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A picture of Delhi’s regional air quality during diminished anthropogenic activities in the COVID-19 era

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Abstract
COVID-19 pandemic lockdown was imposed in 2020 and 2021 globally and in India, which created a temporary switch off for various anthropogenic activities, which helped in improving Delhi’s air quality drastically. The present study discusses air pollution reduction during that lockdown period compared to the previous year. The study tries to establish a comparison between various parameters like particulate matter (PM$_{10}$, PM$_{2.5}$), gaseous pollutants (SO$_2$, NO$_2$, CO, O$_3$), and meteorological data (WS, WD, RH, AT, SR) during the year 2019 to 2021. The whole monitoring period is divided into four phases (P-I, P-II, P-III, and P-IV) based on stage-wise lockdown implementation. The data are analyzed using the R Studio version 1.3.1093. The PM$_{10}$ concentration falls to 46.6% and 19.2% in 2020 and 2021, compared to 2019, and 69% increase in 2021 from 2020. PM$_{2.5}$ reduced to 35% and 8.1% in 2020 and 2021, compared to 2019, and a 48% increase in 2021 from 2020. The O$_3$ concentration shows an increment of about 10% in 2020 and a reduction of 5% in 2021, compared to 2019, and 12%, compared to 2020. The SO$_2$ and CO reductions lie in between 20 and 35% in 2020 and 2021, compared to 2019. The NO$_2$ shows around 56% and 32% reduction during 2020 and 2021 compared to 2019 and a 62% increment in 2021 compared to 2020. An absolute lockdown was imposed in 2020, whereas minimal activity or certain restrictions were only imposed in 2021. Such changes in concentration show that anthropogenic sources played a significant role in determining regional air quality in urban areas. The outcomes of the study show the changes that occurred during that period due to phase-wise implementation of lockdown and other unlocking conditions, which may be helpful for policymakers in implementing certain restrictions based on emissions in a planned manner in the future.

Keywords Anthropogenic activities · COVID-19 · Lockdown · Particulate matter · Urban air pollution

Abbreviations

| AT          | Atmospheric temperature |
| AQI         | Air quality index       |
| AY          | Actual year             |
| BC          | Black carbon            |
| BS-IV       | Bharat stage four       |
| BS-VI       | Bharat stage six        |
| BY          | Base year               |
| µg/m$^3$    | Microgram per meter cube|
| CPCB        | Central Pollution Control Board |
| CO          | Carbon monoxide         |
| CoI         | Cost of illness         |
| COVID-19    | Coronavirus disease     |
| DALYs       | Disability-adjusted life years |
| Hrs         | Hours                   |
| ICMR        | Indian Council of Medical Research |
| IDW         | Inverse distance weighting |
| IQAir       | World Air Quality Report |
| mg/m$^3$    | Milligram per meter cube|
| m/s         | Meter per second        |
| NASA        | National Aeronautics and Space Administration |
| NCR         | National Capital Region |
| NCT         | National Capital Territory |
| NH$_3$      | Ammonia                 |
| NO          | Nitric oxide            |
| NO$_x$      | Nitrogen oxide          |
| NO$_2$      | Nitrogen dioxide        |
| O$_3$       | Ozone                   |
| P-I         | Phase I                 |
| P-II        | Phase II                |

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Introduction

Many countries face globally tremendous issues to mitigate the global pandemic COVID-19, and still, many countries are facing the same (Sikarwar and Rani 2020; Li et al. 2020). The new infectious (COVID-19) disease was first identified in Wuhan City of China in December 2019 (Gautam et al. 2021b; He et al. 2020; Srivastava et al. 2020). The World Health Organization (WHO) in January 2020 declared that the virus could be transferred to humans as a droplet infection and declared a health predicament throughout the globe due to this infectious disease (Sarfraz et al. 2020; Bera et al. 2021). In India, the first case was reported on 30 January 2020 in Kerala, a southern state of the country, and it declared an emergency on 4 February 2020 since another case was reported on the fourth consecutive day (Gautam et al. 2021a). Until the 2nd of March 2020, the country had only three reported cases, but the number of human contacts has increased tremendously in April 2020 (Sarfraz et al. 2020). To control this pandemic, many countries have implemented lockdown.

Similarly, in India also, lockdowns were implemented (Bherwani et al. 2020; Dhaka et al. 2020). In Delhi, the state government implemented a night curfew from March 22, 2020 (19:00 Hrs to 07:00 Hrs). Shortly after that, on March 24, a nationwide lockdown was enforced. Phase I of the lockdown was announced for 21 days from March 25 to April 14, 2020. Furthermore, Phase II was implemented from April 14 to May 3, 2020. During this period of Phases I and II, all activities such as commercial, industrial, and transportation activities at all levels came to a pause except the basic amenities such as medical and food. The Oxford COVID-19 Government Response Tracker report stated that India had one of the strictest implementations of lockdown. Phase III of the lockdown was announced nationwide from May 4 to 17, 2020, giving few relaxations such as the operation of essential government services with 50% occupancy. The Phase IV nationwide lockdown was announced on May 17 and extended until May 31, 2020, with relaxations such as the operation of shops and other essential services during the daytime. After that, the country started to give several relaxations based on the infection rate in a particular location and then the lockdown scenarios were slowly reduced stepwise such as Unlock 1, 2, and 3 and the conditions were resuming back to normal with certain restrictions such as maintaining social distancing and other hygiene practices at the places where the crowd is expected and the scenario continues until 2021, but unfortunately in 2021, the second wave of the pandemic hit harder than the first wave in India. Many Indian cities, including Delhi, had experienced the worst situation, and the patients were reported in large numbers. Even the hospitals in urban regions were running out of beds for patients, and oxygen for medical use was in high scarcity. Due to this, the government of Delhi announced another set of week-wise lockdowns starting from 19 April to 31 May 2021. During this period, minimal movement of people and vehicles was observed. Compared to the movement scenario in 2020, it was a little bit higher in 2021. Despite several issues reported due to pandemic such as economy and human health, it was vice versa for pollution related issues. In 2020 several research studies showed a reduction in pollution levels in Delhi, which reflected improved air quality (Karuppasamy et al. 2020; Agarwal et al. 2020; Sikarwar and Rani 2020; Mahato et al. 2020; Hamaa et al. 2020; Srivastava et al. 2020; Kumar et al. 2020). All types of transportation services, including rail, road, air, and all industrial units except essential services, were suspended in 2020, leading to a dramatic reduction in air pollution (Kumari and Tosniwal 2020), but in 2021 there were exceptions given for movement.

The World Urbanization Prospect in 2018 predicted that the megacities of Asia and Africa are about to experience 90% population growth by 2050 (United Nations 2019). Air pollution has become a critical threat to the environment and causes serious threats to human health. About 80% of the people in urban areas are exposed to air pollution exceeding the air quality standard set by the World Health Organization (WHO). As per the World Air Quality (IQAir) (WORLD AIR QUALITY REPORT 2019) report, six major Indian cities with poor air quality were recorded globally. Delhi has consistently been ranked as one of the most polluted cities in developing countries (Sikarwar and Rani 2020). The sources of air pollution in Delhi include power generation, industry, traffic, household activities, pavement dust,
and biomass burning (Bherwani et al. 2020; Venter et al. 2020). Due to poor air quality, a community health emergency was declared in 2017 for Delhi by the Indian Council of Medical Research (ICMR) (Sikarwar and Rani 2020). To tackle this situation, several short-term and long-term measures were taken to improve the air quality. The short-term remedies such as the odd–even scheme were introduced in 2016 and 2019 when the air quality of Delhi worsened and the levels were extremely high compared to the standards. It showed a particular percentage reduction of pollutants in Delhi (Khaiwal et al. 2021; Mishra et al. 2019; Kumar et al. 2021). Long-term measures include policy changes such as conversion from BS-IV to BS-VI, scrapage of older vehicles, and other policy changes. Global studies found that reducing motor vehicle usage positively affects air quality (Higham et al. 2021). Several studies in the year 2020 found a reduction in air pollution globally due to the lockdown scenarios, and in Indian scenarios, it was also the same, especially the national capital experienced good air quality due to the reduced anthropogenic activities. In Delhi, the complex mixture of the different sources of pollutants is the biggest problem, and during that lockdown period, all the different sources were switched off, which helped in improving air quality. The previous studies during the lockdown period (2020 only) showed how much reduction happened due to the lockdown. This study aims to bring out the changes that occurred not only during the lockdown period (2020) but also during limited sources activity (2021) compared with the usual sources scenario (2019). The objectives of the study is to identify the percentage changes that occurred in Delhi due to the lockdown and series of restriction phases and also to compare it with the previous year. The study utilizes around forty locations data to represent the study area which will be quite helpful for the representation. The outcomes of the study can be used as representative data for the study area since it covers data from all the different locations possible. The study provides information in different scenarios of Delhi along with different sources. The changes that occurred will help in future studies of the location in acting as a baseline measurement of less anthropogenic sources and the limitation of the study is that it compared the data during that particular period only when there was a lockdown or restriction. A summary of a few recent research works published based on COVID-19 lockdown and its impacts on the air quality in Indian cities are depicted in supplementary Table S1.

Methodology

The time series data of various primary pollutants and meteorological parameters are taken from the time period of 25 March to 31 May 2020 for 2019, 2020, and 2021. The period is classified into four phases, namely, Phases I, II, III, and IV, which were classified based on the stepwise lockdown implemented by the government of India in the year 2020. The Phase I (P-I) was from 25 March 2020 to 14 April 2020, Phase II (P-II) from 15 April to 3 May 2020, Phase III (P-III) from 4 to 17 May 2020, and Phase IV (P-IV) from 18 to 31 May 2020. The comparison was made for 2019 with 2020 (when there was a strict lockdown), 2020 and 2021 (when there was a restriction but not a strict lockdown), and 2019 and 2021 (from normal period to minimal anthropogenic activities). This analysis presented a clear picture of the air quality in these 3 consecutive years due to the variation in quantity and quality of sources during the different eras of the COVID-19 pandemic. This comparative study helped to see the effect of lockdown/movement on Delhi’s air quality. The data sets are taken from the Central Pollution Control Board (CPCB) open source. The pollutants (PM$_{10}$, PM$_{2.5}$, SO$_2$, NO$_2$, CO, O$_3$) and meteorological parameters (wind speed, wind direction, temperature, relative humidity, and solar radiation) are taken from the CPCB website (https://app.cpcbccr.com/ccr//#/caaqm-dashboard-all/caaqm-landing/data).

Selection of the study area

The national capital of India, Delhi, has been selected to conduct this study. It is selected for this study since Delhi is among the largest megacities globally, the national capital, and the single largest contributor to India’s urban population (about 7.6%). The land cover is about 1485 km$^2$ area with a population distribution of about 16.8 million. In the past two decades, the population density has increased from 9340 people per sq. km in 2001 to 11,297 people per sq. km in 2011, with an increased rate of 37.6% annually (Mahato et al. 2020). A total of 40 operational monitoring stations in NCR and NCT part of Delhi were taken into consideration for this study (Fig. 1). The different sources of the data providers are given in supplementary Table S2. The various locations selected for extracting the data are provided in supplementary Table S3.

Analyses technique

The data are analyzed using the RStudio version 1.3.1093. Hourly average data were taken from 25 March to 31 May for 3 consecutive years, from 2019 to 2021. The temporal variation of the pollutants during the different phases was taken and a comparison was made between the years 2019 and 2020, 2020 and 2021, and 2019 and 2021. The data set has been divided into four different phases (P-I, P-II, P-III, P-IV) based on the
lockdown implementation as per 2020 government guidelines and simultaneously compared with 2019 and 2021. The percentage change has been calculated using the following equation:

$$PC = \frac{AY - BY}{BY} \times 100$$

(1)

where $PC$ is the percentage change that occurred, $AY$ refers to the average concentration of a particular pollutant in the actual year taken for comparison, and $BY$ refers to the average concentration of a particular pollutant in the base year.

Result and discussion

Bar plot for phase-wise percentage change

The bar plot shows the percentage change that transpired during 2020, taking 2019 as a BY and 2020 as the AY (Fig. 2). It is very clear from the bar plot that the concentration of all the parameters is reduced due to the enactment of strict lockdown. Interestingly, the concentration of $O_3$ increased in P-II, P-III, and P-IV compared to the
BY to a maximum concentration of 62.3 µg/m³ with a percentage increment of 37.2% compared to the normal scenario. The O₃ concentration increased during the strict lockdown period, i.e., in 2020. (Naqvi et al. 2021; Gautam et al. 2021b). The particulate matter (PM₁₀) showed a significant percentage reduction (Srivastava et al. 2020) in P-I, P-II, and P-III and less reduction in P-IV, which may be due to the increased anthropogenic activity on account of various relaxation. The minimum concentration of PM₁₀ recorded was 84.1 µg/m³. PM₂.5 concentration followed the same trend as that of PM₁₀ and the minimum recorded concentration was 34.9 µg/m³ with an average reduction of 35% in all four phases. During the lockdown period, the decrease in PM₂.5 concentration was also around 41–53% (Kumar et al. 2020). The declines in SO₂ (Kumari and Toshniwal 2020) and CO concentrations were also seen (Sarfraz et al. 2020; Gautam et al. 2021b; Sikarwar and Rani 2020). The percentage reduction of pollutants was seen high during P-I, P-II, and P-III and less in P-IV (Bherwani et al. 2020; Vadrevu et al. 2020; Hamaa et al. 2020; Khaiwal et al. 2021; Mahato et al. 2020). The phase-wise overall percentage changes are depicted in Table 1. Recent researchers have found that 79% of PM₁₀ emissions originate from Delhi road dust and resuspensions (Kumar et al. 2020).

The concentrations of PM₁₀, PM₂.5, NO₂, SO₂, CO, and O₃ were recorded high in 2021 compared to 2020 in all phases except P-IV because this particular phase (P-IV) may have the same amount of source contribution. In 2020, certain relaxation was given from strict lockdown during P-IV, and in 2021, in all phases, certain restrictions were only announced, and it was not a complete lockdown in the city (Hamaa et al. 2020). In Fig. 3, the percentage change was calculated using Eq. 1, where BY is 2020 and AY is 2021. The percentage change in P-I for parameters PM₁₀, PM₂.5, NO₂, SO₂, CO, and O₃ is 167%, 104.3%, 142.3%, 42.9%, 70%, and 6.8% respectively. Similarly for P-II, it is 109.9%, 106.6%, 92.3%, 28.9%, 26.5%, and -7.2%. The percentage change for other phases can be observed in Table 1.

Figure 4 depicts exciting results that the concentration of PM₁₀, PM₂.5, NO₂, SO₂, CO, and O₃ is reduced except for some exceptional phases like P-II in the year 2021 compared to 2020.

### Table 1 Phase-wise percentage change calculation

| Phase | BY | AY | PM₁₀ (µg/m³) | PM₂.5 (µg/m³) | NO₂ (µg/m³) | SO₂ (µg/m³) | CO (mg/m³) | Ozone (µg/m³) |
|-------|----|----|--------------|---------------|-------------|-------------|-------------|---------------|
| Phase I | 2019 | 2020 | -62.85 | -48.11 | -61.27 | -37.08 | -46.31 | -13.19 |
| | 2020 | 2021 | 167.09 | 104.32 | 142.37 | 42.91 | 70.08 | 6.83 |
| | 2019 | 2021 | -0.78 | 6.01 | -6.12 | -10.08 | -8.69 | -7.26 |
| Phase II | 2019 | 2020 | -50.60 | -34.27 | -61.71 | -29.90 | -34.24 | 2.65 |
| | 2020 | 2021 | 109.91 | 106.15 | 92.31 | 28.91 | 26.56 | -7.28 |
| | 2019 | 2021 | 3.69 | 35.51 | -26.36 | -9.64 | -16.77 | -4.83 |
| Phase III | 2019 | 2020 | -58.11 | -43.61 | -59.83 | -30.43 | -36.55 | 37.29 |
| | 2020 | 2021 | 18.43 | 4.87 | 27.86 | -12.61 | 18.88 | -20.58 |
| | 2019 | 2021 | -50.39 | -40.86 | -48.64 | -39.21 | -24.57 | 9.04 |
| Phase IV | 2019 | 2020 | -15.22 | -14.39 | -41.36 | -8.60 | -19.53 | 14.75 |
| | 2020 | 2021 | -16.76 | -21.98 | -13.86 | -45.54 | -13.88 | -29.65 |
| | 2019 | 2021 | -29.43 | -33.21 | -49.49 | -50.22 | -30.69 | -19.27 |

Fig. 3 Pictorial representation of percentage change occurred in 2021 compared to 2020 for PM₁₀, PM₂.5, SO₂, NO₂, CO, and O₃ in Phases I, II, III, and IV.
with the usual scenario of 2019. The year 2019 was a normal year in which all the activities were functional. In 2021, certain restrictions were amended and the sources were also restricted. But the lockdown implemented in 2021 was not an absolute switch off to all the sources. The minimum concentration of PM$_{10}$ and PM$_{2.5}$ during 2021 was 131 µg/m$^3$ and 45.8 µg/m$^3$, respectively, whereas the maximum was 235.9 µg/m$^3$ and 93.9 µg/m$^3$, accordingly. The maximum concentration reduction for NO$_2$, SO$_2$, CO, and O$_3$ was seen in P-IV in 2021. The gradual phase-wise reduction of NO$_2$, SO$_2$, CO, and O$_3$ can be seen clearly in Fig. 3. Equation 1 has been used for percentage change calculation for BY and AY. The exact figures of the increment or decrement in percentage can be obtained from Table 1. It shows that anthropogenic activities play a significant role in determining the air quality of a particular region (Higham et al. 2021; Venter et al. 2020).

**Temporal representation of concentration in different phases**

The lockdown impact on the hourly mean concentration of PM$_{10}$ was studied for 3 consecutive years from 2019 to 2021. The values of PM$_{10}$ tend to decrease in 2020 and 2021 compared to 2019. The average mean concentration in 2019 was 226.4 ± 81.8 µg/m$^3$ (P-I), 227.5 ± 101.2 µg/m$^3$ (P-II), 292.2 ± 135.6 29 µg/m$^3$ (P-III), and 185.6 ± 77.7 µg/m$^3$ (P-IV), respectively. It reduced to 84.1 ± 38.5 µg/m$^3$, 112.4 ± 52.3 µg/m$^3$, 122.4 ± 52.5 µg/m$^3$, and 157.4 ± 76.1 µg/m$^3$ in 2020, and also similarly, there was an increment in 2021 when compared to 2020, but the concentrations in
both the year 2020 and 2021 are lesser than the concentration recorded in the year 2019, but in the P-III and P-IV of 2021, they show reduction due to gradual implementation of lockdown process during this phase (e.g., the average mean concentration of PM$_{10}$ was $157.4 \pm 76.1$ µg/m$^3$ in P-IV of 2020 but in 2021 it was $131 \pm 147.2$ µg/m$^3$). Figure 5 depicts the daily average concentration of all the parameters, and it shows that in P-III and P-IV, there is a gradual increase in concentration due to stepwise implementation of the unlocking procedure, and the maximum concentration of pollutants was observed during P-IV of 2020.

In P-IV, the concentration decreases to a minimum level in 2021 (Fig. 6). It indicates that the implementation of lockdown during the time in 2021 influenced the pattern of the curve. In Fig. 7, all the four phases, namely, P-I to P-IV, show a lower concentration of pollutants in 2021 compared to 2019. It shows that the year 2019 has no bound for activities, but in 2021, certain limitations in different
sectors, such as weekend curfew restriction and night curfew for movement of people, played a significant role. Less contribution from different sources had a positive contribution to improving the air quality (Nagpure et al. 2013). The phase-wise changes occurred and its hourly mean average is depicted in Table 2. The PM$_{2.5}$ concentration during the monitoring period shows a similar pattern as of PM$_{10}$, and it can be seen in Figs. 5, 6, and 7. The gaseous parameters showed different patterns influenced by various primary and secondary factors, such as the ozone concentration showed

| Phase | Parameter | Year | 2019 | 2020 | 2021 |
|-------|-----------|------|------|------|------|
|       |           | Mean ± SD | Median | Mean ± SD | Median | Mean ± SD | Median |
| Phase I | PM$_{10}$ (µg/m$^3$) | 226.49 ± 81.87 | 209.67 | 84.14 ± 38.50 | 75.07 | 224.73 ± 87.90 | 209.9 |
|       | PM$_{2.5}$ (µg/m$^3$) | 76.92 ± 36.64 | 68.76 | 39.91 ± 20.55 | 32.83 | 81.55 ± 41.35 | 76.62 |
|       | NO$_2$ (µg/m$^3$) | 48.38 ± 17.95 | 45.38 | 18.74 ± 5.89 | 17.31 | 45.42 ± 19.56 | 43.09 |
|       | SO$_2$ (µg/m$^3$) | 21.61 ± 6.85 | 20.65 | 13.59 ± 4.34 | 12.371 | 19.43 ± 8.87 | 17.6 |
|       | CO (mg/m$^3$) | 1.26 ± 0.56 | 1.0682 | 0.67 ± 0.18 | 0.6217 | 1.15 ± 0.51 | 0.9842 |
|       | O$_3$ (µg/m$^3$) | 44.38 ± 32.13 | 28.571 | 38.53 ± 18.09 | 35.753 | 41.16 ± 29.44 | 32.358 |
| Phase II | PM$_{10}$ (µg/m$^3$) | 227.59 ± 101.29 | 232.17 | 112.42 ± 52.33 | 102.86 | 235.98 ± 120.79 | 211.73 |
|       | PM$_{2.5}$ (µg/m$^3$) | 69.31 ± 32.23 | 62.33 | 45.56 ± 23.57 | 38.509 | 93.92 ± 71.26 | 73.58 |
|       | NO$_2$ (µg/m$^3$) | 47.99 ± 21.70 | 41.75 | 18.37 ± 6.87 | 15.54 | 35.34 ± 16.47 | 30.28 |
|       | SO$_2$ (µg/m$^3$) | 21.26 ± 9.20 | 19.102 | 14.90 ± 4.43 | 14.506 | 19.21 ± 10.95 | 15.513 |
|       | CO (mg/m$^3$) | 1.28 ± 0.56 | 1.0913 | 0.84 ± 0.18 | 0.8135 | 1.07 ± 0.46 | 0.9246 |
|       | O$_3$ (µg/m$^3$) | 48.65 ± 32.18 | 38.486 | 49.94 ± 22.38 | 46.79 | 46.30 ± 34.30 | 39.032 |
| Phase III | PM$_{10}$ (µg/m$^3$) | 292.28 ± 135.65 | 274.53 | 122.43 ± 52.57 | 116.78 | 145 ± 62.00 | 134.5 |
|       | PM$_{2.5}$ (µg/m$^3$) | 98.22 ± 48.61 | 85.34 | 55.39 ± 28.96 | 50.67 | 58.09 ± 11.54 | 54.49 |
|       | NO$_2$ (µg/m$^3$) | 52.02 ± 23.95 | 44.8 | 20.9 ± 7.46 | 18.26 | 26.72 ± 23.96 | 23.45 |
|       | SO$_2$ (µg/m$^3$) | 20.75 ± 10.99 | 17.789 | 14.44 ± 4.13 | 13.365 | 12.61 ± 3.43 | 12.103 |
|       | CO (mg/m$^3$) | 1.36 ± 0.68 | 1.0828 | 0.86 ± 0.17 | 0.8389 | 1.03 ± 0.26 | 0.9668 |
|       | O$_3$ (µg/m$^3$) | 45.38 ± 32.34 | 33.598 | 62.31 ± 28.27 | 60.16 | 49.49 ± 28.39 | 40.44 |
| Phase IV | PM$_{10}$ (µg/m$^3$) | 185.67 ± 77.79 | 173.51 | 157.4 ± 76.17 | 160 | 131.02 ± 147.26 | 99.18 |
|       | PM$_{2.5}$ (µg/m$^3$) | 68.7 ± 30.24 | 65.4 | 58.82 ± 39.20 | 43.982 | 45.88 ± 46.70 | 34.257 |
|       | NO$_2$ (µg/m$^3$) | 51.06 ± 22.73 | 46.93 | 29.94 ± 15.19 | 23.59 | 25.79 ± 12.40 | 21.843 |
|       | SO$_2$ (µg/m$^3$) | 18.25 ± 7.72 | 16.729 | 16.69 ± 8.11 | 14.03 | 9.08 ± 2.00 | 8.467 |
|       | CO (mg/m$^3$) | 1.261 ± 0.50 | 1.1482 | 1.01 ± 0.32 | 0.9172 | 0.87 ± 0.30 | 0.7859 |
|       | O$_3$ (µg/m$^3$) | 47.33 ± 36.51 | 32.104 | 54.31 ± 29.16 | 50.363 | 38.21 ± 22.49 | 32.231 |
an inverse pattern during the year 2020. It may be due to the photochemical reactions of NOx and VOCs influenced by the gases present in the atmosphere with sunlight (Gautam et al. 2021a; Naqvi et al. 2021).

**Box plot model analysis**

The study analyzed the variations in PM$_{10}$, PM$_{2.5}$, NO$_2$, SO$_2$, CO, and O$_3$ concentrations during the different phases from 2019 to 2021. The averaged maximum and minimum concentrations show the range in which the particles are found during those different phases. The pictorial representation of the box plot analysis is depicted in Fig. 8. The maximum and minimum concentration of CO during 2019 in different lockdown phases was 3.3 mg/m$^3$ and 0.5 mg/m$^3$ (Phase I), 3.6 and 0.6 mg/m$^3$ (Phase II), 3.9 mg/m$^3$ and 0.4 mg/m$^3$ (Phase III), and 3.3 mg/m$^3$ and 0.7 mg/m$^3$ (Phase IV) with mean value of $1.2\pm 0.5$ mg/m$^3$, $1.2\pm 0.5$ mg/m$^3$, $1.3\pm 0.6$ mg/m$^3$, and $1.2\pm 0.5$ mg/m$^3$. Similarly, phase-wise values of O$_3$ for 2020 and 2021 can be seen in Fig. 8 and Table 2. During that period, the maximum and minimum concentrations were 95.9 µg/m$^3$ and 7.5 µg/m$^3$. The phase and year-wise concentration variation can be seen in Fig. 8 and Table 2. In 2020, ozone concentration was observed to be high due to secondary formation (Naqvi et al. 2021; Gautam et al. 2021b).

When SO$_2$ was considered, it showed a decrease in concentration in 2020 compared to 2019 (Fig. 4), but comparing 2020 and 2021, it showed an increment in two phases, P-I and P-II, and reduction during P-III and P-IV in 2021 (Fig. 3). The maximum reduction percentage was 45.5% in P-IV 2021 with BY 2019, whereas the increment was 42.9% in P-I 2021 with BY 2020 (Table 1). The recorded minimum concentration was 6.2 µg/m$^3$ during P-IV of 2021 and the maximum was 69.7 µg/m$^3$ during P-III of 2019.

**Pearson correlation coefficient analysis**

Figure 9 represents the Pearson correlation (PC) coefficients with a range of $-100$ to $100$. The value 100 represents “perfect correlation,” 0 represents “no correlation,” and $-100$ represents “perfect inverse correlation.” Pearson correlation analysis was done for particulate matter (PM$_{2.5}$, PM$_{10}$), gaseous pollutants (NO$_2$, SO$_2$, CO, and O$_3$) and meteorological parameters (WS wind speed, WD wind direction, SR solar radiation, RH relative humidity, AT ambient temperature). High correlations were found in O$_3$ and AT, with values ranging from 71 to 87, which shows evidence of the secondary formation of O$_3$ with respect to temperature. The correlation value between PM$_{2.5}$ and SO$_2$ falls in the range of 69–89. Similarly, NO$_2$ with CO showed a value in the range of 79–92, while an inverse correlation was found between NO$_2$ and WS ($-53$ to $-75$). The correlation was also found
Fig. 9  Correlation matrix showing the relationships between all the parameters phase-wise during 2019–2021
varying year to year and phase to phase. The results show a high homogeneity between different phases and years.

**Bivariate polar plot analysis**

Bivariate polar plots examine the role of WS and WD on pollution concentrations. In Figs. 10 and 11, the WS and WD are analyzed for PM$_{2.5}$ and O$_3$. The pattern of the polar plot was quite similar for all parameters. Few other plots can also be referred in the supplementary section (Figures S4–S6.). The lower PM$_{2.5}$ concentrations occur under WS > 3 m/s and show small directional dependence. Similarly, high concentrations of PM$_{2.5}$ under WS < 2 m/s show that the local sources dominate PM$_{2.5}$ concentrations. Resuspension of dust may be the possible reason for this. Those local sources include road transport emissions and domestic heating. Low WS helps accumulate PM$_{2.5}$ emitted by local sources near the monitoring location, resulting in high PM$_{2.5}$ concentrations. At higher WS, PM$_{2.5}$ concentrations are recorded low with possible dispersion towards the WD. The bivariate polar analysis for O$_3$ shows low concentration at lower WS < 1 m/s and high concentration when WS is

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**Fig. 10** Bivariate polar plots of PM$_{2.5}$ in Phases I, II, III, and IV for 2019–2021
above 1.5 m/s. The previous studies revealed that PM$_{10}$ is dominated by the construction sources and dust emissions in Delhi (Hazarika et al. 2016; Pant et al. 2015). A recent study reported that around 79% of PM$_{10}$ originates from sources such as road dust resuspension (Nagpure et al. 2016; Singh et al. 2019). The boundary layer conditions, meteorology are also playing a significant role in the dispersion of the pollutants of that particular city.

**Conclusion**

The pandemic had influenced to switch off the anthropogenic sources globally in 2020. In India, the second pandemic wave created enormous pressure on government and healthcare systems in 2021, especially in Delhi. Even though it caused many tragedies in the economy and life of people, it showed fruitful results in pollution reduction. Many Indian cities experienced a reduction in air
pollution, including Delhi. After the era of urbanization, very first time, the air quality in Delhi dropped down dramatically. The overall PM$_{2.5}$ concentration reduction was found to be 35% during 2020. But at the same time, an increase in O$_3$ concentration of about 10% was observed in all the phases. It may be due to the secondary formation of O$_3$ by solar radiation and other VOCs. This shows that O$_3$ is not only associated with direct emissions in the city. The percentage change in P-I for parameters PM$_{10}$, PM$_{2.5}$, NO$_2$, SO$_2$, CO, and O$_3$ is 167%, 104.3%, 142.3%, 42.9%, 70%, and 6.8% in 2021, respectively. Similarly for P-II, it is 109.9%, 106.6%, 92.3%, 28.9%, 26.5%, and −7.2%. The concentration in 2020 was recorded minimally and can act as baseline data. The study revealed that the concentration in 2020 was reduced multiple folds compared to 2019. The average mean concentration in 2019 was 226.4 ± 81.8 µg/m$^3$ (P-I), 227.5 ± 101.2 µg/m$^3$ (P-II), 292.2 ± 135.6 29 µg/m$^3$ (P-III), and 185.6 ± 77.7 µg/m$^3$ (P-IV), respectively. It reduced to 84.1 ± 38.5 µg/m$^3$, 112.4 ± 52.3 µg/m$^3$, 122.4 ± 52.5 µg/m$^3$, and 157.4 ± 76.1 µg/m$^3$ in 2020. The lower PM$_{2.5}$ concentrations occur under WS > 3 m/s and high concentrations during WS < 2 m/s. While comparing 2020 and 2021, the concentration was slightly increased in 2021, but the concentration in 2021 was still lower than that of 2019. High correlations were found in O$_3$ and AT, with values ranging from 71 to 87, which shows evidence of the secondary formation of O$_3$ with respect to temperature. The correlation value between PM$_{2.5}$ and SO$_2$ falls in the range of 69–89. It shows that the air quality in Delhi is improved to better standards in the year 2020 and 2021. Anthropogenic source’s contribution plays a crucial role in influencing the pattern of air quality. The government of Delhi has implemented many amendments (e.g., ban on diesel generators, ban on crackers usage, odd–even scheme) to reduce air pollution from time to time when it reaches very high beyond the standards. The situation created by the pandemic paved the way for improvement in various sustainable approaches. The study outcome can be used to develop the planned switch-off of anthropogenic sources in the future to improve air quality.

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Author contribution Vignesh Mohan—Conceptualization, visualization, formal analysis, reviewing, and editing.

Rajeev Kumar Mishra—Investigation, discussion, reviewing, and editing.

Data availability Data are taken from public domain resources (CPCB website).

Code availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

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