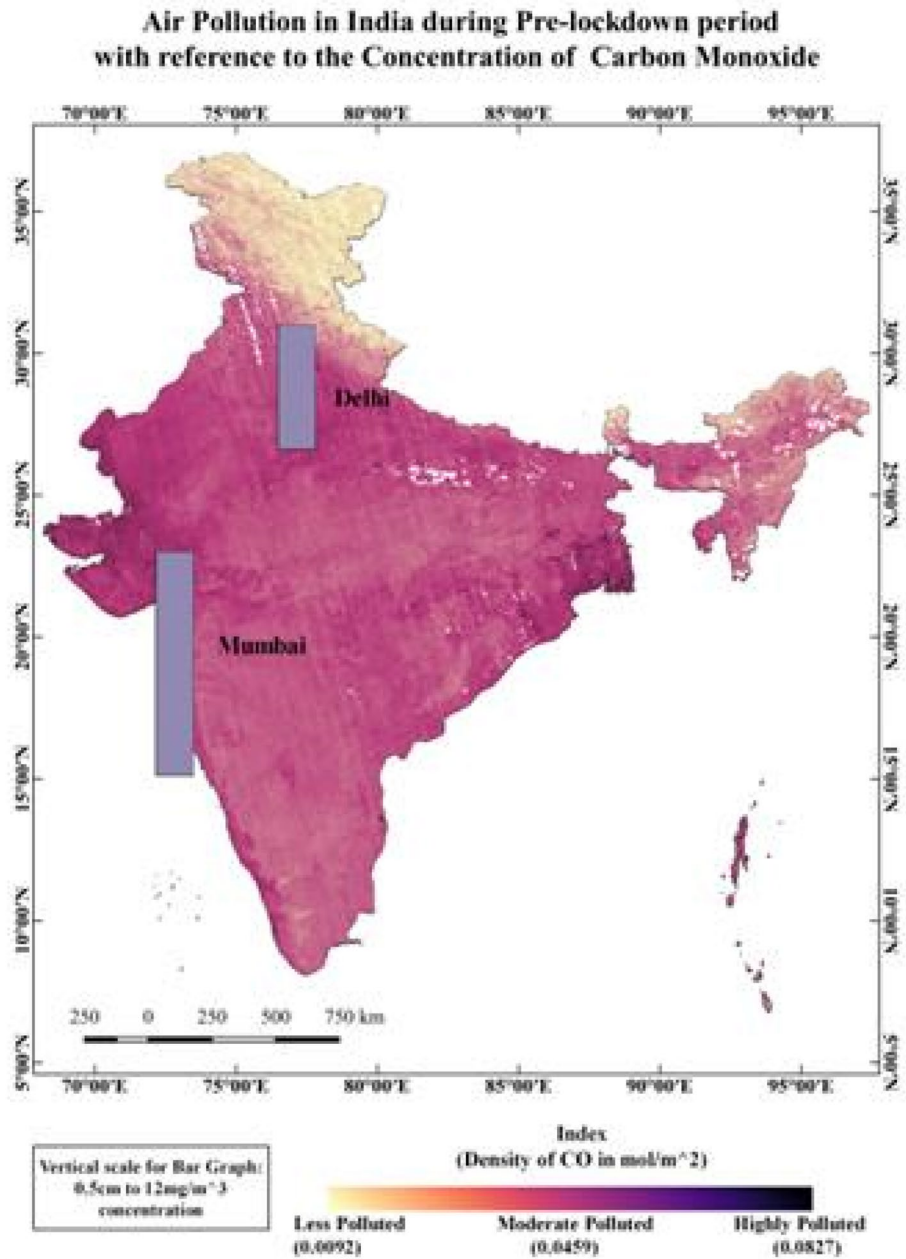
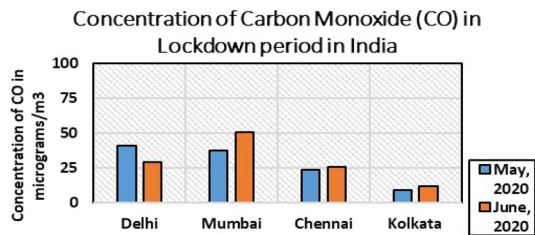


Fig. 10 National level distribution of CO during pre-lockdown period in India, along with its concentration in Delhi and Mumbai city (Data source: CPCB, India, and Sentinel 5P)

Fig. 11 In lockdown period, concentration of CO decreased significantly in the cities (Data source: CPCB)



extensive amount of aerosol. The contamination of aerosol is slightly low but sufficient in a little segment of Rajasthan and West Bengal. Concentration is comparatively less in the East Coast (Odisha, some parts of Andhra Pradesh, etc.); North-Eastern states (Assam, Manipur, Tripura, Arunachal Pradesh, etc.); and some others (Telangana, a few portions of Gujarat, Maharashtra, and Karnataka) than the rest. The CPCB data on air quality also indicates an extreme level of pollution in Delhi but it is very less in Mumbai.

4 Findings

A significant change has been observed in the concentration of the pollutants in India during the lockdown period in comparison with the previous year, especially in the case of PM_{10} , NO_2 , and CO. Also an excessive increase in the concentration of the aforementioned pollutants has been noticed after the lockdown period. The main source of these pollutants is industrial emission, combustion of fossil fuel and vehicular emission. But in the lockdown period due to the suspension of these activities, the air quality was improved. Once the lockdown was over, these activities were also resumed and the air quality again started to deteriorate. There is also another thing that can be noticed the concentration of air pollutants is relatively less in the pre-monsoon and monsoon periods of both lockdowns and pre-lockdown periods while it is very high in the post-monsoon period. As the monsoon brings heavy rain in India, during the rainy season concentration of air pollutants is relatively less over India. From this, it can be stated that the air quality level depends on different meteorological parameters too.

5 Conclusion

From this study, it can be said that lockdown has played a vital role to reduce air pollution levels in India. The decision to lockdown taken by the Government of India caused a serious socio-economic crisis, but it helped to improve the air quality level. The results show a drastic reduction in national-level air pollution, which proved the impact of the lockdown on the improvement of air quality. During the post-lockdown period, a drastic increase has been identified in the concentration of $PM_{2.5}$, PM_{10} and SO_2 concentration in the air again.

The findings of the study suggest that:

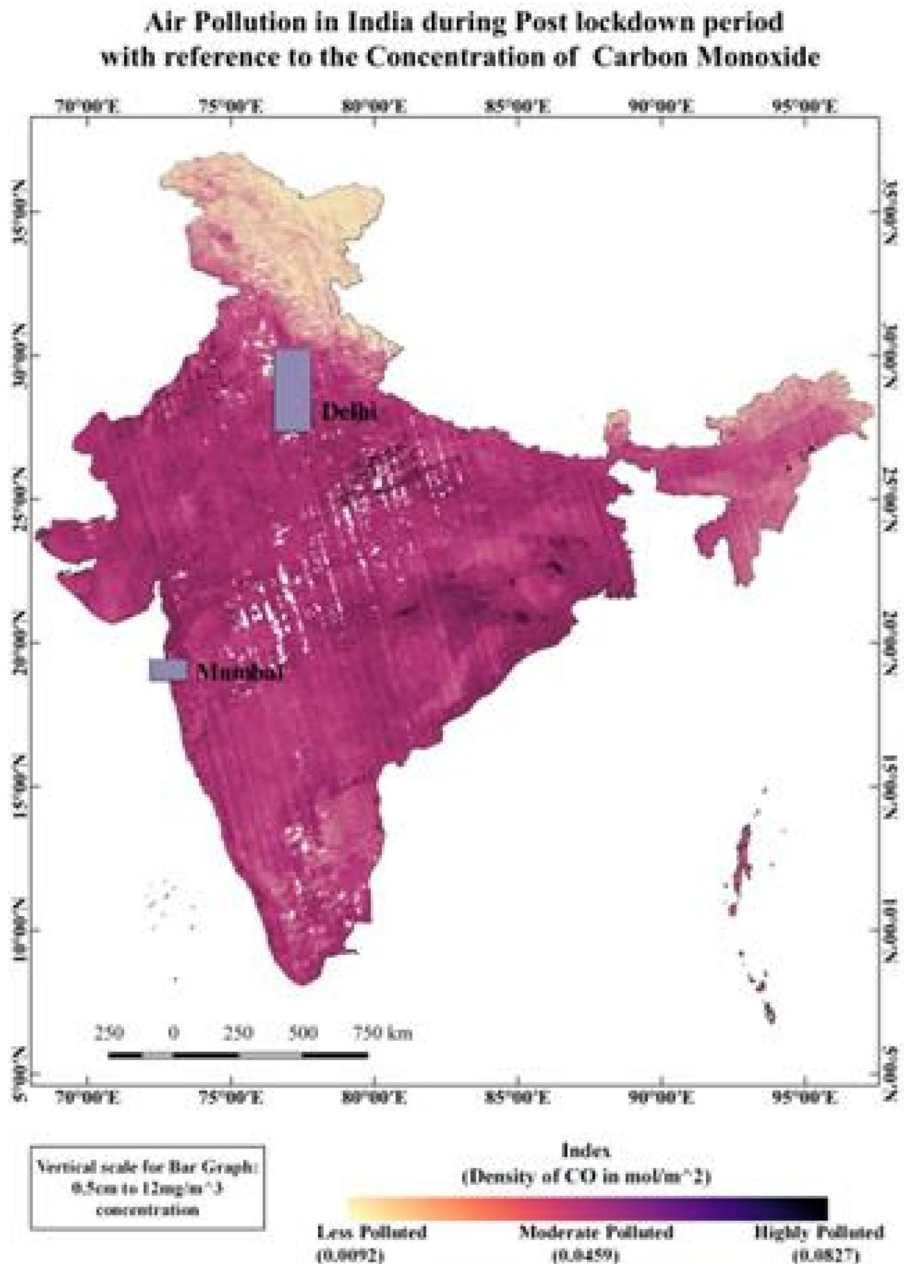


Fig. 12 National level distribution of CO during pre-lockdown period in India, along with its concentration in Delhi and Mumbai city (Data source: CPCB, India, and Sentinel 5P)

Fig. 13 In pre- lockdown period concentration of PM_{10} was alarmingly high in Delhi and Kolkata. This data is not available for Chennai (Data source: CPCB, India)

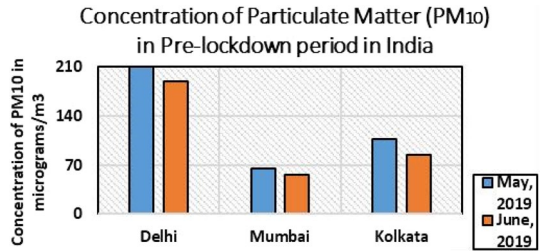
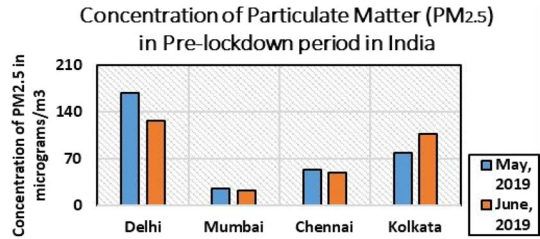


Fig. 14 In pre- lockdown period concentration of $PM_{2.5}$ was alarmingly high in Delhi and Kolkata. This data is not available for Chennai (Data source: CPCB, India)



- Rotational or controlled vehicular and industrial emissions could be an effective measure in the future to improve air quality without harming the economy.
- The result also shows that vehicular flux and combustion of fossil fuel are the two main sources of air pollution in India. So, alternative eco-friendly fuels may reduce the concentration of different air pollutants. More use of ethanol-blended fuel can reduce air pollution significantly (Singh Bisht et al., 2023).
- Use of bicycles may be encouraged in the cities for short-range movement as a mode of 'green transportation'. To encourage it, a separate 'cycle lane' may be introduced in metropolitan cities in India.
- Reduced use of private cars and enhanced use of rapid transit mass public transport will help to reduce air pollution. In the same way, increased use of electric-driven e-rickshaw, and e-vans may be helpful in this regard.
- Combustion of fossil fuel in industries is a major source of air pollution. During the lockdown period when industrial activities were shut down, the combustion of fossil fuel has reduced and the air quality improved. For better air quality, production systems may shift to other non-polluting sources of energy gradually as much as possible and various measures may be imposed to reduce industrial carbon footprint like a carbon credit system.

According to the observations, as the pollution level is higher in the post-monsoon period. So, special strategies may be taken during the winter season to maintain air quality in India. Continuous monitoring of air quality is required in relation to human activities. Hence, such study is needed in the future too for maintaining a healthy environment. Air quality may be compared between normal working days and holidays in the cities.

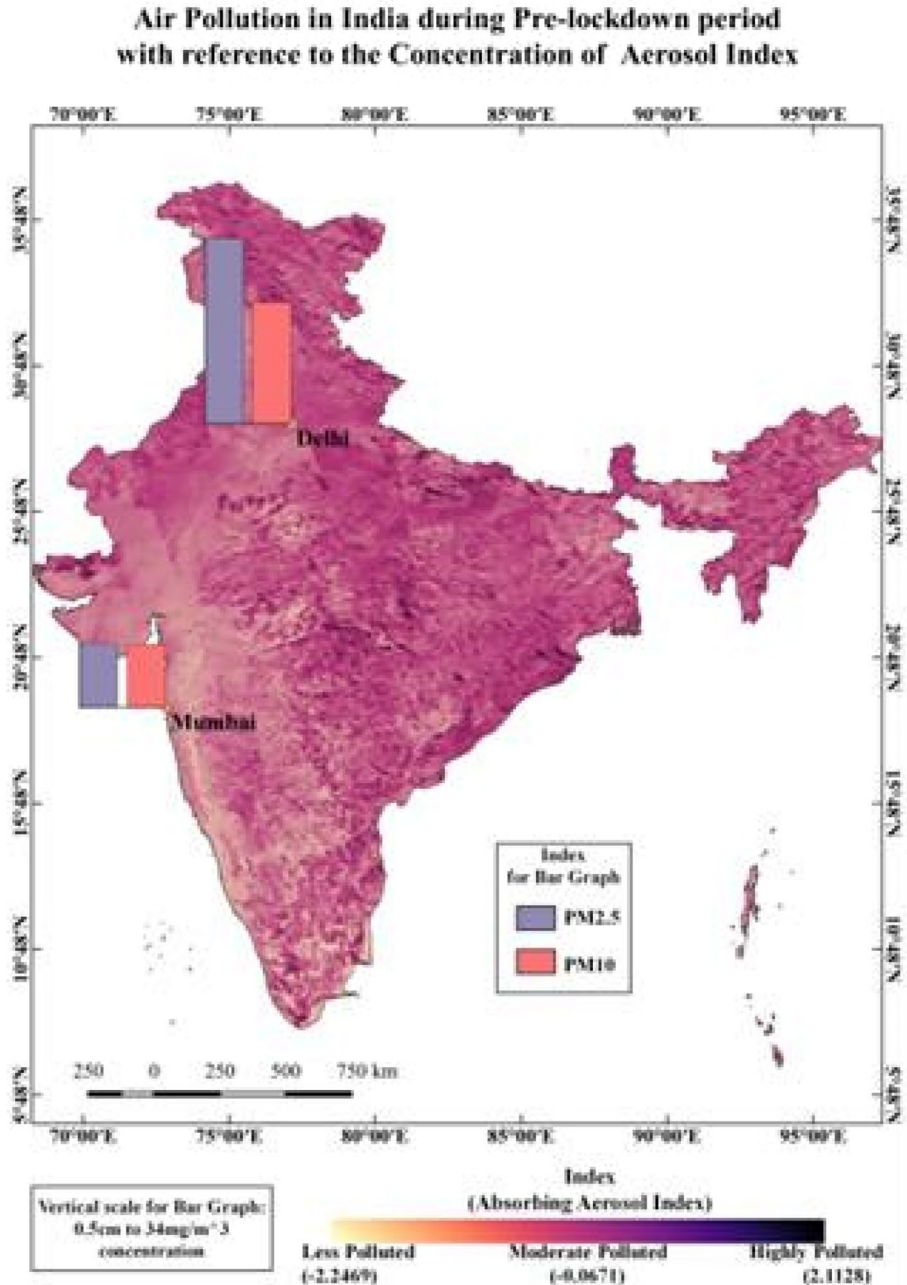


Fig. 15 National level distribution of Aerosol during pre-lockdown period in India, along with their concentration in Delhi and Mumbai city (Data source: CPCB, India, and Sentinel 5P)

Fig. 16 In lockdown period concentration, of $PM_{2.5}$ was high in Delhi and Mumbai (Data source: CPCB)

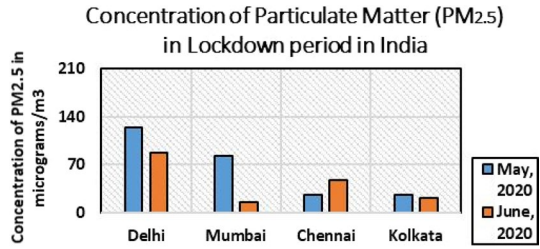
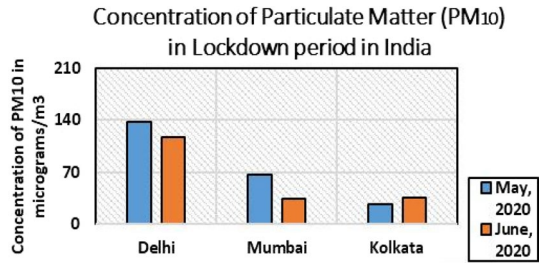


Fig. 17 In lockdown period, concentration of PM_{10} was alarmingly high in Delhi and Mumbai. This data is not available for Chennai (Data source: CPCB)



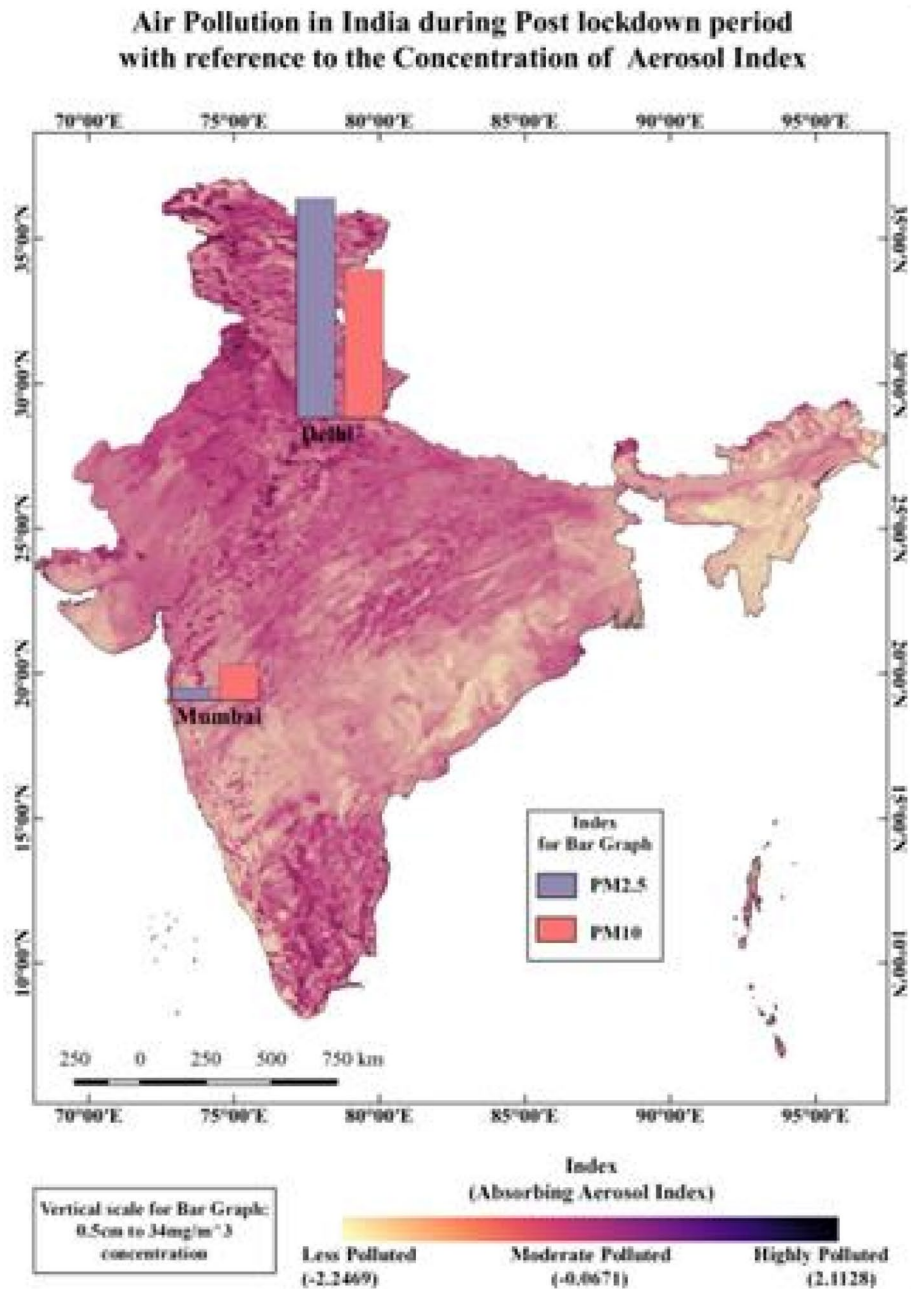


Fig. 18 National level distribution of Aerosol during post-lockdown period in India, along with their concentration in Delhi and Mumbai city (Data source: CPCB, India, and Sentinel 5P)

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Data availability statement Primary data on the tiger attack already have been provided in the main text in the table. Pollution data links will be shared on request.

Declarations

Conflict of interest The author has no relevant financial or non-financial interests to disclose. The author has no competing interests to declare that are relevant to the content of this article.

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