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Impact of COVID-19 induced lockdown and unlock down phases on the ambient air quality of Delhi, capital city of India

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ABSTRACT

The present study deals with the impact of the pandemic outbreak of COVID-19 on the ambient air quality in the capital city of India. Real-time data were collected from eight continuous ambient air quality monitoring stations measuring important air quality parameters (NO\textsubscript{2}, PM\textsubscript{10} and PM\textsubscript{2.5}). Results revealed that the city's air quality had improved significantly during the lockdown period due to COVID-19 outbreak. The concentration of gaseous and particulate matter during the lockdown period (March–May 2020) declined significantly compared with the preceding years' data from the same timeframe. However, the ambient air quality deteriorates with the onset of unlocking phases and post-monsoon season (October 2020). Higher concentration of NO\textsubscript{2}, PM\textsubscript{10} and PM\textsubscript{2.5} were recorded at industrial (S1 and S2) and hotspot (S4 and S5) sites. The lowest concentrations of studied pollutants were observed during the first phase of lockdown (March 24 – May 14, 2020). The present study, once again, establishes the direct effect of anthropogenic activities and deteriorating ambient air quality of Delhi.

1. Introduction

The first case of novel corona virus disease 2019 (COVID-19), caused by severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2), was noticed in Wuhan city, Hubei province, China in December 2019 and very soon, it spread out in most parts of the globe. The disease was declared a global pandemic by the World Health Organization (WHO) on March 11, 2020. In India, the first confirmed positive case of COVID-19 was declared on January 30, 2020 in the student who returned from the Wuhan city while the first-ever death caused by the viral disease was recorded on March 12, 2020. The central government of India took immediate steps to control the spread of highly contagious disease and consequently, the entire country observed four consecutive lockdowns where maximum anthropogenic activities were strictly restricted. The commercial, official and public places were closed and the public transport system were shut down to maintain the social distancing. After that, anthropogenic activities were gradually restored by implementing unlock down phases (Table 1).

Globally, the ambient air quality was found to be significantly affected by the COVID-19 outbreak; due to nil or very limited anthropogenic activities. Literature review suggests that studies on the relationship between COVID-19 induced lockdown phases and concentration of air pollutants are going on worldwide (Cartenì et al., 2020; Menut et al., 2020; Zoran et al. (2020a), Zoran et al.

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Recent studies have shown that the ambient air quality improved substantially in the global mega cities and countries like New York City, USA (Zangari et al., 2020), Ontario, Canada (Adams, 2020), Korea (Ju et al., 2021), Japan (Azuma et al., 2020), Spain (Briz-Redón et al., 2021), Gujarat India (Selvam et al., 2020) etc. A brief account of ambient air quality during COVID-19 induced

### Table 1
Lockdown and unlock down period in Delhi.

| Lockdown/Unlock Period | Period | Restrictions/Permissions | NO₂ (gm m⁻²) (Chemiluminescence) | PM₁₀ (gm m⁻²) (BAM) | PM₂.⁵ (gm m⁻²) (BAM) | Impact on Air Quality |
|------------------------|--------|--------------------------|----------------------------------|----------------------|----------------------|----------------------|
| 14 h people's curfew   | March 22, 2020; 7:00 am to 9:00 pm | Countrywide 14 h curfew where no vehicular movement (except emergency cases) and industrial activities (with a few exceptions like thermal power plants etc.) were allowed | R: 18.1–37.8 M: 22.53 SD: 6.17 | R: 88.3–151.7 M: 118.64 SD: 18.03 | R: 48.7–80.2 M: 68.5 SD: 10.44 | Emission reduced significantly due to least diurnal anthropogenic activities |
| Lockdown 1.0           | March 24, 2020 to April 14, 2020 (21 days) | Industrial activities were shut down, vehicular transport was restricted, Passenger operations of Indian Railway and civil aviation were totally suspended | R: 11–19 M: 15.74 SD: 2.96 | R: 75.1–145.8 M: 107.88 SD: 26.34 | R: 34.4–62 M: 47 SD: 9.43 | Least emissions as maximum anthropogenic activities were shut down |
| Lockdown 2.0           | April 15, 2020 to May 3, 2020 (18 days) | Monitored inter-state movement of the stranded persons was allowed with proper screening, quarantine facilities and health check-ups. Other restrictions of lockdown 1.0 continues. Urban areas were designated in different zones: Red Zone: Complete lockdown Orange Zone: no public transport | R: 10.3–32.16 M: 19.22 SD: 6.5 | R: 96.6–173.2 M: 127.87 SD: 25.67 | R: 39–63.7 M: 49.84 SD: 7.81 | Least emissions as maximum anthropogenic activities were shut down |
| Lockdown 3.0           | May 4, 2020 to May 17, 2020 (14 days) | Red Zone: Complete lockdown Orange Zone: no public transport | R: 11.6–40 M: 22.23 SD: 8.45 | R: 59.3–181.5 M: 131.3 SD: 36.4 | R: 43.7–86.7 M: 65.53 SD: 14.11 | Few relaxations were given Hence slight rise in emissions |
| Lockdown 4.0           | May 18, 2020 to May 31, 2020 (14 days) | Green Zone: Public transport buses with 50% capacity Red Zones were divided into Containment zone and buffer zone Lockdown restrictions in red zone Phase-wise relaxations in activities in other zones. Public places like shopping malls, religious places, hotels and restaurants to reopen from 8 June | R: 15.6–66.5 M: 32.36 SD: 14.78 | R: 109.7–223 M: 129.15 SD: 42.6 | R: 43.6–94.5 M: 68.66 SD: 16.41 | More relaxations allowed hence further increase in emission observed |
| Unlock 1.0             | June 1 to June 30, 2020 | Phase with the onset of summer-monsoon season, concentration of studied parameters tends to decrease | R: 12.17–36.23 M: 26 SD: 8.28 | R: 103.06–163.42 M: 23.92 SD: 123.78 | R: 223.33–388 M: 49.47 SD: 18.41 | Increase in anthropogenic activities but due to summer-monsoon season concentration remains low |
| Unlock 2.0             | July 1 to July 31, 2020 | Restrictions are withdrawn in a phased manner | R: 6.32–40.50 M: 25.07 SD: 9.13 | R: 63.32–103.88 M: 82.66 SD: 14.34 | R: 25.58–41.72 M: 35.34 SD: 4.60 | Increase in anthropogenic activities but due to summer-monsoon season concentration remains low |
| Unlock 3.0             | August 1 to August 31, 2020 | Restrictions are withdrawn in a phased manner | R: 9.83–51.10 M: 24.61 SD: 11.46 | R: 41.86–77.77 M: 57.46 SD: 12.77 | R: 19.02–28.91 M: 24 SD: 3.20 | More relaxations were allowed hence further increase in emission observed |
| Unlock 4.0             | September 1 to September 30, 2020 | Restrictions are withdrawn in a phased manner | R: 9.8–54.51 M: 34.2 SD: 14.4 | R: 105.27–181.5 M: 131.66 SD: 26.65 | R: 41.32–56.95 M: 50 SD: 5 | Anthropogenic activities coupled with weather conditions (post monsoon) causes steep rise in the concentration of air pollutants |
| Unlock 5.0             | October 1 to October 31, 2020 | Restrictions are withdrawn in a phased manner | R: 30–107 M: 64 SD: 27.36 | R: 239–388 M: 312 SD: 51.34 | R: 117–178 M: 147.25 SD: 19.63 | Increase in anthropogenic activities but due to summer-monsoon season concentration remains low |

Source: Ministry of Home Affairs, Govt. of India- https://www.mha.gov.in/notifications/circulars-COVID-19.
R-Range, M- Mean, SD-Standard Deviation.
lockdown in various parts of the world is given in Table 2. However, the literature review also revealed that the extensive and systematic correlational study on lockdown and unlock down phases on air quality has not been carried out in Delhi. The present study has been conducted to assess and establish impact of the lockdown and unlock periods due to COVID-19 pandemic and ambient air quality of Delhi, the capital city of India.

2. Materials and method

2.1. Study region

Delhi (28.61° N and 77.23° E, 216 m above mean sea level), situated on the banks of river Yamuna, is the capital city of India since 1911. Total area of the city is 1484 sq. km and is sustaining over 30 million population which is consistently increasing exponentially and about 11,297 persons per sq. km are residing in the city (NITI Aayog, 2020http://niti.gov.in/niti/content/population-density-sq-km). According to Koppen classification, the climate of Delhi may be defined as Humid subtropical climates with dry winter (Cwa) (Mazzeo et al., 2020). The Indian Meteorological Department divides a year into winter (January–February), pre-monsoon (March to May), summer-monsoon (June–September) and post-monsoon (October–December) seasons (Ghosh et al., 2016). The temperature varies from 5 °C to 10 °C in winter and rises to 45 °C (or more) in peak summer seasons. The city is surrounded by the Indo-Gangetic alluvial plains in the North and East and Aravalli hill ranges in the South. Delhi Ridge is a prominent geological feature carrying patches of vegetation; hence, regarded as the lungs of the city. Around 21.86% of the geographical area is forest-covered. Delhi-NCT, along with the adjoining districts of neighbouring states (Uttar Pradesh, Haryana and Rajasthan), is collectively known as Delhi-National Capital Region (Delhi-NCR).

The total length of roads in the capital city is 33,198 km with 864 signalised and 418 blinkers traffic intersections and having road density of 1749 km of road length per 100 km², which is one of the highest in the country (Kumar et al., 2017). The latest car density of Delhi (108 cars per km) depicts the fast rate at which motor vehicles are flooding the roads of the city. The urban ecosystem of the city may broadly be categorized as residential/institutional, industrial (over nine thousand registered industries), commercial and other hotspots with high traffic interjections. Number of registered factories and motor vehicle have been mentioned in the Tables 3 and 4 (Economic Survey of NCT of Delhi, 2021a; Economic Survey of NCT of Delhi, 2021b).

The ambient air quality of Delhi has always been an environmental issue for the country. Several measures have been taken to improve the ambient air quality. In the 1990 decade, Delhi became one of the most polluted metro cities of India as the city's size and vehicular density was growing tremendously for the last two decades (1971–1991). The available diesel and petrol at that time had significantly higher concentration of sulphur and tetraethyl lead. Delhi Transport Corporation (DTC) buses, private buses, three-wheeled vehicles (auto rickshaw) and taxis were emitting noxious air pollutants. In addition, activities like fossil fuel and biomass

2.2. Table 2

| City/Country | Inference | Study period | Author(s) |
|--------------|-----------|--------------|-----------|
| Delhi, India | Significant decline in the concentrations of NO₂ (up to 52%), PM₁₀ (up to 57%) and PM₂·₅ (up to 39%) during COVID-19 induced lockdown as compared with year 2018 and 2019 data. However, air quality again deteriorating with the onset of unlock down phases and AQI touched the severe category. | January 2018 to October 2020 (34 Months) | Present study |
| Chandigarh, India | Significant decrease in the concentrations of gaseous and particulate matter during first and second phase of lockdown. Reduction of 30–84% in NO₂ during COVID-19 lockdown in western India, Overall improvement of Air Quality Index (AQI) by 58% compared to 2019. | 25th March 2020 to 17th May 2020 | Mor et al., 2021 |
| Gujarat, India | No significant change in fine particulate matter concentrations but oxides of nitrogen concentrations reduced. | January 1, 2020 and April, 20, 2020 | Selvam et al., 2020 |
| Delhi, Bengaluru and Mumbai | Significant decline in the mean concentration of PM₂·₅, PM₁₀ and NO₂ was observed | 25th March to 31st May 2020 | Kumari and Tosnhiwal, 2020 |
| Ontario, Canada | Significant decreases in PM₂·₅ (36%) and NO₂ (51%) concentrations shortly after the shutdown took place. | Week 1 to 17 from January 1 for six years (2015–2020) | Adams, 2020 |
| New York City, USA | Concentration of NO₂ declined by 25.3% during the COVID-19 pandemic compared to previous years. Significant decline in PM₂·₅ concentrations in urban regions. | First 17 weeks (January to May) of 2015–2020 | Zangari et al., 2020 |
| USA | Concentration of NO₂, PM₂·₅ and PM₁₀ declined by 33.7%, 21.8% and 22.9% respectively during the first 3 weeks of lock-down. Sentinel-5P images supported the observations. | January 8th-April 21st in 2017-2020 | Berman and Ebisu, 2020 |
| Thailand | Daily average concentration of NO₂ declined by 64.7%. The mean concentration of finer and coarser particulate matter declined down to 61.89 ± 18.03 μg m⁻³ and 24.78 ± 11.25 μg m⁻³ respectively. | December 1, 2019 – May 31, 2020 (6 Months) | Stratoulias and Nuthammachat, 2020 |
| Milan, Italy | Concentrations of PM₂·₅, PM₁₀ NO₂ decreased by 45.45%, 35.56% and 20.41%, respectively | 1 January–25 April 2020 | Zoran et al., 2020 (a); Zoran et al., 2020 (b) |
| Korea | Concentrations of NO₂ were reduced by 62% and 50%, respectively. | December 2016 to April 2020 | Ju et al., 2021 |
| Barcelona and Madrid (Spain) | | | Baldasano, 2020 |
burning for various purpose, landfill sites, sewage treatment and power production increased the emissions of toxic gases up to many folds (Aneja et al., 2001; Chelani and Devotta, 2007; Goyal et al., 2006). However, since the year 1998, the Govt. of India took various steps to curb down vehicular emissions in the city. Prominent initiatives were implementation of compressed natural gas (CNG) for the urban transport, enforcement of EURO I and II norms, Bharat Stage (BS) standards compline for the public and private vehicles, fuel adulteration was checked, concentration of sulphur and benzene in automobile fuels were lowered down and introduction of Delhi Metro for urban mass transportation (Chelani and Devotta, 2007; Doll and Balaban, 2013; Khillare et al., 2008; Ravindra et al., 2006; Sharma et al., 2014). Other non-point sources (like diesel-based generator sets, open burning of agricultural and solid waste, construction and demolition activities) had significantly contributed to deteriorating the ambient air quality of the city. Nitrogen dioxide and particulate matter are important criteria pollutant which are used to compute the air quality index. Also, it is widely reported that these pollutants adversely affect the human health (Bishoi et al., 2009; Kumar and Goyal, 2011). Particulate matter and nitrogen dioxide are the primary air pollutants. Coarser and fine particulate matter originates from natural and anthropogenic sources and cause serious health and environmental issues (Bishit et al., 2015; Grantz et al., 2003). Primary sources of particulate matter can broadly be categorized as vehicular emissions, biomass and fossil fuel burning, road dust etc. (Hama et al., 2020; Pant et al., 2015). Earlier, researchers have suggested that the vehicular exhaust (road transportation) (34%), thermal power generation (30%) and industries (30%) are the biggest emitters of oxides of nitrogen (Garg et al., 2006). Nitrogen dioxide acts as the precursor of ozone and other secondary pollutants in the atmosphere (Ghosh et al., 2016). In Delhi, higher concentrations of NO₂, PM₁₀ and PM₂.₅ have been recorded historically (Beig et al., 2013; Goyal et al., 2006; Hama et al., 2020). Therefore, these pollutants were considered for the present study.

Table 3
Industry-wise registered factories in Delhi.

| Industry                                         | 2018  | 2019  |
|--------------------------------------------------|-------|-------|
| Food Product                                     | 350   | 142   |
| Beverages, Tobacco and Tobacco Product           | 53    | 34    |
| Textiles products                                | 2008  | 1519  |
| Wood products, Furniture and Fixtures            | 273   | 98    |
| Paper and Paper products Printing publishing & Allied | 795   | 587   |
| Leather and Leather Fur products (except repair) | 303   | 139   |
| Rubber, Plastic, Petroleum Coal Products         | 699   | 754   |
| Chemical & Chemical products (except Petroleum & Coal) | 290  | 173   |
| Non-metallic Mineral products                    | 73    | 11    |
| Basic Metal & Alloy Industry                     | 517   | 775   |
| Metal products and Parts Machinery & Transport Equipment - Machine tools including Electrical Appliances | 1928  | 757   |
| Electricity, Gas and Stream Water Works and Supply | 132  | 195   |
| Wholesale Trade in Fuel, Chemicals, Perfumery, Ceramics Glass | 99    | 0     |
| Public Administration and Defence Services       | 9     | 47    |
| Sanitary Services                                | 20    | 31    |
| Repair of Capital Goods & Repair Services        | 570   | 219   |
| Miscellaneous unspecified Group                  | 1002  | 3141  |
| Total                                            | 9121  | 8622  |

Source: Economic Survey of NCT of Delhi, 2021a, http://delhiplanning.nic.in/sites/default/files/12.%20Transport.pdf.

Table 4
Total registered motor vehicle in Delhi.

| Type of Vehicle                                         | 2017–18  | 2018–19  | 2019–20  |
|--------------------------------------------------------|----------|----------|----------|
| Cars and Jeep                                           | 3,246,637| 3,249,670| 3,311,579|
| Motor Cycles & Scooters/Two Wheelers                   | 7,078,428| 7,556,002| 7,959,753|
| Ambulances                                             | 3220     | 2358     | 2287     |
| Auto Rickshaws (Passengers)                            | 113,074  | 113,240  | 114,891  |
| Buses                                                  | 118,060  | 109,780  | 122,476  |
| Taxies                                                 | 35,285   | 32,218   | 33,302   |
| Other Passenger Vehicles Tractors                      | 76,231   | 81,422   | 85,477   |
| Goods Vehicles (All Types)                             | 335,080  | 246,861  | 263,112  |
| Others                                                 | 10,986,015| 11,391,551| 11892877*|

Source: Economic Survey of NCT of Delhi, 2021b, http://delhiplanning.nic.in/sites/default/files/9%29%20Industrial.pdf.

* Number of vehicles registered are excluding NOC, RC Cancellation, Surrendered, De-registered and Scrapped Vehicles (Record available in Vahan 4.0 database).
2.2. Sampling and analysis

The Delhi Pollution Control Committee (DPCC) provided monthly mean data for thirty-four months (January 2018 to October 2020) of NO$_2$, PM$_{10}$ and PM$_{2.5}$ from eight real-time ambient air quality monitoring stations established by the DPCC in October 2017. Selected sites are distributed in the city and represent industrial, residential/institutional, hotspot and background areas (Fig. 1). Two sites each were chosen under the category of industrial (S1 and S2), residential/institutional (S3 and S7), hotspot (S4 and S5) and background (S6 and S8). Industrial zones have dense clusters of micro, small, medium and large-scale factories/industries and related activities. Residential/institutional zones contain residences, institutions, colleges, hospitals and commercial establishments. Hotspots have been categorized by the DPCC on the basis of persistent high concentration of particulate matter (PM$_{10}$ and PM$_{2.5}$). These are designated regions having high anthropogenic activities, prolonged traffic interjections/jams, railway station, inter-state bus terminal etc. Background sites (S6 and S8) have comparatively less anthropogenic activities and traffic interaction and are situated at a significant distance from the nearest commercial/industrial hub. Although, NO$_2$ is present in the significant concentration at these sites,

Fig. 1. Sampling stations in Delhi.
lowest concentration of particulate matter (PM$_{10}$ and PM$_{2.5}$) were recorded at background sites.

Particulate matter (PM$_{10}$ and PM$_{2.5}$) concentrations were analysed by Beta Ray Attenuation Method (BAM 1020/Spirant BAM 1020; Met One, USA/Ecotech, Australia) while nitrogen dioxide samples were analysed with Chemiluminescence method (Serinus 44; Ecotech Australia). Study and sampling period has been broadly categorized as pre-COVID (January 2018 to December 2019), and COVID period (January 2020 to October 2020). On the basis of lockdown and unlock down, the period divided into two phases; Lockdown phase (March 24, 2020 to May 31, 2020; 67 days) and unlock period (June 1, 2020 to October 31, 2020; 153 days). Graphs were plotted using Origin Pro 2020.

3. Results and discussion

The obtained data set has been discussed upon the temporal (impact of seasons and COVID & Non-COVID periods) and spatial (impact of sites) variations. The change in the concentration of pollutants (NO$_2$, PM$_{10}$ and PM$_{2.5}$) was assessed for winter (January–February), pre-monsoon (March to May), summer-monsoon (June–September) and post-monsoon (October–December) seasons.

### Table 5

| Station code | Station name     | Coordinates (DDS) | Region       | Remarks                                                                 | NO$_2$ (µg/m$^3$) (Chemiluminescence) | PM$_{10}$ (µg/m$^3$) (BAM) | PM$_{2.5}$ (µg/m$^3$) (BAM) |
|--------------|------------------|-------------------|--------------|-------------------------------------------------------------------------|---------------------------------------|-----------------------------|-----------------------------|
| S1           | Narela           | 28.822836 N 77.101981 E | Industrial   | Plastic, polymer and packaging industries, cable industries, Footwear, auto-light parts, dying etc. | R: 10.07–65.18                       | M: 38.53                    | SD: 11.80                   |
| S2           | Pooth Khurd Bawana | 28.776200 N 77.051074 E | Industrial   | Plastic, polymer and packaging industries, bulbs and lights industries, cables and wires industries etc. | R: 8.87–72.1                         | M: 36.33                    | SD: 16.53                   |
| S3           | Ashok Vihar      | 28.695381 N 77.181665 E | Residential/Hotspot | Institutions, Colleges, Offices, Hospitals | R: 16.37–80                          | M: 43.26                    | SD: 18.31                   |
| S4           | Mundka           | 28.684678 N 77.022119 E | Hotspot      | Anthropogenic activities including sporadic agricultural activities, dust laden roads and highways increases in particulate matter concentration | R: 17.01–79.37                       | M: 37.35                    | SD: 14.14                   |
| S5           | Anand Vihar      | 28.646835 N 77.316032 E | Hotspot      | Border of Delhi and U.P., High traffic density and interjection, Inter-state bus terminal (ISBT), Railway station etc. | R: 20.82–147                         | M: 74.73                    | SD: 34.45                   |
| S6           | Najafgarh        | 28.570173 N 76.933762 E | Background   | Remote Area, No significant anthropogenic activities                      | R: 6.3–52.7                          | M: 27.49                    | SD: 11.98                   |
| S7           | Nehru Nagar      | 28.567890 N 77.250515 E | Residential/Institutional | Institutions, Colleges, Offices, Hospitals | R: 18.58–102.18                      | M: 48.55                    | SD: 18.96                   |
| S8           | Dr. Karni Singh Shooting Range | 28.498571 N 77.264840 E | Background   | Situated in front of Asola Wildlife Sanctuary, Remote Area, No significant anthropogenic activities other than low traffic | R: 11.27–74.2                        | M: 42.11                    | SD: 21.96                   |

### Table 5 (b)

| Pollutants       | WHO Standards | Indian Standards |
|------------------|---------------|-----------------|
|                  | Time Weighted Average Standards (µg/m$^3$) | Time Weighted Average Standards (µg/m$^3$) | Ecological Sensitive Area (Notified by Central Govt.) (µg/m$^3$) |
| Nitrogen dioxide (NO$_2$) | Annual Mean 40 | Annual 40 | 30 |
|                  | 1 Hour Mean 200 | 24 h 80 | 80 |
| Particulate Matter – 10 PM$_{10}$ | Annual Mean 10 | Annual 60 | 60 |
|                  | 24 Hours Mean 25 | 24 h 100 | 100 |
| Particulate Matter – 2.5 PM$_{2.5}$ | Annual Mean 20 | Annual 40 | 40 |
|                  | 24 Hours Mean 50 | 24 h 60 | 60 |

DDS- Degree Decimal System; R- Range; M- Mean; SD- Standard Deviation; BAM- Beta ray Attenuation Method. Range, Mean and Standard Deviation are for the period January 2018–October 2020.
Also, we classified the study period as the non-COVID phase (January 2018 to December 2019; 24 months) and the COVID phase (January 2020 to October 2020; 10 months). Similarly, impact of anthropogenic activities on the ambient air quality at different sites can easily be observed. The concentration range and mean concentration of gaseous pollutant (NO₂) and particulate matter (PM₁₀ and PM₂.₅) during the study period (January 2018 to October 2020) have been given in Table 5(a). The concentration of air pollutants varied according to the anthropogenic activities being carried out in different regions. Particulate matter concentrations were found significantly higher than the permissible standards of India and guidelines by the World Health Organization (WHO) (Table 5b).

Percentage change in the concentration of gaseous and particulate matter pollutants was calculated using the following equation:

\[
\text{Percentage change in concentration} = \left\{ \frac{(C_{2020} - C_Y) \times 100}{C_Y} \right\}
\]

Where, \(C_{2020}\) is the mean concentration of pollutants in 2020 and \(C_Y\) is the mean concentration of pollutants in previous years.

3.1. Ambient air quality from January 2018–December 2019

As mentioned earlier, the hotspot regions were categorized by the DPCC based on the high concentration of particulate matter (PM₁₀ and PM₂.₅) recorded in these regions. Being the hotspot regions of anthropogenic activities (very dense traffic interjections, dusty roads, inter-state bus terminal, railway station etc.), very high annual mean concentrations of particulate matter were observed at S4 (2018: PM₁₀ 386.37 ± 150.04 µgm⁻³ and PM₂.₅ 155.64 ± 101.88 µgm⁻³; 2019 PM₁₀ 289.46 ± 103.21 µgm⁻³ and PM₂.₅ 126.42 ± 78.00 µgm⁻³) and S5 (2018: PM₁₀ 376.5 ± 120 µgm⁻³ and PM₂.₅ 154.86 ± 84.77 µgm⁻³; 2019 PM₁₀ 283.25 ± 97.01 µgm⁻³ and PM₂.₅ 129.46 ± 78.1 µgm⁻³). It is necessary to mention here that the sampling station S5 could not run for the entire month of July 2018 due to maintenance shut down. Significant concentrations of the NO₂ were recorded at S4 and S5, where the concentrations

Fig. 2. (a): Variation of NO₂ concentration across the sites. (b): Variation of PM₁₀ concentration across the sites. (c): Variation of PM₂.₅ concentration across the sites.
varied from 17.01–79.37 μgm⁻³ at S4 and 22.61–147 μgm⁻³ at S5 between January 2018 to December 2019. Sampling stations S1 and S2 represent industrial region where clusters of plastic engineering industries, along with other industries, are present. The concentration of NO₂ at the industrial sites (S1 and S2) varied from 10.07–65.18 μgm⁻³ and 25.82–57.65 μgm⁻³, respectively. The annual mean concentrations of NO₂ at S1 and S2 were recorded as 38.21 ± 15.78 and 40.71 ± 9.8 μgm⁻³ for the years 2018 and 2019 respectively. Higher concentrations of coarse and finer particulate matter were recorded for the two industrial sites S1 and S2, in the year 2018 and 2019, respectively. The annual mean concentrations of gaseous and particulate matter in residential/institutional areas were found well above the permissible standards and WHO guidelines (Table 5b). Residential/institutional sites (S3 and S7) constitute residential colonies, markets, institutions, colleges, govt. and private offices, hospitals and research laboratories etc. Therefore, these sites have a high population density and significant traffic interjections. Ring road at site S7 (Nehru Nagar) is one of the highest congested roads of the city where traffic jam is a daily event. The annual mean concentration of pollutants for 2018 and 2019 at S7 were: NO₂ (56.34 ± 21.38 μgm⁻³ and 47.1 ± 11.47 μgm⁻³), PM₁₀ (255.71 ± 131.35 μgm⁻³ and 227.95 ± 107.5 μgm⁻³) and PM₂.₅ (129.74 ± 101.35 μgm⁻³ and 125 ± 93.61 μgm⁻³). Significantly lower concentrations of particulate matter were recorded at S6 and S8. Hence, these sites were designated as background sites. However, these sites are not devoid of vehicular interjections, therefore, significant concentrations of NO₂ were observed at the background sites. The mean concentrations of PM₁₀ and PM₂.₅ during the study at S6 and S8 were as PM₁₀ 171.24 ± 74.5 μgm⁻³ and PM₂.₅ 85.5 ± 50.31 μgm⁻³. Similarly, for S8, the mean concentrations of PM₁₀ and PM₂.₅ were 185.56 ± 88.60 μgm⁻³ and 91.6 ± 63.66 μgm⁻³, respectively. We compared the lockdown-unlock down phases (March–October) of the COVID period in 2020 with the same time frame of year 2018 and 2019. Compared to 2018, few sites observed a decline in NO₂ concentration (–2% to –21%) while at the other sites, a significant rise in NO₂ concentration (5% to 110%) in March–October 2019. The PM₁₀ (–6% to –32%) and PM₂.₅ (–1% to –19%) showed a declining trend for the same period, which can be due to various steps taken by the govt. and authorities to curb down the air pollution load in the city.

3.2. Seasonal variation and ambient air quality

Seasonal variation significantly affects the air pollution level. The seasonal variation in the present study has been conducted as per
the IMD classified seasons (Ghosh et al., 2016). Ambient air quality drops significantly in post-monsoon (October–December) and winter season (January–February) as the pollutants could not get dispersed in the cold dense air and hinder vertical mixing. Pollution level tends to decrease in summer-monsoon season (June–September) as the pollutants are washed away by rain. Other researchers have also observed similar research (Bishoi et al., 2009). In winter (January and February) and post monsoon (October–December) seasons, NO$_2$ concentration was recorded high at all the sites in 2018 and 2019 (Fig. 2a–c). The concentration of NO$_2$ started decreasing in pre-monsoon season (March–May) and reached to the lowest concentration during the summer-monsoon period (June–September). A similar trend was observed for the year 2020. Particulate matter concentrations were lowest during summer-monsoon while concentrations were significantly high during rest part of the year (especially winter and post-monsoon seasons). Sites (S1, S2, S3, S4, S5 and S7) having dense anthropogenic activities were recorded with high concentration of NO$_2$ and particulate matter (PM$_{10}$ and PM$_{2.5}$). Since the anthropogenic activities were going at the usual pace before the COVID-19 induced lockdown, similar trends have been observed during the non-COVID phase (January 2018–March 21, 2020). The concentrations of NO$_2$ and particulate matter (PM$_{10}$ and PM$_{2.5}$) were found higher in January–June (2018–19), October–December (2018–19) and September–October 2020 (unlock down phase). However, pollutants concentration remains in lowest range during the summer-monsoon season. Except the background sites (S6 and S8), higher concentrations of particulate matter were found at all sites in pre-COVID phase. The concentrations of NO$_2$ and particulate matter tend to increase tremendously during October 2020 due to the coupled effect of post-monsoon season and sudden rise in anthropogenic activities with the further relaxations in Unlock down phase 5 (Fig. 2a, c).

As compared to 2018, a steep rise in NO$_2$ concentration was observed in 2019 at S2 where the percentage change was as high as 110% between March and October. Site S4 observed a decline in NO$_2$ concentration by 21% between 2018 and 2019. The concentration of coarse and fine particulate matter showed a declining trend at all sites during March–October (2018 and 2019). The highest decline in PM$_{10}$ was observed at S6 (–32%) while for PM$_{2.5}$, it was observed at S1 (–19%) and S5 (–18%) (Table 6).

Fig. 2. (continued).
Table 6
Mean concentration and percentage change in concentrations of pollutants [March – October (2018–2020)].

| Sites | NO$_2$ | PM$_{10}$ | PM$_{2.5}$ | NO$_2$ | PM$_{10}$ | PM$_{2.5}$ | NO$_2$ | PM$_{10}$ | PM$_{2.5}$ | NO$_2$ | PM$_{10}$ | PM$_{2.5}$ | NO$_2$ | PM$_{10}$ | PM$_{2.5}$ | NO$_2$ | PM$_{10}$ | PM$_{2.5}$ | NO$_2$ | PM$_{10}$ | PM$_{2.5}$ | NO$_2$ | PM$_{10}$ | PM$_{2.5}$ |
|-------|--------|-----------|-----------|--------|-----------|-----------|--------|-----------|-----------|--------|-----------|-----------|--------|-----------|-----------|--------|-----------|-----------|--------|-----------|-----------|--------|-----------|-----------|
| S1    | 32.71  | 239.77    | 93.93     | 38.24  | 204.49    | 75.78     | 34.67  | 164.03    | 64.57     | 17%   | -15%      | -19%      | 6%    | -32%      | -31%      | -9%    | -20%      | -15%      | -2%    | -26%      | -24%      |
| S2    | 21.38  | 249.94    | 102.97    | 44.80  | 209.68    | 89.08     | 26.62  | 170.47    | 72.53     | 110%  | -16%      | -13%      | 24%   | -32%      | -30%      | -41%   | -19%      | -19%      | -20%   | -26%      | -24%      |
| S3    | 41.34  | 239.60    | 75.78     | 43.21  | 187.34    | 75.29     | 27.1   | 124.3     | 60.3      | 5%    | -22%      | -1%       | -34%  | -48%      | -20%      | -37%   | -34%      | -20%      | -36%   | -42%      | -20%      |
| S4    | 36.37  | 320.42    | 95.86     | 28.55  | 253.71    | 82.17     | 31.84  | 169.95    | 65.06     | -21%  | -21%      | -14%      | -12%  | -47%      | -32%      | 12%    | -33%      | -21%      | -2%    | -41%      | -27%      |
| S5    | 65.6   | 314.66    | 103.24    | 75.05  | 240.34    | 85.05     | 44.04  | 134.74    | 65.91     | 14%   | -24%      | -18%      | -33%  | -57%      | -36%      | -41%   | -44%      | -23%      | -37%   | -51%      | -30%      |
| S6    | 27.64  | 195.53    | 62.81     | 29.48  | 133.11    | 61.07     | 14.59  | 126.35    | 54.13     | 7%    | -32%      | -3%       | -47%  | -35%      | -14%      | -51%   | -5%       | -11%      | -4%    | -23%      | -13%      |
| S7    | 47.3   | 191.00    | 71.96     | 46.48  | 168.42    | 68.24     | 41.37  | 119.08    | 56.10     | -2%   | -11%      | -5%       | -13%  | -38%      | -22%      | -11%   | -30%      | -18%      | -12%   | -34%      | -20%      |
| S8    | 39.63  | 169.20    | 67.78     | 32.86  | 158.50    | 57.45     | 34.71  | 113.38    | 47.36     | -17%  | -6%       | -15%      | -12%  | -33%      | -30%      | 6%     | -28%      | -18%      | -4%    | -31%      | -24%      |
3.3. Impact of lockdown and unlock down

On March 22, 2020 the central govt. requested the people to follow 14 h curfew (Janata Curfew) imposed as a precursor of lockdown, and COVID-19 induced lockdown was implemented on March 24, 2020. The anthropogenic activities (industries, tertiary sector, transportation including railways and civil aviation) were ceased (or reached to its all-time low level) and the energy demands were reduced unprecedentedly with the implementation of lockdown period due to COVID-19 outbreak. Therefore, the emissions from the human activities also reduced. Lower range of concentrations were observed for NO\textsubscript{2} at industrial (19–33.90 \(\mu\text{g m}^{-3}\)), residential/institutional (16.37–38.7 \(\mu\text{g m}^{-3}\)), hotspot (18–55.78 \(\mu\text{g m}^{-3}\)) and background sites (11.27–38.7 \(\mu\text{g m}^{-3}\)) from March to May 2020 (lockdown phase). Results revealed that NO\textsubscript{2} concentration was all-time low at nearly all the sites during March 24 – April 14, 2020. Also, results depicted that the concentration of NO\textsubscript{2} was higher at almost all the sites during May 04–31, 2020 (lockdown). During lockdown (March 24–May 31, 2020), the concentration of NO\textsubscript{2} was well below the permissible annual mean concentration (40 \(\mu\text{g m}^{-3}\)) at all the sites except S4 where it was 66.5 \(\mu\text{g m}^{-3}\) during May 18–May 31, 2020. (Fig. 3a).

During the lockdown period (March–May 2020), coarse and fine particulate matter concentrations were found significantly below the concentrations recorded in years 2018 and 2019 at nearly all sites during the same time frame (Fig. 2b and c). During the lockdown, the highest concentrations of PM\textsubscript{10} were recorded at S1 (216 \(\mu\text{g m}^{-3}\)), S2 (223 \(\mu\text{g m}^{-3}\)) and S4 (218 \(\mu\text{g m}^{-3}\)) between May 18 – May 31, 2020. Similarly, for PM\textsubscript{2.5}, highest concentrations were observed at S1 (76.5 \(\mu\text{g m}^{-3}\)), S2 (86 \(\mu\text{g m}^{-3}\)), S3 (94.5 \(\mu\text{g m}^{-3}\)), S4 (70.76 \(\mu\text{g m}^{-3}\)) and S5 (71.1 \(\mu\text{g m}^{-3}\)) during the same period (May 18 – May 31, 2020). Concentration of particulate matter increases in the atmosphere during the pre-monsoon/summer season, contributed by various natural and anthropogenic sources (Hama et al., 2020). The concentrations of pollutants tend to increase from March to May (pre-monsoon) and then reach the lowest level during monsoon. The steep rise may easily be observed during post monsoon season (October onwards). In post-monsoon and winter period, vertical mixing of the air column is minimum; particulate matters gets trapped and remains suspended in the air, which further increases the concentration of particulate matter (Guttikunda and Gurjar, 2012; Hama et al., 2020). The lowest concentration of PM\textsubscript{10} and PM\textsubscript{2.5} at all the sites were recorded from March 24–April 14, 2020.

Our results were in good agreement with other studies conducted in different parts of the country. In Ghaziabad, a constituent city of Delhi NCR, the authors observed a sharp decline in NO\textsubscript{2} (48.7%), PM\textsubscript{10} (50.8%) and PM\textsubscript{2.5} (85.1%) during lockdown as compared to the concentration in January 2020 (Lokhandwala and Gautam, 2020). Similarly, in a short-term study, a significant decrease in the concentrations of NO\textsubscript{2}, PM\textsubscript{10} and PM\textsubscript{2.5} by 51%, 52% and 41%, respectively were observed during lockdown (March 25 to April 6, 2020) (Jain and Sharma, 2020). Kumar et al. (2020) observed fine particulate matter mean concentration in Delhi was 40 ± 24 \(\mu\text{g m}^{-3}\) with a decline of – 41% to – 53% during the lockdown phase (25 March to 11 May 2020).

With the unlock down phases, anthropogenic activities started rapidly, and the concentration of pollutants started rising accordingly. Therefore, the concentrations of the said pollutants tend to rise with phased un-lock. However, due to the seasonal variation (summer-monsoon season), the concentration of pollutants did not increase rapidly. However, as the post monsoon season started (October 2020), a sharp rise in gaseous and particulate matter concentration is visible. Nehru Nagar (S7) has one of the busiest traffic interjections in the city. Consistent rise in gaseous pollutant concentration at S7 after the lockdown is expected one. The rise in NO\textsubscript{2} concentration at S8 follows earlier year’s trend, and it may be due to vehicular emissions. The highest and lowest mean concentrations of NO\textsubscript{2} were recorded at S5 (44.04 ± 22 \(\mu\text{g m}^{-3}\)) and S6 (14.6 ± 7.73 \(\mu\text{g m}^{-3}\)) during March – October 2020. In 2020, the highest monthly mean concentrations of NO\textsubscript{2} were noticed for October at S1 (54 \(\mu\text{g m}^{-3}\)), S2 (59 \(\mu\text{g m}^{-3}\)), S3 (60 \(\mu\text{g m}^{-3}\)) and S8 (107 \(\mu\text{g m}^{-3}\)). Similarly, the concentration of coarser (PM\textsubscript{10}) and fine (PM\textsubscript{2.5}) particulate matter increased significantly in October 2020 and varied from 239 \(\mu\text{g m}^{-3}\) (S6) – 388 \(\mu\text{g m}^{-3}\) (S4) and 117 \(\mu\text{g m}^{-3}\) (S6) – 178 \(\mu\text{g m}^{-3}\) (S1) respectively. Stubble burning in the adjoining agricultural states is also considered as an important contributor in air pollution. A higher concentration of gaseous and particulate matter may certainly harm the citizens, especially having pre-existing co-morbidities like respiratory and cardiovascular diseases (Romano et al., 2020). Deteriorated ambient air quality and novel Corona virus may worsen the condition and may claim more health issues with the consistent and exponential rise in COVID-19 patients.

Comparing the dataset of March–October 2018 and 2020, an increment in the concentration of NO\textsubscript{2} was observed at S1 (6%) and S2 (24%) while for the rest of the sites, the concentration of gaseous pollutants showed a declining trend (– 12% to – 47%). However, lower concentration of PM\textsubscript{10} (– 32% to – 57%) and PM\textsubscript{2.5} (– 14% to – 36%) for the same period. As compared with the mean concentration for eight months (March to October 2019–20), the reduction percentage range for the concentration of PM\textsubscript{10} and PM\textsubscript{2.5} in 2020 was noticed as – 5% (S6) to – 44% (S5) and – 11% (S6) to – 23% (S5) respectively. The nominal increase was observed in NO\textsubscript{2} concentration at S4 (12%) and S8 (6%), whereas significant decline was observed at other sites (– 9% to – 51%). Similarly, the percentage change in concentration between the mean concentration of 2018–19 and 2020 for NO\textsubscript{2} varied from – 2% (S1 and S4) to – 49% (S6). Coarse particulate matter (PM\textsubscript{10}) ranges between – 23% (S6) to – 51% (S5). Similarly, for fine particulate matter (PM\textsubscript{2.5}), concentration declined and varied from – 11% (S6) to – 23% (S5) (Table 6). Since the anthropogenic activities almost ceased during the lockdown phase, the sharp decline in the air pollution level and increased ambient air quality clearly indicates that the anthropogenic activities from industrial, transportation, residential/institutional, and commercial sectors are core sources of pollutants in the city.

4. Conclusion

The impact of lockdown, due to COVID-19 outbreak, and unlock down phases on the ambient air quality of the capital city of India was assessed by analysing the concentration of NO\textsubscript{2}, PM\textsubscript{10} and PM\textsubscript{2.5} for 34 months (January 2018 to October 2020) obtained on an hourly basis by the real-time ambient air quality stations established by the DPCC. The study indicates that the air quality improved
significantly due to minimal emissions during COVID-19 induced lockdown, particularly in the first phase (March 24 – April 14, 2020). Compared with the data for the year 2018–19, the gaseous and coarser particulate matter concentrations have been reduced nearly up to 50% whereas the maximum reduction in finer particulate concentration was noticed up to 30%. However, the concentration of pollutants increases at a significant rate during unlocking phases as anthropogenic activities are growing up at a full pace. Hence, the direct correlation of anthropogenic activities and deteriorating ambient air quality has once again established. It should be noticed here that during the pandemic outbreak of COVID-19, falling air quality may aggravate the symptoms and increase the number of patients up to many folds.

Credit author statement

Dr. Mayank Pandey: Conceptualization, manuscript original draft, review and editing, data curation, Formal analysis, Software. Dr. M.P. George: Project administration, Conceptualization, Investigation, manuscript - review and editing. Dr. R.K. Gupta: Project administration, Conceptualization and Resources. Dr. Deepak Gusain: Conceptualization, Formal analysis, manuscript review & editing. Mr. Atul Dwivedi: Investigation, Software.

Fig. 3. (a): Site wise variation in NO₂ concentration during lockdown and unlock down phases. (b): Site wise variation in PM₁₀ concentration during lockdown and unlock down phases. (c): Site wise variation in PM₂.₅ concentration during lockdown and unlock down phases.
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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2021.100945.

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