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Revisiting air quality during lockdown persuaded by second surge of COVID-19 of megacity Delhi, India

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ABSTRACT

Is the impact of city-scale lockdown in response to 2nd surge of COVID-19, behavioural changes in people owing to yearlong cohabitation with COVID-19, and partial vaccination on air quality different from the impact of nationwide lockdown during COVID-19's 1st surge in March 2020? Targeting this objective, the present work has selected four phases pre-lockdown and lockdown of 1st and 2nd cycles of lockdown taking average air quality index (NAQI) from Central Pollution Control Board (CPCB). The results clearly show that both the nationwide lockdown and the city-scale restriction are responsible for improving air quality in India's megacity Delhi, but the rate of improvement was higher (39%) during the first cycle of lockdown (nationwide) than during the second cycle of lockdown (city-scale). During city-scale lockdown, the disparity in NAQI between the core and the periphery is obvious. Due to the effect of economic activities surrounding Delhi, around 10 km of the city's interior has experienced high NAQI. The reason for the lower NAQI improvement during the second lockdown cycle is likely due to relief from initial fear following a year of cohabitation with COVID-19, partial vaccination, and partial relaxation in industrial sectors to avoid the economic hardships experienced during the first lockdown cycle.

1. Introduction

The world has faced the biggest catastrophe since World War II (World Health Organization, 2020), with the appearance of the first COVID-19 case in December of 2019 (Andrews et al., 2020; Ferdous et al., 2020). Not only did the virus spread to practically every country and continent on the planet (Jiang et al., 2020; Alah et al., 2020; Ghislain et al., 2021), but it also afflicted over 100 million people, with over 2 million deaths till now. Following an assessment of the situation, the World Health Organization (WHO) decided to designate the outbreak a worldwide pandemic (Cucinotta and Vanelli, 2020). COVID-19 has had a significant impact on the global economy, in addition to influencing people's everyday lives all around the world (Brodeur et al., 2020). The economic effect was significant in contrast to recent periods due to severe restrictions put on public health efforts aimed at containing the spread (Prem et al., 2020; Fong et al., 2020; Johns Hopkins University, 2020). Due to the effectiveness of strict social distancing norms (Keskinocak et al., 2020; Singh et al., 2020) in halting exponential growth and reducing pressure on the medical response (Dong et al., 2020), countries all over the world closed down large mass gatherings such as offices, schools, community centres, and places of business, as well as stern lockdown measures with only allowances for essential travel.

COVID-19 outbreaks in India have been linked to severely polluted megacities such as Mumbai and Delhi since 2020 (Yadav et al., 2020).
The outbreak of this previously unknown sickness, which had no known treatment or therapy, had forced the world to go into lockdown at various times depending on the severity of the situation in the affected countries. India was likewise put under lockdown from the 25th of March to the 31st of May 2020 in order to combat COVID-19 infection. People around the world are terrified by the rapidly increasing illness and death toll. The lockdown was a huge success as a result of this in terms of arresting the outbreak. 

To make it work, the world had to deal with severe economic crisis, chronic hunger, massive unemployment, and a slew of other issues (Rasul et al., 2021; Berkowitz and Basu, 2021), all of which the world is still dealing with (Kassa and Grace, 2020). Despite the economic downturn, there was one positive outcome in terms of air quality (Das et al., 2021; Mahato et al., 2021), water quality improvement (Khan et al., 2021; Chakraborty et al., 2021). According to Mahato et al. (2020), the air quality index (NAQI) in Delhi improved significantly during the nationwide lockdown, and particulate matter (PM) concentrations decreased significantly across the megacity. The impact of the lockdown, which was executed in every corner of India, was felt everywhere. Long days of such illnesses have not only claimed the lives of 211,839 people as of April 30th, 2021, but have also weakened the individual and national economies (Pai et al., 2020; Kumari and Toshniwal, 2020; Kharshiing et al., 2021; Uddin et al., 2021). Infection rate and death rates decreased significantly over time, encouraging people to live a quasi-normal existence in the name of new normality. However, 

Fig. 1. Administrative unit and air quality monitoring stations of NCT-Delhi; timeline of 1st and 2nd surge of COVID-19 pandemic.
COVID-19’s second wave swept around the globe, including India. In this second COVID spike, Mumbai and Delhi have emerged as India’s most severely afflicted cities. According to the Government of India’s report (https://www.mygov.in/covid-19) dated 30th April, 2021, India’s daily infection count is 4,01,993. On the same day, the rate in Delhi is 27,047. The Delhi government has imposed a city-wide lockdown in order to prevent this. To avoid the economic hardships that citizens encountered during the first cycle of lockdown, a nationwide lockdown has yet to be enacted.

A large number of studies have already been conducted focusing on the effect of lockdown induced by COVID-19, which was attacked for the first time in the world (Querol et al., 2021; Briz et al., 2021; Ju et al., 2021; Gupta et al., 2021). When it struck in 2020, there was no known medicine or vaccination for the disease, so people were terrified, and lockdown rules were strictly obeyed. It was made possible by the government’s efforts and the people’s fear. However, during the second surge of COVID-19 in 2021, when people have become more accustomed to the situation and vaccination has begun in some parts of the world, is the lockdown equally successful and is the effect of it equally reflected on air quality in the mega city where lockdown has been implemented? Furthermore, lockdown has not been adopted for entire India during second surge of COVID-19. It has been adopted in a few isolated megacities, such as India’s capital city Delhi. Is the effect of such city scale lockdown on air quality the same as it was during nationwide lockdown amid the first surge of COVID-19? In light of these two key issues, the current study looked into the impact of city-scale lockdown on air quality in Delhi after a year of cohabitation with COVID-19.

2. Study area and its lockdown scenario

The National Capital Territory (NCT) of Delhi, which covers an area of 1484 km², was chosen for this study. Population of Delhi after Census of India, 2011 is the largest urban agglomeration in India, with 1.68 crores of people and a high population density (11,297 persons/km²). In this region, a semi-arid climate prevails, with strong wet and dry spells, as well as hot and cold spells, occurring in four distinct seasons: (1) pre-monsoon/summer season (March to May), (2) monsoon season (June to September), (3) post-monsoon season (October to November), and (4) winter season (December to February). The region’s average annual rainfall is 617 mm, with monsoon months accounting for about 80% of that (Perrino et al., 2011). During the summer season, the average maximum temperature ranges between 30° and 40° C, and during the winter season, it ranges between 4° and 10° C. Fog and smog pollution are common in this region during the winter months, and they create a significant barrier to normal economic activities. Because the region is ranked as the world’s most polluted city and India’s most polluted city, it attracts attention when it comes to dealing with urban air pollution. When the topic of improving air quality for any incident arises, the name of this city comes to mind almost immediately. Mahato et al. (2020) published a study on the improvement of air quality as a result of the COVID-19 disease lockdown. The authors attempted to revisit the air pollution state in the newly imposed lockdown when the region was once again caught by the same problem and city scale lockdown was implemented instead of nationwide lockdown as was previously. The city-wide lockdown in 2nd surge of COVID-19 began on 20th April, 2021. This lockdown does not have the same characteristics as the nationwide lockdown during 1st surge of COVID-19 that began on March 24, 2020. There was no lockdown beyond the NCT boundary at recent time, and industrial sectors continue to operate even when the lockdown was in effect. Fig. 1 depicts the present study area, which includes 34 CPCB operational air quality monitoring stations from which data was obtained. There are 39 CPCB monitoring sites in Delhi, but five of them are either inactive or have insufficient data. The remaining 34 contain data for the whole study period.

3. Materials and methods

3.1. Materials

NAQI and data related to seven parameters constituting NAQI (Sulphur Dioxide (SO₂), Carbon Monoxide (CO), Nitrogen Dioxide (NO₂), Ozone (O₃), Ammonia (NH₃), Particulate Matters (PM₂.₅), Particulate Matters (PM₁₀)) have been collected from Central Pollution Control Board (CPCB) web portal (https://app.cpcbccr.com/ccr/#/ caaqm-dashboard-all/ccaqm-landing) in four phases like (1) pre-lockdown during 1st wave of COVID-19, 2020 (2) post-lockdown during 1st wave of COVID-19, 2020 (3) pre-lockdown during 2nd wave of COVID-19, 2021 (4) post-lockdown during 2nd wave of COVID-19, 2021. In every phase, daily data of consecutive seven days was collected and averaged in order to avoid randomness in result for all 34 pollution monitoring stations separately and based on which analysis and mapping were done. i. For computing NAQI, daily NAQI of the considered seven days at each phase was averaged separately. Quality assurance and quality control (QAQC) is very necessary to avoid the effect of abnormal values. CBCB on principle, maintain the quality of data before dissemination. Moreover, we carried out outlier analysis of each pollutant data for deleting any odd data. However, we did not find any such odd value in our considered data set for each pollutant. Kriging interpolation was used to create all of the maps. It was critical to examine the result of uncertainty (Drobinski et al., 2016; Pellecione et al., 2018). As a result, the class of uncertainty 25–50% covered the majority of the territory (Supplementary Table 5). It was discovered that there was a steady decline in the pre-lockdown stages of both cycles. Regional areas with a decent coverage of monitoring stations are included in this class of uncertainty. Only a small percentage of the region was classified as high uncertainty (50–75%). The highest uncertainties (>75%) were seen at the region’s borders, whereas the lowest uncertainties (0–25%) were observed surrounding the air pollution monitoring station.

3.2. Methods for national air quality index (NAQI) in 1st and 2nd surge of lockdown

National air quality index (NAQI) of CPCB (https://cpcb.nic.in/National-Air-Quality-Index/) has been adopted for computing air
quality. CPCB has defined the permissible limits for all the pollutant parameters (PM$_{10}$, PM$_{2.5}$, SO$_2$, NO$_2$, CO, O$_3$, NH$_3$) (Supplementary Table 1) and forwarded six NAQI classes (good to severe) and associated health impact state (Supplementary Table 2). Here it is to be mentioned that CBCB has also forwarded different parameters-based subclasses and related health state (Supplementary Table 2). Detail method of NAQI computation is given in supplementary section. The NAQI has been calculated using PM$_{10}$, PM$_{2.5}$, NO$_2$, SO$_2$, CO, O$_3$.

### 3.3. Identifying direction and degree of NAQI change

The estimation of trend value in linear regression was done as a function of intercept ($\alpha$) and slope or trend rate ($\beta$) (Mudelsee., 2018), which is written as follows: (Eq. (1)). This method was used to examine the NAQI trend at each monitoring site. In order to determine the direction and degree of NAQI change over time, the intercept and coefficient of determination ($R^2$) were computed, and maps were made accordingly.

\[ Y = \alpha + \beta X \]  

(1)

$X$ denotes the passage of time, while $Y$ denotes the intensity of each measuring station's NAQI value. Eqs. (2) and (3) were used to calculate $\alpha$ and $\beta$ respectively.

\[ \alpha = Y - \beta X \]  

(2)

\[ \beta = \frac{\sum X Y - \frac{\sum X \sum Y}{n}}{\sum X^2 - \frac{\left(\sum X\right)^2}{n}} \]  

(3)

Where, $n$ is number of observation.

The coefficient of determination, or $R^2$, is another important measure in a trend line analysis. It indicates the degree to which variations in NAQI can be explained by time and is expressed as the ratio of Explained Sum of Square (ESS) to Total Sum of Square (TSS) (Eq. (4)), both of which were calculated using Eqs. (5) and (6).

\[ R^2 = \frac{\text{Explained Sum of Square (ESS)}}{\text{Total Sum of Square (TSS)}} \]  

(4)

\[ ESS = \beta \left( \sum X Y - \frac{\sum X \sum Y}{n} \right) \]  

(5)

\[ TSS = \sum Y^2 - \frac{\left(\sum Y\right)^2}{n} \]  

(6)

### 3.4. Analyzing instability of NAQI

The fluctuation of continuous events or time series data, such as pollution records, can be estimated using instability measures. Any pollution-controlling strategy can result in a considerable shift in the pollutant flow regime, which may be recognised via stability analysis. Because it considers both internal variability and degree of trend, the Instability Index (IX) is an effective tool for quantifying pollution data instability. This approach was used to detect dynamic in pollution levels caused by lockout because of its inherent capability of expressing both internal variability and trend. In Eq. (7), Cuddy and Valle (1978) created the instability index (IX).

\[ IX = CV \times \frac{1 - R^2}{\sqrt{R^2}} \]  

(7)

$CV$ (%) = (standard deviation/mean)*100 of selected time series NAQI, where IX is Instability Index, $R^2$ is coefficient of determination, and $CV$ is Coefficient of Variation. Instability is reduced when the IX value is low, and vice versa.

### 3.5. Consistency of NAQI

During the first and second waves of the COVID-19 outbreak, consistency analysis was conducted using the diurnal frequency of high and low pollution levels at each pollution monitoring station in the study region, both before and after the lockdown. NAQI consistency is calculated using Eq. (8). In this section, the number of dates with NAQI above a certain threshold is calculated and expressed as a percentage in each phase. To implement it in a software environment, the daily NAQI map of a specific phase was first converted into a binary map, with 1 assigned to the class whose consistency is being assessed and 0 to the other classes. All of a phase's seven binary maps have been combined and expressed as a percentage.

\[ PPFL = \frac{\sum x_i}{n} \times 100 \]  

(8)

$PPFL$ represents Pollution Presence Frequency at an assumed level; $x_i$ means number of observed days and $n$ refers total number of days taken for analysis.
3.6. Analysis of the pattern of NAQI hot and cold spot

The clustering of high and low NAQI at a spatial scale is referred to as a hot spot and a cool spot. Hot and cold spot here means the statistically significant clustering of high (hot spot) and low (cold spot) NAQI values. For evaluating the pattern of hot and cold spots, Getis-Ord or Gi statistics are often utilized. The methods for deriving it are shown in Eq. (9). In this context, the Z and P values can be used to determine whether a region is statistically significant as a hot or cool area. At the 0.05 and 0.01 level of significance, Z values between 1.96 and 2.58 demonstrate that the data is statistically significant (Table 1). This research unit’s hot and cold spots are calculated using a geostatistical technique in an Arc GIS environment. The optimized hot spot analysis is regarded an efficient suitable analysis scale. It also adjusts multiple testing, false discovery rate (FDR), and spatial dependence automatically, which is quite convenient. Both approaches are used to calculate NAQI, and the optimum approach is determined by cross-referencing the results with the original data. A hot spot analysis of the remaining pollution components was conducted based on this.

\[
G_i = \sum_{j=1}^{n} wijx_j - \frac{\sum_{j=1}^{n} wijx_j - \bar{x} \sum_{j=1}^{n} wij}{\sqrt{\left(\frac{\sum_{j=1}^{n} x_j^2 - (\sum_{j=1}^{n} x_j)^2}{n}\right)^3}}
\]

Where, \(X_j\) is the attribute value for feature \(j\), \(wij\) is the spatial weight between all pair of feature/pollution monitoring sites \(i\) and \(j\), \(n\) is equal to the total number of features, \(\bar{x}\) bar is the mean of all measurements and \(s\) is the standard deviation of all such measurement.

\[
\bar{x} = \sum_{j=1}^{n} x_j
\]

\[
s = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{x})^2}
\]

4. Results

4.1. NAQI in 1st and 2nd cycle of lockdown

Fig. 2 depicts the NAQI of the megacity of Delhi in four phases during the pre- and post-lockdown phases of the COVID-19 outbreak’s first and second waves. During pre-lockdown period, all the monitoring stations recorded NAQI above 100 which were reduced to below 100 in all the stations after 1st lockdown, 2020 showing by 64% improvement in AQI. NAQI was dropped from 166.50 to 59.64 on an average. After withdrawal of lockdown, on May 31, 2020, air quality begun to deteriorate and reverted to its previous poor quality status. In the second phase of the city scale lockdown in Delhi, the NAQI has improved by 25% compared to the pre-lockdown situation. NAQI dropped from 240.18 to 173.08 on an average (Fig. 3). All parts of the study region had NAQI levels above 100 prior to the 2nd wave of COVID-19 outbreak’s lockdown, and no areas had NAQI levels below 100 after the lockdown. Pre-lockdown, 79.77% of the area had a NAQI of 201 (poor condition), but after city scale lockdown, 80.18% of the area had a NAQI of less than 201 but greater than 100 (moderately polluted condition) (Supplementary Table 3). This rate of improvement, however, is not as good as it was during COVID-19’s first wave of lockdown. In reference to the NAQI constituent parameters, significant drop was identified in both the lockdown periods but its rate of drop was less during lockdown 2021. In case of particulate matter (PM10 and PM2.5), the significant rise of such PM concentration was recorded immediate after four days after announcing 2nd phase lockdown. Trend of these graph was highly matched with NAQI (Fig. 3) and it signifies that particulate matter was the major determinant of air quality.

4.2. Spatio-temporal variability and trend of NAQI

The spatial variability of NAQI in different phases was calculated in Fig. 2, using the coefficient of variation (CV). CV is clearly higher during lockdown periods in comparison to pre-lockdown situations, as shown in the diagram. The average CV during the first and second lockdown cycles were found to be 22.76% and 36.48%, respectively. In terms of time series NAQI change, regression slope (b) was found to be negative in most of the monitoring stations during the first phase of lockdown, but this changed dramatically during the second cycle due to the unlocking of some economic sectors. The computed index of instability (ix) of the NAQI was also statistically significant (Z and P values) of the computed Gi.

Table 1

| Statistical significance (Z and P values) of the computed Gi. |
|---------------------------------------------------------------|
| z-score (Standard Deviations) | p-value (Probability) | Confidence level | Null hypothesis |
| < -1.65 or > +1.65 | < 0.10 | 90% | Accepted |
| < -1.96 or > +1.96 | < 0.05 | 95% | Rejected |
| < -2.58 or > +2.58 | < 0.01 | 99% | Rejected |
high in both the lockdown phases, however higher during second cycle, keeping parity with the coefficient of variation and coefficient of determination.

During 2nd cycle core periphery divide of pollution concentration was quite clear. In this area, about 10 km of the periphery are prone to such high levels of pollution, indicating the effect of the surrounding states' unlocking situations. There was no such strong core-periphery NAQI divide in the first lockdown cycle.
4.3. Condition of the individual pollutant

Fig. 4a-4t depicts the spatial status of individual pollutant components collected for analysis over various time periods. In the first and second cycles of lockdown, for example, PM$_{2.5}$ concentration was reduced by 54.43% and 32% respectively; PM$_{10}$ was by 61.53% and 48%, CO level by 32% and 27%, NO$_2$ level by 58% and 41%, and SO$_2$ by 28% and 15%. All of these changes signify that the air quality improvement was more during nationwide lockdown than city scale lockdown. However, due to a temporary reduction in O$_3$ erosive emissions, the concentration of O$_3$ was increased by 25% and 18.12%, respectively 1st and 2nd cycles (Fig. 3).
4.4. Land use specific degree of dispersions

Fig. 5 depicts a box plot of the median, quartile deviation (1st and 3rd), inter quartile range (IQR), maximum, lowest, upper and lower Whisker, and other parameters of NAQI and constituent pollutants in lockdowns in 2020 and 2021. In comparison to the situation of 1st phase lockdown, the median NAQI, related other pollutants, and degree of dispersions of those components were significantly higher in 2nd phase lockdown in industrial, residential, and commercial regions. This is due to a city-wide lockdown and the partial easing of some industrial activities. This situation is very similar to various unlock periods of the first phase shutdown in India (Das et al., 2021). If the spatial disparity between residential, commercial, and industrial areas is rated regionally, the industrial and commercial areas are considered to be the worst. Based on their source control, NO$\textsubscript{2}$, CO dispersion was found extremely high in commercial areas, PM$\textsubscript{2.5}$, PM$\textsubscript{10}$, SO$\textsubscript{2}$ level and dispersion were found extremely high in industrial regions, and O$_3$ level and dispersion are found to be very high in residential areas.

4.5. Consistency of NAQI

Fig. 6 represents consistent appearance of NAQI below 100 (satisfactory to good) and above 300 (very poor to severe polluted) in pre-lockdown and lockdown periods of both the cycle. In 1st cycle of lockdown, consistency of NAQI below 100 was more prominent and no such monitoring stations were identified where NAQI was above 300. Contrarily, consistency of NAQI above 300 is quite greater in 2nd cycle of lockdown.

4.6. Spatial pattern of NAQI hot and cold spots

Figs. 7 and 8 exhibit the hot and cold spot pattern of the NAQI state in various phases, as well as NAQI constituent factors. It is clear from the analysis that during the pre-lockdown period of the first wave of COVID-19, about 32% of the area in the industry-dominated areas of northwestern Delhi appeared as a hot spot, which was statistically significant at the 0.05 level of significance because the Z value was above 2.58 and the P value was 0.05. There was no cold spot throughout this time. Following the execution of the lockdown, the area under hot spots was reduced to 20% in the same geographical location, and a new cold spot covering 12% area was developed in south eastern Delhi, which is significant at a 95% confidence level (Supplementary Table 4). The optimise hot spot study did not indicate a clear difference in hot spot locations between pre-lockdown and lockdown in 2020, but it did reveal the appearance of a cold spot. In 2021, a cold spot region was identified in the pre-lockdown period across a larger portion of the south eastern section of Delhi (13%), but it was almost vanished during the lockdown time, expanding the area under hot spot. However, during the pre-lockdown period, the gap between high and low NAQI values was wide over the study area. The spatial distribution of PM$\textsubscript{2.5}$, PM$\textsubscript{10}$ hot spots matched that of NAQI hot spots (Fig. 8a, b, c, d), demonstrating that this component of air pollution plays a significant role in regulating NAQI hot spots. In the considered phases, SO$\textsubscript{2}$, CO, and O$_3$, no such hot or cold regions were identified across a larger area.

4.7. Relationship between NAQI and pollutants

The kernel density estimation plot of NAQI and other pollutants in reference to pre and lockdown of 2020 and 2021 were analyzed in Fig. 9. A strong positive correlation between PM$\textsubscript{2.5}$, NO$\textsubscript{2}$; PM$\textsubscript{2.5}$, SO$\textsubscript{2}$; NAQI, PM$\textsubscript{2.5}$; NAQI, PM$\textsubscript{10}$; NAQI, SO$\textsubscript{2}$ was found in pre-lockdown phases in 2020 and 2021 ($r \geq 0.6$) but its strength was found weaker during lockdown phases. However, it was weaker in 1st cycle than 2nd cycle of lockdown. Based on the magnitude of correlation between NAQI and other pollutants, it can be inferred that PM$\textsubscript{10}$ and PM$\textsubscript{2.5}$ play the most significant role in polluting the air. A negative relation is found between NAQI and O$_3$ both during pre-lockdown and lockdown phases. But its magnitude was stronger in lockdown phase of 2020 than 2021.

5. Discussion

During the first cycle of lockdown in 2020, nearly all transportation, industrial, and tertiary activities were shut down, and air quality improved dramatically. During the first lockdown cycle, air quality improved by 82%. Administration’s keen attention, public awareness, and public concern about the undedicated COVID-19 disease The first lockdown was a huge success, with a noticeable impact on air quality in this city (Mahato et al., 2020; Sharma et al., 2020; Navinya et al., 2020) and other parts of the world (Magazzino et al., 2021), Mexico City (López-Feldman et al., 2021), Lima (Velásquez and Lara, 2020), Dhaka (Rahman et al., 2021), 11 Spanish cities (Briz et al., 2021), different Chinese cities (Zhang et al., 2020), Paris, Lyon, and Marseille (Magazzino et al., 2020), etc. The magnitude of NAQI improvement was not uniform around the world, but there was a positive trend. However, the air quality improvement in the second cycle of lockdown, which was prompted by the second surge of COVID-19 in the world in general and India’s capital city Delhi in particular, is not as uniform as it was in the first cycle. Vaccination in Delhi, as well as long days of cohabitation with COVID-19, has helped to alleviate people’s fears. This effect is visible in the study unit’s NAQI. Furthermore, because the surrounding areas of Delhi did not experience lockdown during this time period, free air turbulence and mixing is partly to blame for the air quality not improving to the expected level as it did during the first lockdown cycle. The air quality improved by 22.46% in
2020

PM_{10} (100 \text{ mg/m}^3)

PM_{2.5} (60 \text{ mg/m}^3)

NO_{2} (80 \text{ mg/m}^3)

SO_{2} (80 \text{ mg/m}^3)

CO (2 \text{ mg/m}^3)

O_3 (100 \text{ mg/m}^3)

2021

(caption on next page)
the second lockdown cycle when compared to the NAQI just before the lockdown was announced. This difference in NAQI improvement between the first and second lockdown cycles could be attributed to the isolated lockdown and people's behaviour.

Fig. 5. Box plots shows the median of NAQI and constituting pollutant components, their degree of dispersions in residential, commercial and industrial areas in pre-lockdown and lockdown periods of 1st and 2nd phase of lockdown in 2020 and 2021.

Fig. 6. Consistent appearance of NAQI below 100 (satisfactory to good) and above 300 (very poor to severe polluted) in pre-lockdown and lockdown periods of both the cycle.

Fig. 7. Getis-ord hotspot and Optimized NAQI hotspot of pre-lockdown and lockdown in persuasion of 1st and 2nd wave of COVID-19 outbreak.
following large-scale vaccination and a year of cohabitation with the disease. One could argue that the difference in NAQI could be due to other meteorological functions, particularly rainfall. To avoid ambiguity, we sleeted those consecutive seven days when there was no rainfall within this period and no rainfall in the five days prior to this period.

Normally, NCT Delhi has a low SO$_2$ concentration due to its very interior location within the Indian subcontinent, far from the sea, where the major pollutant originates from cruise ships, large cargo ships, and ferries (Mahato et al., 2020). Even before lockdown, it results in a low SO$_2$ concentration. After lockdown in the first cycle, there was a slight decrease in SO$_2$ levels, but in the second cycle, it was almost unchanged. Because agriculture is the primary source of NH$_3$ and Delhi is dominated by the non-agricultural sector, its level is typically low. During lockdown phases, however, there is a noticeable difference due to the absence of NH$_3$ from non-
agricultural sources. Due to the complete and partial lockdown of the Chloro-Fluro-Carbon (CFC) sources, the $O_3$ concentration in the air was increased during both the phases of lockdown. Due to restrictions in the public and private transportation sectors, CO level was improved during lockdown. Due to the relaxation of some specific transport activities, the rate of improvement was lower in the second cycle of lockdown.

Fig. 10. Status of NAQI and concentration of PM$_{2.5}$ from January 2020 to April 2020 of Delhi.
Significant reductions in air pollution in India during the COVID-19 lockdown are primarily due to a reduction in major anthropogenic activities such as vehicles, industries, and other fugitive sources such as household cooking, emissions from local industries, food eateries (street food vendors, semi-open cooking in restaurants), and other non-exhaust emissions. Intermittent rain events were also seen throughout the lockdown in several regions of India; hence meteorology played an essential role in emission reduction during the lockdown. Sharma et al. (2020) also said that the weather conditions were good during the lockdown; otherwise, PM$_{2.5}$ levels were expected to be approximately. Sharma et al. (2020) also experienced the weather conditions were favourable during the lockdown; otherwise, projected PM$_{2.5}$ levels might be roughly 33% higher than those seen during the lockdown. As previously stated, the proportion of sources to total PM$_{2.5}$ emissions varies by city owing to traffic congestion, industrial activity, and population lifestyle. PM$_{10}$ and PM$_{2.5}$ concentrations in metropolitan areas are heavily influenced by local meteorological and local emission sources such as transportation. According to the TERI report (2018), PM$_{10}$ and PM$_{2.5}$ emissions in Delhi are mainly accounted for by transportation (38.70%); all dust contributes 26.50%, 8.7% of residences are shared, 14.30% comes from the industrial sector, and 3.70% from waste burning. The majority of industrial emissions, exhaust and non-exhaust, all construction and demolition emissions, and waste burning emissions were all prohibited during the first lockdown cycle. Though industrial sectors are not restricted during the second cycle, PM$_{2.5}$ concentrations are not reduced as they are during the first cycle.

From January 2020 to April 2021, Fig. 10 displays the status of NAQI and PM$_{2.5}$ concentrations (24 h). Both the NAQI and PM$_{2.5}$ concentrations decline in 2020 during the first cycle of lockdown (last week of March) and continued to fall until the lockdown was ended (31st May 2020). However, because of the monsoon rainfall, the low concentration was further dropped to extremely low level (till first week of September). Following that, because of the excessive stubble burning in Punjab and Haryana, the AQI and PM$_{2.5}$ concentrations continued to rise. Stubble burning severely harmed Delhi's air quality during this season for years (Jain et al., 2014; Singh et al., 2018; Kulkarni et al., 2020; Beig et al., 2020; Laskar et al., 2020; Sahu et al., 2021).

The difference in NAQI between the city's core and perimeter explains the effects of lockdown within the city and the unlock scenario in its surrounding territories. Because the neighbouring areas' economic activities were ongoing, admixing of air pollutants from those places polluted the air in the study area's periphery. The northwestern area of the study region is densely populated with industrial regions were more prone to high PM$_{2.5}$ concentrations and NAQI state, followed by the commercial and residential sectors. Kaushik et al. (2006), Kumar et al. (2010), Mathew et al. (2015), Shaistingu et al. (2018), Mihankhah et al. (2020) reported similar results. This is primarily due to high level of pollution emitted by the companies. In the first lockout cycle, the NAQI improvement rate in industrial regions was significantly higher than in residential areas. The same trend of results was detected due to partial relaxation in industrial sectors in the second cycle of lockdown. During the pre-lockdown phases of the first and second cycles of lockdown, respectively, 21.75% and 38.91% of the region had persistently high NAQI. In the second cycle’s lockdown phase, 31.38% of locations recoded high NAQI owing to industrial pollutants.

6. Conclusion

The study revealed that the effect of NAQI improvement after the first lockdown was 39% greater than after the second lockdown cycle. The NAQI level was higher in the outside of the city than in the interior, owing to the effect of the city-wide lockdown. The northwestern half of the study region dominated by industry, was identified as statistically significant hot spots in all the stages. The impact of a nationwide lockdown was greater than that of a city scale lockdown. Population behaved relatively freely even during tough COVID situations after a yearlong cohabitation with this COVID-19 disease, immunization among the people, and the removal of initial dread. This type of research is needed in various cities throughout the world to fully understand the impact of isolated regional lockdowns on pollutants level and NAQI state. There is still room for more investigation into the effects of NAQI on people in the second cycle of lockdown. Although climatic elements were not examined in this study, it is clear that precipitation and wind movements are crucial for changing the pollutants level in very small areas. More research incorporating meteorological factors in this area may enable to explain the spatial variability of pollutants. Some studies have previously concluded that lockdown is a lesson in air quality control. However, bad air quality returned after the first lockdown cycle. It indicates that such a lesson has not been successfully applied in this area so far. So, improving technologies that can aid with efficient energy use and lower pollutant yield is one way to decrease pollutants and improve NAQI without affecting economic production. Another option is to pose a greater emphasis on the usage of renewable energy, which can arrest pollution level to some extent. The improvement in air quality during the lockdown also brings up the question of how the people perceive the air quality. There have been several media stories regarding the improvement in air quality in different places, but how it impacts individual behaviours and their contribution to air quality has to be investigated further. During COVID-19, the behavioural component of the public must be tapped in order to engage them in sustainable behaviours and change the momentum to promote air pollution reduction and assure sustainability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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