Impact of Lockdown on Air Quality During COVID-19 Pandemic: A Case Study of India

Pennan Chinnasamy1,2 · Zeel Shah3 · Shamsuddin Shahid4

Abstract
It is crucial to study air quality and its impact on human health, as it can leave not only short-term effects but also have long-term effects, especially on people suffering from cardiovascular and lung diseases. During the COVID-19 pandemic, a major lockdown of almost 70 days in four different phases was announced in India. Due to this exercise, many visually observed a drastic change in air quality; however, actual quantifications were limited. Therefore, there is a need to quantify how air quality changed from before to during and post-lockdown scenarios. This study quantifies the COVID-19 India lockdown impact on air quality by analyzing the change in major air pollutants such as SO2, NO2, CO, O3, PM2.5, and PM10. The major objectives of this study are to quantify the change in major air pollutants across India during the lockdown and to identify their trends and respective hotspots. In order to achieve these objectives, air quality estimates are obtained from Sentinel 5P satellite, while PM2.5 and PM10 values are taken from Central Pollution Control Board’s ground monitoring stations. For temporal analysis, different time intervals starting from before the lockdown (i.e., March 1, 2020) till the end of the fourth lockdown (i.e., May 31, 2020) were analyzed across India. Results state that (1) There was a significant decline of −48.11% and −11.56% in concentrations of SO2 and NO2, respectively, after averaging values at their respective hotspots (2) A decrease of −6.78% and −0.42% was observed in O3 and CO concentration during the lockdown period in the year 2020 compared with the same period in the year 2019. (3) For PM2.5, Kolkata had the maximum drop of −83.28%, while Bengaluru had the least drop of −38.86%, whereas, for PM10, Kolkata had the maximum drop again of −80.53%, while Delhi, on the other hand, had an increment of 13.42% at the end of the fourth lockdown. The results indicate the indirect benefit of the COVID-19 lockdown on air quality. It also provides a better understanding of hotspots and trends that can aid the government and the policy-makers to identify precautionary measures to reduce air pollution and prioritize hotspots.

Keywords Air quality · Air pollutants · COVID-19 · Lockdown · Google Earth Engine · India

Introduction

The COVID-19
An illness caused by a novel coronavirus was first identified on December 31, 2019, in Wuhan City, Hubei Province, China, known as Coronavirus disease 2019 (COVID-19) or Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2). Because of its major outbreak throughout the world, the World Health Organization (WHO) declared it a global pandemic on March 11, 2020 (Cennimo & Bergman, 2020). In India, the first case of COVID-19 was reported on January 30, 2020, and many measures were proposed to prevent the spread of the virus (Rawat, 2020). To overcome the challenging situation, a lockdown for 21 days on March 24, 2020, was announced by the Indian government, however, since the COVID-19
cases did not reduce, the initial lockdown was then followed by three more lockdowns of 19 days, 14 days, and 14 days, respectively (Kachroo, 2020). From June 1, the government announced three unlock phases (barring the containment zones). The total number of cases before the lockdown (i.e., on March 24, 2020) was 564 cases and at the end of 4th lockdown (i.e., on May 31, 2020) was 173,763 cases (Basu et al., 2020). At the end of the 4th lockdown, India ranked first with the highest number of confirmed cases in Asia, and fourth highest in the world. This makes it important to predict the spread of COVID-19 along with taking precautionary measures to prevent it (Tomar & Gupta, 2020).

India’s Air Quality Scenario

It is important to keep track of the air quality, as it may not only have short-term effects but can also have long-term effects on the health of the people, particularly for those who have cardiac or respiratory issues. The COVID-19 and associated lockdown scenarios had sensitized everyone on how air quality exists in business-as-usual scenarios (Lewis, 2020). Due to the lockdown, the decrease in traffic and shutting down of industrial units provided a rare scenario that can help identify the re-emergence characteristics of air pollutants. This information can then be used to develop scientifically validated air quality management plans. The Government and policy-makers can make better laws and policies to reduce air pollution by directly targeting their respective hotspots.

According to the report (IQAir, 2019) on the global compilation data of PM2.5 particulate pollutants by IQAir, a company that assesses the air quality worldwide, India was ranked the fifth most polluted country in the year 2019, with Ghaziabad in the National Capital Region being ranked as the most polluted city at the global level. Among the top ten most polluted cities in the world, six cities were located in India, with Delhi at the fifth position (IQAir, 2019). Delhi, being the capital of India, makes it very crucial to have strict control actions to improve the air quality and document the sources of air pollutants, so that better management plans can be formulated and precautionary measures can be taken on a pro-active basis to control air quality. In addition, multiple air quality parameters have degraded India’s air quality concerns, some of which are discussed in this section.

Over the past few decades, a huge increase in the generation of electricity obtained from coal is observed, resulting in high emissions of sulfur dioxide (SO₂). The increase in industrial processes like extracting metal from ore, natural sources like volcanoes, as well as man-made processes like burning of fuel in vehicles, ships, and other locomotives, have also contributed to the increase in sulfur content (Li et al., 2017). One of the major consequences of

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**Fig. 1** Flowchart indicating the methodology

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Source: Springer
Table 1 Source, units, spatial resolution, time interval and reference link for all pollutants

| Parameter | Units   | Satellite/monitoring station | Source                          | Spatial            | Time interval | Link                                                                 |
|-----------|---------|-------------------------------|--------------------------------|--------------------|---------------|----------------------------------------------------------------------|
| SO₂       | mol/m²  | Sentinel-5P                   | Google earth engine            | 7 × 3.5 km²        | One day       | https://developers.google.com/earth-engine/datasets/catalog/sentinel-5p |
| NO₂       | mol/m²  | Sentinel-5P                   | Google earth engine            | 7 × 3.5 km²        | One day       | https://developers.google.com/earth-engine/datasets/catalog/sentinel-5p |
| CO        | mol/m²  | Sentinel-5P                   | Google earth engine            | 7 × 3.5 km²        | One day       | https://developers.google.com/earth-engine/datasets/catalog/sentinel-5p |
| Ozone     | mol/m²  | Sentinel-5P                   | Google earth engine            | 7 × 3.5 km²        | One day       | https://developers.google.com/earth-engine/datasets/catalog/sentinel-5p |
| PM 2.5    | ug/m³   | Monitoring station            | Central pollution control board| –                  | One day       | https://app.cpcbccr.com/cct/#/caaqm-dashboard-all/caaqm-landing       |
| PM 10     | ug/m³   | Monitoring station            | Central pollution control board| –                  | One day       | https://app.cpcbccr.com/cct/#/caaqm-dashboard-all/caaqm-landing       |

Fig. 2 Variation in SO₂ during various stages of lockdown at two hotspots: (hotspot1) Villupuram, Cuddalore, Vridhachalam (Tamil Nadu region) (hotspot2) Singrauli (M.P), Sonbhadra (U.P), Surguja (Chhattisgarh)
increased $SO_2$ in the atmosphere is acid rain. During acid rain, the $SO_2$ mixes with rain water to create sulfuric acid rain, which results in the lowering of soil pH, death of trees and water species, corrosion of sedimentary rocks like limestone, etc. (Singh & Agrawal, 2007).

Another major air pollutant is Nitrogen dioxide ($NO_2$). It is produced from the making of nitric acid, usage of explosive chemicals, manufacturing for commercial and food products, refining of petrol, etc. But the major source of production of $NO_2$ is the combustion of fossil fuels such as

![Fig. 3 Variation in $SO_2$ between lockdown scenarios in India for hotspot1 and hotspot2](image1)

![Fig. 4 Variation in $NO_2$ during various stages of lockdown at three hotspots: (hotspot1) Delhi, Ghaziabad and Gautam Buddha Nagar (U.P), Faridabad (Haryana), (hotspot2) Sidhi and Sonbhadra (M.P), Korba, Bilaspur, Raipur, Durg, Janjgir, Rajgarh, Jangir-Champa, Jharsuguda and Sambalpur (Chhatisgarh) and (hotspot3) Bankur, Bardhhaman and Birkhum (West Bengal), Jamtara, Dhanbad and Bokara (Jharkhand)](image2)

![Fig. 5 Variation in $NO_2$ for hotspot1, hotspot2 and hotspot 3 between pre-lockdown and fourth lockdown scenario in India](image3)
as coal and gas, especially in vehicles. The major consequences of NO₂ is increase in respiratory infection and a reduction in lung’s function, especially in children. Also, NO₂ may turn into harmful acids, at higher concentrations, which may lead to the corrosion of building materials in the presence of moisture (World Health Organization, 2006).

Ozone (O₃) occurs in two layers of the atmosphere, one closest to the surface of the earth (in the troposphere) and another 9–48 km far away from the Earth’s surface (in the stratosphere) (World Health Organization, 2006). The ground-level ozone is the bad ozone and is considered an air pollutant, as it is harmful to breathe as well as damages the trees and agricultural crops. Also, it is the main ingredient in urban smog, which usually occurs in industrial boilers, chemical refineries, plants and emissions from automobiles (Gorai et al., 2017), whereas the O₃ layer in the stratosphere is considered as the good ozone, as it protects our skin from the sun’s harmful ultraviolet (UV) rays. But, due to the increase in air pollution, the stratospheric ozone layer is depleting day by day (Yang, 2020). This leads to an increase in the amount of the ground-level ozone which humans directly breathe. Due to which, the major consequences observed are an increase in the number of cases of respiratory diseases like asthma, especially in children, older people and outdoor workers (Gorai et al., 2017).

Other than incomplete combustion from vehicles, the total anthropogenic emissions contribute to 41% to the production of carbon monoxide (CO) (World Health Organization, 2006), whereas the contribution from industrial and transportation sectors is estimated as 30% and 28%, respectively. Anthropogenic emissions, being the primary source of CO, are found highest over the megacities such as Mumbai, Ahmedabad, Delhi, Kolkata, Thiruvananthapuram, and the Indo-Gangetic Plain region.

**Fig. 6** Variation in O₃ during various stages of lockdown for year 2019 across India
In terms of consequences, CO does not actively react with the atmosphere to produce pollutants, but it has 210 times more affinity for haemoglobin (Hb) than oxygen (O₂). As a result, with continuous exposure to vehicular emissions, CO may cause severe CO intoxication, and lower respiratory tract disorders such as cough and pain with inspiration (Sood et al., 2014).

Another air quality parameter is PM2.5 which is generally described as fine particles (Ventura et al., 2017). Short-term problems like irritation in the eyes, nose, throat, or lungs, shortness of breath, coughing, etc., can be caused by constant exposure to fine particles of PM2.5. According to scientific studies, with the increase in the level of PM2.5, the cases related to cardiovascular and respiratory diseases have increased in hospitals (Dagher et al., 2005). Similarly, if a particulate matter (PM) is less than or equal to 10 μm in diameter, it can be defined as PM10. The primary source of PM10 is wind-blown dust from the construction sites, open lands, pollen grains, wildfires, etc. (Thurston & Spengler, 1985). As the PM10 particulates are very small,
they can easily enter our bodies and may cause a direct physical effect on the lungs as PM10 gets absorbed into the blood easily. In terms of consequences, the effect of the particulates depends on their composition, concentration, and presence of other pollutants (World Health Organization, 2006).

For an Indian pollution level analysis, there is a need for high spatial and temporal resolution data. While the government agency data on air quality exist, the spatial and temporal resolutions are limited owing to the high costs of maintaining air quality monitoring stations. In such scenarios, remote sensing data can aid in monitoring air quality at high spatial and temporal resolutions, and at a free cost while using opensource data (Chinnasamy et al., 2021; Chinnasamy & Sood, 2020). Such remote sensing data are used in a GIS environment in this study to understand air quality issues.

The primary objective of this study is to understand the impact of lockdown scenarios on air quality parameters in major cities of India, using a unison of in-situ observation data and remote sensing data. Secondary objectives include the identification of major hotspots and temporal analysis of air quality parameters.

**Materials and Method**

**Lockdown and Modes in India**

On March 22, 2020, India observed four mandatory lockdowns in COVID-19 hotspots and all major cities, from...
which the progressions in lockdown occurred. The time interval of the four lockdowns given in India is as follows; Lockdown 1—March 25th to April 14th, Lockdown 2—April 15th to May 3rd, Lockdown 3—May 4th to May 17th and Lockdown 4—May 18th to May 31st.

Intra-state travel relaxations were given in Lockdown 3 and Red, Orange, and Green Zones (as severe to safe) were defined across the country. Activities like the movement of goods, private offices with only 33% of capacity, Inter-/Intra-district buses with only 50% capacity were allowed, whereas railway services, public gatherings, educational institutions, places of worship, cinema halls, etc., were totally restricted (Delhi, 2020). Inter-state travel relaxations were given in Lockdown 4, and inter-state movement of transport vehicles with the mutual consent of states was allowed. Thus, the amount of traffic and fuel combustion drastically were reduced, directly impacting the air quality to the extent that optical measurements reported improved performances (Ghodpage et al., 2021).

Relevant dates were selected for the remote sensing assessment in this study. The time interval for each lockdown scenario chosen for the study are; Lockdown 1—
April 1st to April 10th, Lockdown 2—April 20th to April 30th, Lockdown 3—May 12th to May 17th, Lockdown 4—May 21st to May 27th. The date selection was based on the availability and coverage of the data for the country and the quality of the data. Since the quality of data and availability of data could vary, the time intervals may vary in each lockdown period.

**Methodology**

The methodology (Fig. 1) is divided into four major stages and discussed in the following subsections:

**Data Collection**

In India, the Central Pollution Control Board (CPCB) calculates the air quality index (AQI) for five major air pollutants, and to safeguard public health, certain standards are established for national air quality. The higher the AQI value, the higher will be the level of air pollution and higher will be the health concerns (Kumar & Goyal, 2011). These major pollutants are SO$_2$, NO$_2$, CO, PM2.5, PM10 and O$_3$, and since there are limitations in acquiring high spatial and temporal resolution observation data, remote sensing data were used in this study. Among the satellite datasets, the Sentinel-5 satellite, which is operated by the European Space Agency (ESA), has been globally used to monitor air quality parameters, especially SO$_2$, O$_3$, NO$_2$ and CO (Veefkind et al., 2012). The TROPOspheric Monitoring Instrument (TROPOMI), which is onboard the Sentinel 5 precursor (S5P) and launched in October 2017, has a high spatial resolution (at a grid spacing of $3.5 \times 7$ km$^2$ for all aforementioned gases, except for CO and methane, which is at a grid spacing of $7 \times 7$ km$^2$) and

![Variation in PM2.5 during various stages of lockdown for Mumbai](image-url)
temporal resolutions (24 h) and is free of cost and open source dataset (Vellalassery et al., 2021). The open source data were collected from the Sentinel 5P dataset using the Google Earth Engine interface. As the PM2.5 and PM10 data are not available from Sentinel 5P, ground-monitoring stations were used for acquiring the same using Central Pollution Central Board (CPCB) portal (https://cpcb.nic.in/real-time-air-quality-data/). The location of the CPCB monitoring stations was taken from the portal (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing) and is shown in Fig. S1. The CPCB portal provides data for major air pollutants across India. Data can be obtained in tabular, excel, or graph format for an available period for a given monitoring station. For using these data, a master excel sheet was generated for the current study which included the daily concentration values of PM2.5 and PM10 with their corresponding ground control station. The data were geocoded by adding longitude and latitude to excel; for further analysis in a GIS platform—QGIS. The relevant data used and sources are indicated in Table 1.

The location of the monitoring stations (Fig. S1) indicates that since the stations are situated in a clustered pattern, the interpolation within the particular clustered area is more advisable rather than interpolating it for the whole India. Interpolation across India would lead to skewed values, and hence, clusters were mapped to major cities and interpolation was done within the city. On this note, four major cities like Delhi, Mumbai, Bengaluru and Kolkata were selected, as they have a good number of monitoring stations within the city. However, along with the high rate of urbanization, these cities are also exposed to the higher rates of pollution due to economic and

Fig. 13 Variation in PM2.5 during various stages of lockdown for Bengaluru
industrial growth (Chinnasamy & Parikh, 2021).

**QGIS Software**

QGIS stands for Quantum GIS. It is an open source software used for geographic information system (GIS), which is licensed under the GNU General Public License (Graser, 2013). QGIS software of version 3.12 was used for the generation of maps for all the air pollutants for five phases, i.e., Before Lockdown, First Lockdown, Second Lockdown, Third Lockdown, and Fourth Lockdown.

**Geospatial Analysis**

For analysis and change detection for \( \text{SO}_2 \), \( \text{NO}_2 \), PM10, and PM2.5, the Zonal Statistics tool in QGIS was used for their respective hotspots. Zonal statistics tool helps in providing statistical values like average, sum, mean, maximum, minimum, etc., of the raster layer, for a specified zonal boundary. Here, the hotspot regions are taken as the zonal boundary layers, whereas the pollutant raster layer is taken as input value. The input value layer should be in raster format only, whereas the zonal boundary layer can either be vector or raster. Whereas for \( \text{O}_3 \) and \( \text{CO} \), as identification of hotspots is not possible because it has a continuous layer, temporal change analysis was done between 2020 and 2019 year for the same time interval.

**Results and Discussion**

**Air Pollutants**

**Sulphur Dioxide (SO\(_2\))**

Since the coal-based power plants are the key polluting agents, the coal-based power plants were plotted with the background image of \( \text{SO}_2 \) scenario before the lockdown, as shown in Fig. S2. The hotspots were clustered and included: (hotspot1) Villupuram, Cuddalore, Vridhachalam
Keeping the SO$_2$ before the lockdown as the base map for its hotspots, it was clearly observed that these regions were also the highest density of coal power plant. Thus, the coal power plant cluster is one of the major sources of SO$_2$ emission in India, and thus, focusing on these regions for lockdown scenarios was critical.

The comparative results of mean SO$_2$ concentration before, during and after major lockdowns are shown in Fig. 2 for the entire India, while the specific comparison between the cluster hotspots is shown in Fig. 3. Both the figures indicate a gradual decrease in mean SO$_2$ values at hotspot1 till the 3rd lockdown. A sudden increase in hotspot1 values at the 4th lockdown may be the result of the relaxations given at that time. A gradual decrease is also observed in values of SO$_2$ at hot spot2 till the 2nd lockdown, along with a sudden fluctuation during the 3rd and 4th lockdowns. The net trend indicates that due to the lockdowns, a net change in SO$_2$ was $-46.08\%$ and $-50.14\%$ (decrease) at hotspot1 and hotspot2, respectively. While the lockdown scenarios have led to a clear decreasing trend in SO$_2$, the degree of decrease depends on the cluster’s size and how they efficiently conducted the lockdown.
Nitrogen Dioxide (NO₂)

An analysis of the pre-lockdown NO₂ map indicated the need to have three hotspots as follows: (hotspot1) Delhi, Ghaziabad and Gautam Buddha Nagar (U.P), Faridabad (Haryana), (hotspot2) Sidhi and Sonbhadra (M.P), Korba, Bilaspur, Raipur, Durg, Janjgir, Rajgarh, Jangir-Champu, Jharsuguda and Sambalpur (Chhattisgarh) and (hotspot3) Bankur, Bardhhaman and Birkhum (West Bengal), Jamtara, Dhanbad and Bokara (Jharkhand) (Fig. S3). The hotspots coincide with regions with a higher number of coal-based power plants.

The high concentration of NO₂ in clusters indicated the possibility of coal combustion being a primary source of NO₂. Compared to the pre-lockdown scenario, a gradual decrease is observed in the values of NO₂ at hotspot1 in the 1st lockdown, while the values kept increasing slowly until the 4th lockdown. A gradual decrease is also observed in values of NO₂ at Hotspot2 till the 2nd lockdown, along with a minor increase in values at 3rd and 4th lockdown, leading to a higher value at 4th lockdown than values before the lockdown. A gradual decrease is also observed in values of NO₂ at Hotspot3 till the 3rd lockdown, along with a minor fluctuation in values in 3rd and 4th lockdown. This can also be seen in Figs. 4 and 5. The net change in mean NO₂ between the pre-lockdown scenario and 4th lockdown was −17.64%, 5.74% and −22.77% at hotspots 1, 2 and 3, respectively.

OZONE (O₃)

Results from the analysis of the O₃ data indicate from April to August in the Indian subcontinent, due to meteorological factors, a usual high O₃ level is observed (World Health Organization, 2006), which is the reason for an increase in the amount of ozone from the period of 1st
lockdown. As per (Gorai et al., 2017), an increase in NOx levels will reduce the level of O3 (as per the following equation: NO + O3 = NO2 + O2). Therefore, from the aforementioned sections and as NO and NO2 pollutants had increased due to relaxations given (i.e., post 3rd lockdown), the ozone level decreased. As shown in Figs. 6 and 7, a comparison between the year 2019 and the year 2020 is done for the same time interval as the lockdown given in the year 2020.

An increasing trend is observed in India in both the years, i.e., 2019 and 2020, as the levels of NO and NO2 have decreased during the lockdown, the level of O3 has increased. But, as the level of NO and NO2 increased due to the relaxations given from 3rd lockdown, the level of O3 has shown a reducing trend in 2020 compared to the level of O3 in 2019. As a result, because of the increase in the levels of NO and NO2, the deduction observed in the level of O3 in the year 2020 was more than that in the year 2019, as shown in Figs. 6 and 7. The same can also be statistically proved by Fig. 8, which indicates that the change in O3 (i.e. before lockdown to 4th lockdown) was 6.7% in 2019, while − 0.87% in 2020, as shown in Fig. 8.

Carbon Monoxide (CO)

As the major sources of CO, i.e., vehicular incomplete combustion and biomass burning, have reduced due to lockdowns, a decrease in the value of CO is observed in the year 2020, while there was an increase in CO in the year 2019 (Figs. 9, 10). In 2020, a minor increase is seen in the 4th lockdown, as the possible result of the given relaxations. Even though the values at the end of 4th lockdown are higher in 2020 than in 2019, the percentage decrease is higher in 2020 compared to 2019. Change in CO (before lockdown to 4th lockdown) was: − 4.22% in 2019, while − 4.64% in 2020, as shown in Fig. 11.

Air Pollutants from Monitoring Stations

Particulate Matter 2.5 (PM2.5)

Results indicate that the lockdown positively reduced the PM 2.5 values across all four cities (Figs. 12, 13, 14, 15). Before the lockdown, the value of PM2.5 was recorded highest for Delhi, while Bengaluru had the lowest value. Till the 2nd lockdown, the values for PM2.5 for all cities

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have drastically decreased. After the 2nd lockdown, the values in Mumbai, Delhi and Bengaluru have increased at a slower pace compared to Delhi. At the end of 4th lockdown, Delhi still had the highest value, while Kolkata had the lowest value. The percentage change between before and after 4th lockdown scenario for the four cities indicates that Kolkata had the highest reduction (by $-83\%$), followed by reductions in Mumbai, Delhi and Bengaluru with $-55\%$, $-47\%$ and $-39\%$, respectively (Fig. 16).

### Particulate Matter 10 (PM10)

Before the lockdown, the value of PM10 was recorded highest for Delhi, while Kolkata had the lowest value (Figs. 17, 18, 19, 20). Results indicate that, up to the 2nd lockdown, the values for PM10 for all cities have decreased, with varying rates. After the 2nd lockdown, the value in Mumbai and Delhi increased, while in Kolkata and Bengaluru, it decreased at a slower pace. The percentage change between before and after 4th lockdown scenario for the four cities indicates that Kolkata had the highest reduction (by $-81\%$), followed by reductions in Mumbai, Bengaluru and Delhi with $-63\%$, $-50\%$ and $-13\%$, respectively (Fig. 21).

The overall results from the remote sensing-based estimates and observation data indicate that the lockdown scenarios have reduced air pollution parameters and have brought the values down to favorable and healthy limits in many regions. The results from this current study also match with other studies that analyzed different periods of lockdown in India (e.g., Kumari & Toshniwal, 2020; Mahato et al., 2020; Singh & Chauhan, 2020; Vadrevu et al., 2020). However, certain comparisons do exist, for which Table 2 is produced below to discuss the key find-
ings from similar studies, and how the current study differed in methods and results.

Conclusion

For most of the air pollutants, the corresponding values of the pollutants at their hotspots or major cities for the 4th lockdown are decreasing compared to before lockdown values. The COVID-19 lockdown scenarios can provide valuable insights to the authorities on polluting agents and options to choose environment-friendly alternatives. The shift between lockdowns also showed how emissions and pollutants can resurface to pre-lockdown levels. Such learnings can aid in implementing intermittent measures to curb pollution and also to understand the rate of increase. While it was out of scope in the current study, future studies should assess the economic costs of such lockdowns and weigh the pros and cons to understand if such temporary lockdown scenarios can aid in reducing air pollution. Globally, many countries do practices off day traffic and encourage carpooling or public transport to curb air pollution. A nation’s growth needs to be sustainable and
needs the participation of all its citizens, and such pollution reducing activities can aid sustainable growth. This study shows that air pollutants can be curbed, and the public should be more aware and use alternative measures for maintaining good air quality.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12524-022-01619-3.

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Data Availability All data used for this research are collected from open source platforms from the mentioned links.

Declarations

Conflict of interest The authors declare no conflict of interest.

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Table 2 Comparison with various research papers and difference in our study

| Sr. no | Paper title | Author’s name | Key findings/methods | Difference in this current study |
|--------|-------------|---------------|----------------------|---------------------------------|
| 1      | Enchanted Improvements in Air Quality across India—A Study from COVID-19 Lockdown Perspective | Kannamani Ramasamy, Dr. Jayakumar S., Dr. Somasundaram M. (Kumari & Toshniwal, 2020) | Based on study conducted in five major cities—Delhi, Bangalore, Mumbai, Chennai and Kolkata, it was observed that there is a reduction in AQI levels from minimum 42% to the extent of 66% which is under the acceptable to satisfactory category leads to the comfortable living of human beings | In the current study rather than directly using the AQI (Air Quality Index), which provides information only related to the quality of air, here the concentrations of each pollutant are taken for analysis and change detection is performed. Rather than comparing the air quality change only in major cities, here even the hotspot regions where drastic changes are observed are also taken into consideration. |
| 2      | Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India | Susanta Mahato, Swades Pal, Krishna Gopal Ghosh (Ramasamy, 2020) | Seven pollutant parameters (PM10, PM2.5, SO2, NO2, CO, O3 and NH3) for 34 ground monitoring stations spread over the megacity were employed to assess National Air Quality Index (NAQI) to show the spatial pattern of air quality in pre- and during-lockdown phases | The time interval taken into consideration is till 14th of April, i.e., till 1st lockdown, whereas as this current study has incorporated all the four lockdowns. Apart from limiting the research boundaries to Delhi, the paper uses NAQI value which only provides qualitative change detection, whereas this current study used the exact concentration. |
| 3      | Impact of lockdown on air quality in India during COVID-19 pandemic | Ramesh P. Singh, Akshansha Chauhan (Mahato et al., 2020) | The aim of this paper is to study the impact of a complete lockdown in India on air quality (PM2.5, AQI, and NO2) during COVID-19 by comparing air quality parameters during March 2019 and 2020 | All the other major air pollutants like PM10, SO2, CO and O3 are also included. The study is limited to March 2020 only, whereas this study has a longer timeseries to understand the complete picture. |
| 4      | Impact of lockdown measures during COVID-19 on air quality—A case study of India | Pratima Kumari, Durga Toshniwal (Singh & Chauhan, 2020) | To study the impact of lockdown on air quality by comparing the data of PM10, PM2.5, NO2, SO2 and O3 from three different Indian cities, i.e., Delhi, Mumbai and Singrauli located in northern, western and eastern Indian regions, respectively for the first lockdown period | The study limited to 15th April, i.e., 1st lockdown. In the study, only ground monitoring is used, whereas this current study used satellite data as well. This study also included Bengaluru, Kolkata and other hotspots as well, apart from Delhi, Mumbai and Singrauli. |
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