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Air Quality, Atmospheric Variables and Spread of COVID-19 in Delhi (India): An Analysis

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ABSTRACT

Based on a time series analysis of the criteria pollutants, meteorological parameters, and COVID-19 positive cases, this paper explores the impact of epidemic prevention and control actions on air quality for five different periods of COVID-19 outbreak in Delhi, India. The study found that under the epidemic control measure during 11 May–19 June 2020, the average concentrations of atmospheric air pollutants $PM_{2.5}$, PM_{10}, NO_2, and CO were reduced to 42.15 µg m^{-3}, 128.68 µg m^{-3}, 27.31 ppb, and 0.83 ppm respectively, and were 73.85%, 46.48%, 63.43%, and 50.18% lower than the pre-COVID-19 level of January 2020, respectively. The steep fall of $PM_{2.5}$, NO_2, and CO was due to a drastic reduction in vehicular emission, but PM_{10} did not fall below the National Ambient Air Quality Standard. Between January 2020 to 11 May–19 June 2020 period, the pollutants O_3 and SO_2 increased significantly by 217.33% and 57.58 % respectively. The rise of SO_2 in Delhi was due to long-distance transfer, power plant emissions, and biomass burning. The sharp increase of O_3 happened due to accumulation in the atmosphere. During the peak COVID-19 phase (9 April–10 May 2020) Delhi had unprecedented improved AQI classes of II and III only. However, the pivotal pollutants in terms of their cumulative contribution to the AQI classes were PM_{10} and O_3. Low RH and low-temperature situations exhibited positive correlations with the new COVID-19 infection cases in Delhi. Comparatively lower NO_2 level in the air demonstrated a significant negative correlation with new COVID-19 cases while average SO_2 concentration in the air, when increased to 24.05 ppb, showed a negative correlation with new COVID-19 cases in Delhi. This study indicated a possibility of O_3 exhibiting a positive correlation with new COVID-19 cases under the condition of comparatively low temperature and low humidity.

Keywords: COVID-19, Delhi, Air pollutants, Air Quality Index, Meteorological variables

1 INTRODUCTION

The COVID-19 epidemic or Coronavirus epidemic is a current epidemic reeling the world that causes severe acute respiratory syndrome (SARS Cov-2). The first case of COVID-19 was seen in Wuhan, China, in December 2019. The World Health Organization (WHO) declared the outbreak as a public health emergency of international concern on 30 January 2020 and later only on 11 March 2020, WHO declared it an epidemic. A similar outbreak has occurred in the past that of Severe Acute Respiratory Syndrome Coronavirus (SARS-CoV) and of the Middle East Syndrome Coronavirus (MERS-CoV) which created fear all over the world and the subsequent global health threat due to zoonotic disease (Al-Tawfiq *et al.*, 2014). The present COVID-19 virus could spread more rapidly from one person to another than the other two zoonotic diseases of the past. Countries of the world resorted to non-pharmaceutical interventions 'lockdown' to fight out the invisible enemy like COVID-19 with different timeframes in the absence of treatment or a vaccine. Table S1 shows that out of the 44 countries, 34 countries announced 'lockdown' during March 2020, including India.

In India, the first case of COVID-19 was reported on 30 January 2020. On 22 March 2020, India observed a voluntary public curfew for spreading mass awareness, and from 24 March 2020,

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India announced an initial phase of nationwide lockdown for 21 days. Subsequently, because of the increasing number of confirmed cases, the lockdown period was further extended in steps. Due to the lockdown effect, keeping the vast population of the country in mind, the mortality rate is considered still less in India if compared with some other countries like the USA, China, France, and Italy (Krishnakumar and Rana, 2020).

The rate of spread of diseases and mortality is showing a differential pattern in different countries and even different regions of the same country (Contini and Costabile, 2020). Exploratory research studies are encouraged in multiple disciplines to unearth variables that are potentially involved in the spread of COVID-19 and related mortality or morbidity. Many studies around the world are indicating a possible role in air pollution and meteorological variables for the differences in disease impact across different geographic locations (Conticini *et al*., 2020). Extensively affected countries like Italy felt the urgent need for understanding the relative weight of air pollution and other confounders in containing the spread of the pandemic (Italian Aerosol Society, 2020). Coccia (2020a) found in a more recent study, in the context of 55 Italian cities, that cities with frequent high levels of ozone or particulate matter had a higher rate of COVID-19 infection and mortality. The positive effect of PM pollution and negative effect of temperature and humidity were found to be two important dimensions of COVID-19 infection spread in Italy (Carteni *et al*., 2020; Coker *et al*., 2020; Lolli *et al*., 2020). In a three French city study, two pollutants (PM_{10} and $PM_{2.5}$) were found to be correlated with COVID-19 mortality (Magazzino *et al*., 2020). Studies from China also claimed to have found a relationship between COVID-19 spread, air pollution, and meteorological variables. Ma *et al.* (2020) found that there was a positive correlation between COVID-19 mortality of Wuhan city with diurnal temperature range (DTR). In a Seoul (Korea) based study it was observed that air pollutants like CO_2, CO, and NO_2 were mainly got influenced by lockdown restrictions rather than the handiwork of meteorological conditions (Park *et al*., 2020). In USA where COVID-19 speedily spread, there was a substantial reduction of ambient NO_2 in cities like Los Angeles, Fresno, Bakersfield, and San Francisco due to COVID-19 related containment measures (Naeger *et al*., 2020). Pansini and Fornacca (2020) in a three-country study of China, Italy, and USA, indicated a possible role of poor air quality, namely with $PM_{2.5}$, CO, and NO_2 with COVID-19 inflicted mortality. He *et al*. (2020) studied the air quality indices (AQIs) in Chinese cities, both with and without lockdown, and found the much-improved air quality in the authority enforced lockdown cities in comparison. The role of climate variables on the daily new cases of COVID-19 related deaths was explored in the origin city of the pandemic i.e., Wuhan and found a significant correlation between AQI, humidity, and mortality (Fareed *et al*., 2020). Similarly, Zhang *et al*. (2020) threw light on the total effect of ambient temperature and air quality on COVID-19 transmission in China and indicated that rising temperature restricted deterioration of air quality which in turn reduced disease transmission. Bilal *et al*. (2020) echoed in a similar line and emphasized the strong connection found out between temperature and COVID-19 infection spread in Germany and credited the ‘controlled’ pollution status for restraining the pandemic spread in the country. With the upswing of the pandemic, the government imposed several restrictions on vehicle movements in worst effected Chinese cities to control air pollution, and the private vehicle restriction policy could bring down $PM_{2.5}$ pollution by 32% (Chen *et al*., 2020). Li and Tartarini (2020) highlighted that NO_2 and SO_2 had the highest reduction in concentration during the lockdown period in Singapore and linked their associations with restricted mobility trends.

The success or failure of efforts to defeat COVID-19 depends on the air quality prevailing in the hugely populated Indian cities (Coccia, 2020b). Investigation of air quality and its relationship with COVID-19 cases is highly important where both epidemic and air pollutions are currently high (Zoran *et al*., 2020). The previous reports have also been showing air pollution (both ambient and household) as key risk factors in terms of disease spread for the Indian population (Cowling *et al*., 2014; Gargava and Rajagopalan, 2015; Dutta and Jinsart, 2020).

Against the above background, in this paper, we first made a review of the literature related to air pollution, and COVID-19 impact in the Indian cities contributed by various researchers in the recent past. The objective of the review was to explore the areas of prior scholarship, key findings of the research, air pollutants and meteorological considered, geographic (city) areas covered, and importantly finding research gaps to avoid duplication. We used the keywords such as air pollution, COVID-19, and Indian city to search for the relevant literature for the purpose at hand. We included the literature from computer searches and bibliographic databases (e.g., Google Scholar, Pub Med, Academia, and Research Gate) in the analysis. Approximately 110 articles published after the outbreak of COVID-19 in India in the English language on air quality related to Indian cities as well as COVID-19 found but 36 journal articles could be used for detailed review for the simple reason of their proximity with the objective in hand (Table 1). Out of 36 journal articles reviewed, 25 (70**%)** studies considered the highly polluted Indian capital city Delhi, as their study location while others explored the lockdown effect of different state capitals and also small cities of India (Table S2). These studies successfully indicated the lockdown effect on different air pollutants by considering different time- periods (phases), both before and after the formal lockdown date, i.e., 25 March 2020. The current analysis presented as a part of this work differs from previous lockdown studies (Table 1) in the following unique ways. Firstly, five different phases of the epidemic outbreak were considered for time series analysis of the particulate matter, gaseous pollutants, meteorological parameters, new positive COVID-19 cases, and cumulative total COVID-19 cases in Delhi. This consideration of 1–5 phases of lockdown period and analyses of air pollutants thereof has allowed developing critical understanding in respect of air pollution for an extended period covering 1 January 2020 to 19 June 2020. Besides, how different levels of regulatory enforcement can affect air pollution concentrations of the most polluted city in the world became apparent. Secondly, in this study, the interaction of COVID-19 morbidity with environmental parameters (both criteria pollutants and meteorological variables) of Delhi has been explored through correlation and time-series analyses under two different periods of lockdown. The impact of environmental pollutants and climate indicators on the outbreak of COVID-19 has gained considerable attention in the recent literature, mostly in highly COVID-19 affected countries like China, Italy, and the USA. The exploration of the interaction of COVID-19 morbidity with environmental parameters and findings thereof is essential also for Indian policymakers to decide the future course of pandemic preventive action for the city of Delhi. Thirdly, unlike previous efforts (Table 1), this study has not only made a comparison of air pollutants prevailed during pre and post lockdown phases and established the AQI classes, but also made an in-depth analysis of indicatory air pollutants in each class of AQIs. The understanding of how the predominance of indicatory air pollutants altered during the different phases of lockdown measures is a valuable reference for future research on improving the air quality of Delhi.

The objective of this paper, therefore, is to fill the above-noted research gaps by investigating, comparing, and discussing the air quality of Delhi, including the air pollutants $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3, and AQIs from January to 19 June 2020 under five different phases of pre and post lockdown. Also, to specifically indicate the impact of the COVID-19 epidemic prevention and control actions on air quality with the identification of indicatory air pollutants for the different AQI classes. Additionally, to establish the interaction of COVID-19 morbidity with environmental parameters (both criteria pollutants and meteorological variables) of Delhi for the lockdown periods through correlation and time-series analyses and come out with some critical findings related to how air quality could play a supplementary role in controlling the current epidemic.

2 METHODS

The state-wise spread of COVID-19 cases in India has been assessed to single out Delhi as the state/city most affected in terms of the infection spread per million population. Day wise time series data for particulate matter, gaseous pollutants, meteorological parameters, new positive COVID-19 cases, and cumulative total COVID-19 cases were collected and analyzed for the five different time-periods (phases) of the epidemic outbreak in the city of Delhi. The air pollutants considered are a particulate matter of diameter less than 2.5 microns and 10 microns ($PM_{2.5}$ and PM_{10}), Ozone (O_3), Nitrogen Dioxide (NO_2), Carbon Monoxide (CO), and Sulphur Dioxide (SO_2) while the meteorological parameters are temperature, and relative humidity (RH). The daily average data of these pollutants were collected from the Central Pollution Control Board (CPCB). The daily average data in respect of meteorological variables were collected from the Central Meteorological Department, Delhi.

The five phases considered were January 2020 (Phase 1), February 2020 (Phase 2), March 2020

Table 1. Cities studied that reported air pollution reduction during COVID-19 related lockdown.

SL. No	Author	City studied*	Time Period PL: Pre-Lockdown PDL: Post/During Lockdown		Variables considered M: Meteorological P: Pollutants		Correlation with Mortality /morbidity.	IAP analyse of classes of AQIs	Results
			PL	PDL	M	P			
1	Navinya *et al*. (2020)	Delhi (17)	a) 1 Feb–24 Mar, 2019	a) 1 Feb–4 Mar, 2020 b) 25 Mar–3 May, 2020	WS, T, RH	$PM_{2.5}$, PM_{10}, SO_2, NO_2, CO	NC	NC	a) $PM_{2.5}$, PM_{10}, NO_2, and CO declined during lockdown. b) little changes in meteorology during lock down.
2	Jain and Sharma (2020)	Delhi (5)	a) Mar–April, 2019 b) 10–20 Mar, 2020	a) Mar–April 2020 b) 25 Mar–6 April, 2020	T, WS, RH	$PM_{2.5}$, PM_{10}, NO_2, O_3, CO	NC	NC	a) Significant decline in all the pollutants except for ozone. b) meteorological parameters also played a significant role in the reduction in air pollution levels.
3	Kumar *et al*. (2020)	Delhi (6)	25 Mar–11 May (2015–19)	25 Mar–11 May, 2020	NC	$PM_{2.5}$	NC	NC	a) Reduction (41–53%) of $PM_{2.5}$ in Delhi. b) Cities with more traffic, had more reduction.
4	Kotnala *et al*. (2020)	Delhi	15–31 Mar 2020	1 Jan–31 Mar, 2020	NC	PM_{10}, CO, NO_x, NH_3, NO, NO_2, SO_2	NC	NC	Sharp decline (nearly 200%) of $PM_{2.5}$ and PM_{10}.
5	Mahato *et al*. (2020)	Delhi	a) 2–21 Mar, 2020 b) 24 Mar–14 April, (2017–2019)	a) 25 Mar–14 April, 2020 b) 24 Mar–14 April, 2020	NC	PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3, CO, NH_3	NC	Yes Partial	a) PM_{10} and $PM_{2.5}$ declined by more than 50%) in comparison to PL phase. b) In compare to 2019, PM_{10} and $PM_{2.5}$ was reduced by 60% and 39% respectively.
6	Gautam (2020)	India	31 Mar–5 April (2016–19)	31 Mar–5 April, 2020	NC	NC	NC	NC	Reduction (50%) in air quality of Indian region.
7	Srivastava *et al*. (2020)	Delhi (2)	1–21 Feb, 2020	25 Mar–14 April, 2020	NC	$PM_{2.5}$, SO_2, NO_2, CO	NC	NC	a) Significant improvement of $PM_{2.5}$, NO_2 and CO in both the cities. b) SO_2 marginally declined.
8	Beig *et al*. (2020)	Delhi (6)	20 Feb–23 Mar, 2019 and 2020	24 Mar–14 April, 2020	T, WS, RH	$PM_{2.5}$, NO_2,	Up to 22–May, 2020	NC	a) COVID-19 mortality has strong correlation with $PM_{2.5}$ levels. b) Morbidity negatively correlated with T.
9	Mor *et al*. (2020)	Chandigarh	4–24 March, 2020	25 Mar–17 May, 2020 (3 phases)	T, RH, WS, WD, SR, RF	PM_{10}, $PM_{2.5}$, NO_2, NO, NO_x, SO_2, O_3, NH_3, CO, VOC's	NC	NC	a) Concentrations of most pollutants reduced during first two phases but increased during the third phase of PDL. b) Concentrations of SO_2, O_3, and m, p-xylene kept on increasing during PDL. c) Benzene decreased continuously during 3 phases of PDL.

Table 1. (*continued*).

SL. No	Author	City studied*	Time Period PL: Pre-Lockdown PDL: Post/During Lockdown		Variables considered M: Meteorological P: Pollutants		Correlation with Mortality /morbidity.	IAP analyse of classes of AQIs	Results
			PL	PDL	M	P			
10	Sharma *et al.* (2020)	22 cities (India)	16–24 Mar, (2017–2019)	25 Mar–14 April, 2020	WS, WD, T, RH	PM_{10}, $PM_{2.5}$, CO, NO_2, O_3, SO_2	NC	At the regional level	a) $PM_{2.5}$ had maximum reduction in most regions. b) $PM_{2.5}$, PM_{10}, CO, and NO_2 were reduced by 43, 31, 10, and 18% in India during PDL. c) AQI reduced by 44, 33, 29, 15 and 32% in north, south, east, central and western India respectively.
11	Selvam *et al.* (2020)	9 cities of Gujarat	a) 1 Jan–23 Mar 2020 b) 1 Jan–30 April, 2019	a) 24 Mar–20 April, 2020 b) 1 Jan–30 April, 2020	NC	$PM_{2.5}$, PM_{10}, NO_2, CO, SO_2, O_3, AQI	NC	At the regional level	a) $PM_{2.5}$, PM_{10}, and NO_2 concentrations were reduced by 38–78%, 32–80% and 30–84%, respectively. b) Reduction of 30–84% in NO_2 during lockdown but increase in O_3 (16–58%). c) AQI improved by 58% during Jan-April, 2020 than in 2019.
12	Ranjan *et al.* (2020)	Delhi (4) (+10 coal mines)	a) 25 Mar–14 April b) 15 April–3 May c) 4 May–15 May (2000–2019)	a) 25 Mar–14 April b) 15 April–3 May c) 4 May–15 May (2020)	NC	NC	NC	NC	a) All the four cities metropolitan cities had negative Aerosol Optical Depth (AOD) anomaly during PDL. b) Delhi had the highest negative AOD anomaly (−36.5%) during PDL (25 March–15 May 2020).
13	Shehzad *et al.* (2020)	Delhi (2)	1 Jan–24 Mar, 2019	25 Mar–20 April, 2020	NC	NO_2	NC	NC	a) Satellite images indicate that daily NO_2 level of PL (30 and 65 µg m^{-3}) declined to 12 to 25 (µg m^{-3}) during PDL in Delhi. b) Daily level of NO_2 emission also significantly declined during PDL in Mumbai.
14	Rodríguez-Urrego and Rodríguez-Urrego (2020)	Delhi (50)	18–24 Mar, 2020	26 Mar–1 April, 2020	NC	$PM_{2.5}$	NC	NC	Delhi, with a weekly average of 140 µg m^{-3}, had the highest reduction in $PM_{2.5}$ level compared to other Asian countries (40% reduction during PDL)
15	Singh *et al.* (2020)	Delhi (+4 regions)	15 Feb–24 Mar (2017–2019)	25 Mar–3 May 2020 (Strict phase)	WS, WD, T, PPT	$PM_{2.5}$, PM_{10}, NO_2, O_3, CO, SO_2	NC	NC	a) Significant reduction in $PM_{2.5}$, PM_{10}, NO_2, and CO in all the regions during PDL while SO_2 increase slightly.

Table 1. (*continued*).

SL. No	Author	City studied*	Time Period PL: Pre-Lockdown PDL: Post/During Lockdown		Variables considered M: Meteorological P: Pollutants		Correlation with Mortality /morbidity.	IAP analyse of classes of AQIs	Results
			PL	PDL	M	P			
									b) for Delhi, PM_{10} (~59%) had highest reduction followed by NO_2 (~56%), $PM_{2.5}$ (~47%), CO (~33%), SO_2 (~23%) while O_3 increased by 23%.
16	Aman *et al.* (2020)	Ahmedabad	1 Feb to 23 Mar, 2020	24 Mar–23 May, 2020	NC	NO_2, $PM_{2.5}$, PM_{10}	NC	NC	NO_2, $PM_{2.5}$, and PM_{10} decreased to a considerable extent during PDL.
17	Babu *et al.* (2020)	Delhi	1 Mar–23 Mar, 2020	24 Mar–30 June, 2020	T_{max}, T_{min}, T_{ave}, $T_{diurnal}$, DTR, DP, RH, WS, RF	$PM_{2.5}$, PM_{10}, CO, O_3, NO_x, AQI	Yes	NC	a) T_{max}, T_{min}, T_{ave}, DP and WS had significant positive correlation with daily COVID-19 cases. b) Diurnal T, DTR, RF, and RH had non-significant correlations with daily COVID-19 cases. c) AQI over Delhi was mostly moderate (within 100–200 for 57 days) during the study period.
18	Agarwal *et al.* (2020)	Delhi (6) (also 6 cities of China)	1 Feb–23 Mar, 2020	24 Mar–30 April, 2020	NC	$PM_{2.5}$, NO_2	NC	(AQI $PM_{2.5}$ and AQI NO_2)	Cities had average drop in AQI $PM_{2.5}$ and AQI NO_2 of 20.21% and 59.26%, respectively after 1 week of lockdown.
19	Bera *et al.* (2020)	Kolkata	25 Mar–15 May (2017, 2018, 2019)	25 Mar–15 May, (2020)	LST	PM_{10}, $PM_{2.5}$, O_3, SO_2, NO_2, CO	NC	NC	a) CO, NO_2, and SO_2 significantly decreased during PDL while O_3 slightly increased during PDL. b) Mean concentration of PM_{10}, and $PM_{2.5}$ reduced by 17.5% during PDL than the previous year. c) LST reduced slightly during PDL.
20	Karuppasamy *et al.* (2020)	23 cities	30 Dec, 2019–24 Mar, 2020	25 Mar–28 April, 2020	T, RH, WS	$PM_{2.5}$, NO_2, AQI	NC	NC	a) Average concentration of $PM_{2.5}$ (145.51 µg m^{-3}), NO_2 (21.64 µg m^{-3}), and AQI index (55.58) continuously decreased during PDL. b) WS and T increased during PDL.
21	Dhaka *et al.* (2020)	Delhi	1–24 Mar, 2020	25 Mar–14 April, 2020	SR, WS, RF, RH, T	$PM_{2.5}$, O_3	NC	NC	a) $PM_{2.5}$ substantially decreased (50 ± 15%) during PDL. b) O_3 remained high during PDL. c) Complex interplay between the baseline pollution and meteorology.

Table 1. (*continued*).

SL. No	Author	City studied*	Time Period PL: Pre-Lockdown PDL: Post/During Lockdown		Variables considered M: Meteorological P: Pollutants		Correlation with Mortality /morbidity.	IAP analyse of classes of AQIs	Results
			PL	PDL	M	P			
22	Siddiqui *et al*. (2020)	Delhi (8)	11–23 Mar, 2020	a) 24 Mar–7 April, 2020 b) 8–21 April, 2020	NC	NO_2, AQI	NC	NC	a) Average NO_2 and AQI decreased by 46% and 27% respectively during the first PDL phase. b) Locations of high NO_2 exposure coincides with higher COVID-19 cases.
23	Singh and Chauhan (2020)	Delhi (5)	a) 10–21 Mar, 2019 b) 22–31 Mar, 2019	a) 10–21 Mar, 2020 b) 22–31 Mar, 2020	NC	$PM_{2.5}$, AQI, NO_2	NC	NC	a) NO_2 concentration declined during the PDL periods in 2020. b) During the total lockdown period the air quality has improved significantly.
24	Kumari and Toshniwal (2020)	Delhi (3)	1–24 March, 2020	25 Mar–15 April, 2020	NC	PM_{10}, $PM_{2.5}$, NO_2, SO_2, O_3	NC	NC	PM_{10}, $PM_{2.5}$, NO_2 and SO_2 reduced by 55%, 49%, 60% and 19%, and 44%, 37%, 78% and 39% for Delhi and Mumbai respectively during PDL.
25	Kumar and Kumar (2020)	Mumbai	NC	27 April–25 July, 2020	T_{min}, DP_{max}, RH_{max}, RH_{avg}, RH_{min}, P_{max}, P_{avg}, P_{min}	NC	Yes	NC	RH and P had significant correlation with active number of COVID-19 cases in the city.
26	Sarkar *et al*. (2020)	Kolkata (2)	22 Feb–23 Mar, 2020	24 Mar–3 May, 2020	NC	$PM_{2.5}$, PM_{10}, NO_2, SO_2, NH_3, O_3, CO	NC	NC	a) $PM_{2.5}$, PM_{10} and NO_2 mean concentration reduced by 58.71%, 57.92% and ~55.23% respectively. b) O_3 increased during PDL. c) Air quality improved from the 'poor' to 'good' category in both the cities during PDL.
27	Lokhandwala and Gautam (2020)	Ghaziabad	10 Jan, 30 Jan, 19 Feb, 10 Mar, 30 Mar, 19 April (2019) 10 Jan, 30 Jan, 19 Feb, 10 Mar (2020)	30 Mar, 19 April, 2020	NC	$PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3, NO, NH_3, CO, Benzene	NC	NC	a) $PM_{2.5}$, PM_{10}, NO_2 and SO_2 reduced up to 85.1% in between 14 Jan to 14 April 2020. b) $PM_{2.5}$, PM_{10}, NO_2 and SO_2 reduced up to 46.1% in between 14 Jan, 2019 to 14 April 2020.
28	Kumar (2020)	Delhi (6)	a) 1 Mar–31 May, 2017–2019	a) 1 Mar–31 May, 2020 b) 25 March–31 May (for	T, H, AH	$PM_{2.5}$, PM_{10} NO_2, AOD	Yes	NC	a) Positive association between daily COVID-19 cases and T. b) RH and AH had mixed association with COVID-19 cases.

Table 1. (*continued*).

SL. No	Author	City studied*	Time Period PL: Pre-Lockdown PDL: Post/During Lockdown		Variables considered M: Meteorological P: Pollutants		Correlation with Mortality /morbidity.	IAP analyse of classes of AQIs	Results
			PL	PDL	M	P			
				NONO_2 and AOD)					c) Maximum AOD and NO_2 reduction found to be 60% and 45%, respectively during PDL. d) $PM_{2.5}$ PM_{10} and NO_2 also reduced in all cities during PDL.
29	Mahato and Ghosh (2020)	Delhi (10)	a) 10–23 Mar, 2020 (for AQI and pollutants) b) 1–23 Mar (2018–2019) (for AOD)	a) 24 Mar–13 April, 2020; 14–20 April, 2020, 21 Mar–20 April, 2020 (for AQI and pollutants) b) 24 Mar–May, 2020 for AOD	NC	PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, NH_3, O_3, AOD	NC	NC	a) PM_{10} and $PM_{2.5}$ concentrations reduced below the permissible limit during week +1 of PDL. b) CO and NO_2 reduced to about –30% and –57% respectively during PDL. c) AOD was reduced to about 36% and 18% in contrast to April 2018 and April 2019 respectively.
30	Sharma *et al*. (2020)	Ajmer (7)	10–20 Mar, 2020	25 Mar–17 May, 2020	NC	$PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3	NC	NC	a) All pollutants except for ozone (O_3) declined during PDL. b) NO_2 concentration had the highest decline of 64% during PDL.
31	Reshmi *et al*. (2020)	Kannur	1–24 March, 2020	a) 25 Mar–19 April, 2020 b) 20 April–9 May, 2020 c) 10–17 May, 2020	SR	O_3, NO, NO_2, CO, SO_2, NH_3, VOC's, PM_{10}, $PM_{2.5}$, AQI	NC	NC	a) O_3 concentration increased by 22% while NO and NO_2 decreased by 61% and 71% respectively during 10–17 May, 2020. b) CO, VOC's (BTEX), SO_2 and NH_3 declined by 67%, 61%, 62% and 16% respectively during 10–17 May, 2020.
32	Gautam *et al*. (2020)	Delhi (5)	17 Feb–24 Mar, 2020	25 Mar–4 May, 2020	NC	$PM_{2.5}$, PM_{10}, NO_2, NH_3, SO_2, O_3, CO, AQI	NC	NC	a) The AQI improved by up to 30–46. 67% during PDL. b) O_3 was high at Delhi during PDL.
33	Mitra *et al*. (2020)	Kolkata	1–30 April, 2019	1–30 April, 2020	NC	CO_2	NC	NC	Significant temporal variation of CO_2 level during PDL.
34	Somani *et al*. (2020)	Delhi (4)	15–24 Mar, 2020	a) 25 Mar–14 April b) 15 April–3 May	NC	$PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, CO	NC	NC	a) PM, O_3 and NO_2 levels in Delhi showed a sharp during 22–29 March 2020. b) PM_{10}, O_3 and SO_2 increased during 15 April–3 May phase in Delhi and Chennai.

Table 1. (*continued*).

SL. No	Author	City studied*	Time Period PL: Pre-Lockdown PDL: Post/During Lockdown		Variables considered M: Meteorological P: Pollutants		Correlation with Mortality /morbidity.	IAP analyse of classes of AQIs	Results
			PL	PDL	M	P			
				c) 4–17 May, 2020					
35	Bedi *et al*. (2020)	Delhi (4)	10–24 Mar, 2020	25 Mar–April, 2020	T, RH, WS, P	$PM_{2.5}$, PM_{10}, NO_2, NH_3, SO_2, CO, O_3	NC	NC	a) NO_2 (29.3–74.4%) had highest reduction and SO_2 had least reduction during PDL. b) 0_3 increased during PDL.
36	Kumari *et al*. (2020)	Delhi (39)	24 Mar–31 May, 2019	24 Mar–31 May, 2020	NC	$PM_{2.5}$, PM_{10}, NO_2, NH_3, SO_2, CO, O_3, AQI	NC	NC	a) PM_{10}, $PM_{2.5}$, CO and NO_2 decreased in all the cities while O_3 fluctuated across the cities during PDL. b) Patiala registered largest AQI improvement amongst the 39 cities considered.

Abbreviations: PL: Pre-Lockdown; PDL: Post/During Lockdown; IAP: Indicatory Air Pollutants; WS: Wind speed; T: Temperature; RH: Relative Humidity; NC: Not considered; WD: Wind direction; SR: Solar radiation; RF: Rainfall; PPT: Precipitation; DTR: Diurnal Temperature Range; DP: Dew point; H: Humidity; AH: Absolute Humidity; P: Pressure; AQI: Air Quality Index; VOC: Volatile Organic Compound; BTEX: benzene, toluene, ethylbenzene and xylene; AOD: Aerosol Optical Depth.

* Figures in brackets indicate the number of cities considered in the study including the prominent city mentioned.

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(Phase 3), 9 April–10 May 2020 (Phase 4), and 11 May–19 June 2020 (Phase 5). Phase 1 was a period when there were no cases of reported COVID-19 infection in the city with no real epidemic control measures in place. Phase 2 was characterized by no positive COVID-19 cases reported, but the city was readying epidemic control measures in case of an outbreak of the epidemic. During phase 3, the city made a slow start of reporting COVID-19 positive cases with a rapid increase later in tandem with activated epidemic control measures like lockdown by the government. Phase 4 witnessed a rapid increase in new cases of COVID-19 infection with strict enforcement of epidemic control measures all around the city. During phase 5, there was a rapid increase in new cases of COVID-19 infection, but with the initiation of 'unlocking' operation or relaxation in the city. The daily 'major pollutant' was also identified to understand their presence and comparative contribution to the constitution of the Air Quality Index (AQI) for the city during the five phases of the COVID-19 outbreak.

Descriptive statistics and Pearson's correlation coefficients have been used to analyze the behavior of criteria pollutants and meteorological parameters with respect to the spread of infection (daily new COVID-19 cases) since the advent of the diseases in Delhi from March through 19 June 2020. The air pollutants considered are $PM_{2.5}$, O_3, NO_2, and SO_2 while the meteorological parameters are temperature and RH. The analysis has been done for two different time periods, one; 1 March–10 May marked by inception and rapid increase of the diseases with strict enforcement of epidemic control measures, and two; from 11 May–19 June 2020 marked by the rapid increase of the diseases but with initiation of 'unlock' operation.

3 STUDY LOCATION

The study was conducted in Delhi, the capital of India (Fig. 1). Delhi is in the list of the top 20 most populated cities in the world. Burning of fuels, industrial factories, construction sites, power plants, stubble burning of agricultural biomass residue, and vehicular movement is found to be the primary cause of instantaneous air pollution in the city. Delhi has an extreme climate. It is very hot in summer (April–July) and cold in winter (December–January). The average temperature can vary from 25°C to 45°C during the summer and 22°C to 5°C during the winter. The spring season is February to March while the monsoon session is from July to Mid-September.

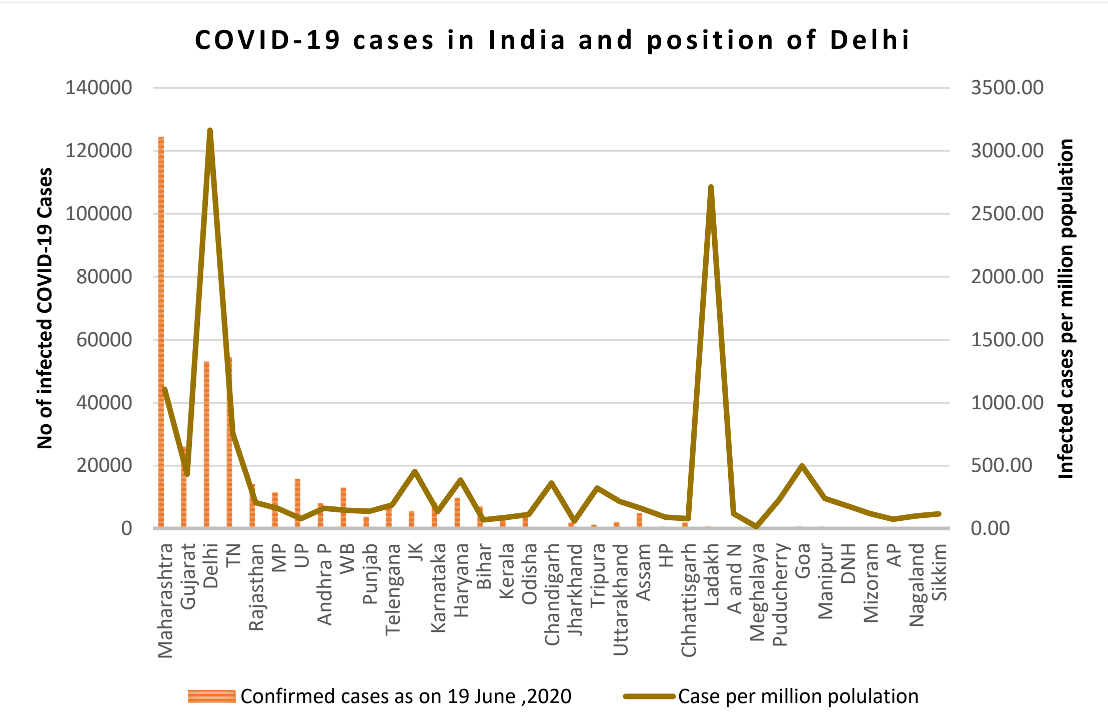

Fig. 1. State-wise COVID-19 cases and infected cases per million population.

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4 RESULT AND DISCUSSION

4.1 The Onset of COVID-19 in Delhi

In India, as of 19 June 2020, the total number of confirmed cases stood at 385,783 with state-wise variations (COVID-19 Dashboard India, 2020). As can be seen from Table S3 and Fig. 1, the state of Maharashtra topped the list with 124,331 cases, and six states like Maharashtra, Gujarat, Delhi, Tamil Nadu (TN), Rajasthan, and Uttar Pradesh (UP) accounted for more than 74 % of the total confirmed cases of India. In terms of cases of infection per million population, the capital city, Delhi is ahead of other Indian states with 3,164 cases per million population. The first COVID-19 positive case surfaced in Delhi on 4 March 2020 and thereafter rapidly increased in the subsequent months with 3,395 in April, 16,329 in May, and 33,272 during June (up to 19 June 2020) (Health & Family Welfare, Delhi, 2020).

Table 2 and Fig. 2 below depicts the history of the spread of the highly infected diseases in the city of Delhi. The infection spread in Delhi fluctuated with the highest 3,137 cases per day to zero, the average being 477 cases per day, during 1 March–19 June 2020. The dispersion of COVID-19 cases around the mean stood at 142.76% as revealed from the co-efficient of variation. Up to 24 March, i.e., on the day Government of India formally declared 'lockdown' in the country there were only 31 cases in Delhi. Then came a ‘super spreader’ in the form of a Tablighi Jamaat, an Islamic religious gathering that took place at Nizamuddin, Delhi. The rise of cases became comparatively steeper after that in Delhi as evident from the fact that as of 30 April there were 3,515 COVID-19 cases in Delhi which rose to 6,929 by 10 May 2020 by registering a 97% rise. The spike in the number of confirmed cases in April and May 2020 can easily be noticed in Fig. 2.

4.2 Air Pollution in Delhi: A Comparison

The average concentrations for $PM_{2.5}$, PM_{10}, SO_2, CO, NO_2, and O_3 in all the five phases of COVID-19 infection spread in Delhi are shown and compared in Figs. 3(A)–3(F), respectively. The Fig. 3(A) indicates that during January 2020, the average $PM_{2.5}$ concentration was recorded as 161.17 µg m^{-3} in Delhi with a minimum of 65.95 µg m^{-3} and a maximum of 444.47 µg m^{-3}. During February, Delhi recorded an average $PM_{2.5}$ concentration of 114.67 µg m^{-3} where maximum and minimum were 198.69 µg m^{-3} and 52.34 µg m^{-3} respectively. During March 2020, the average $PM_{2.5}$ concentration went down to a further low of 50.30 µg m^{-3} with a maximum of only 93.6 µg m^{-3} and a minimum of 15.23 µg m^{-3}. Interestingly, there was further lowering of $PM_{2.5}$ in Delhi during the

Table 2. Spread of COVID-19 in Delhi.

City	Total cases of infection (01-03-20 to 19-06-20)	Maximum number of cases reported in a day	Minimum no of cases reported in a day	Mean	SD	Co-efficient of variation (%)
Delhi	53,116	3,137	0	476.53	683.15	142.76

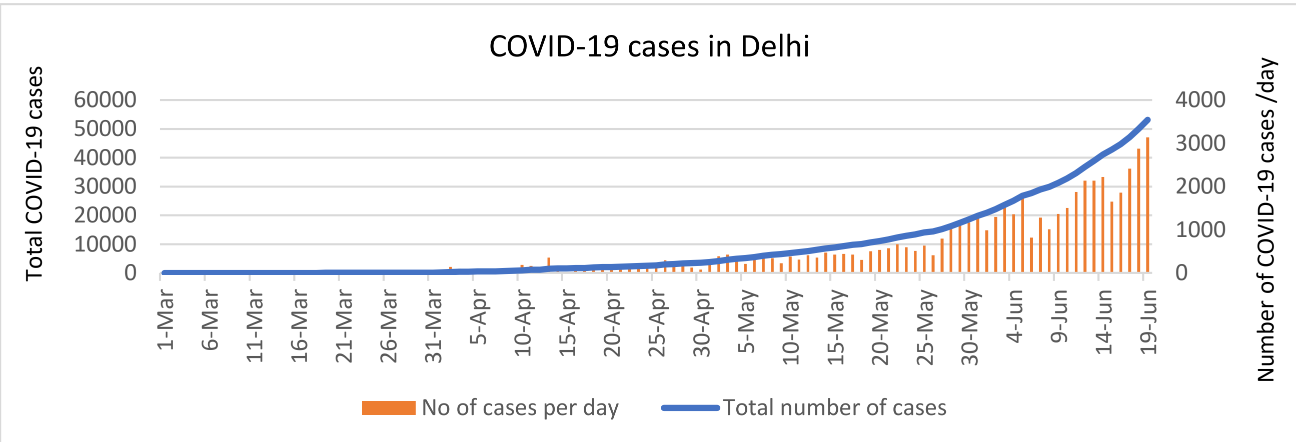

Fig. 2. Delhi and confirmed cases.

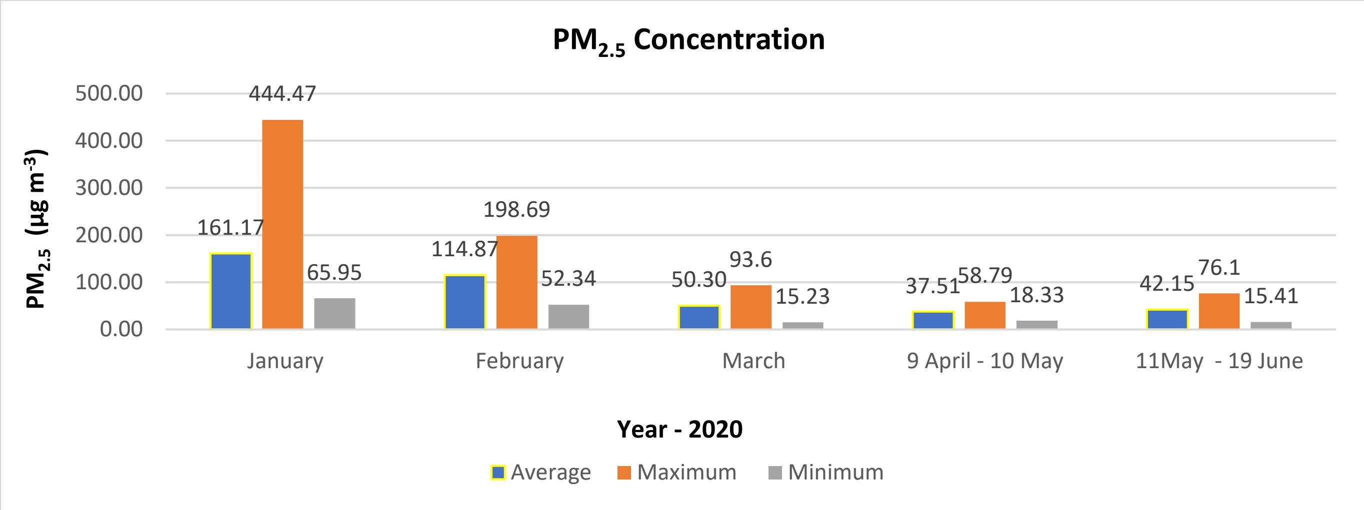

Fig. 3(A). The average $PM_{2.5}$ concentrations of Delhi during five phases of COVID-19 outbreak.

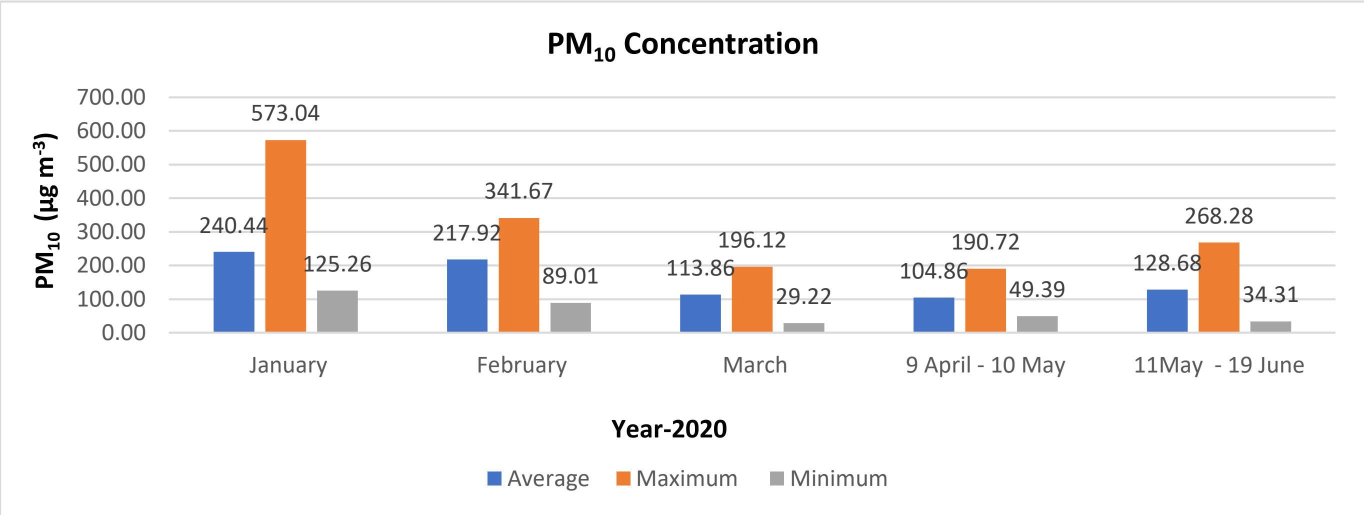

Fig. 3(B). The average PM_{10} concentrations of Delhi during five phases of COVID-19 outbreak.

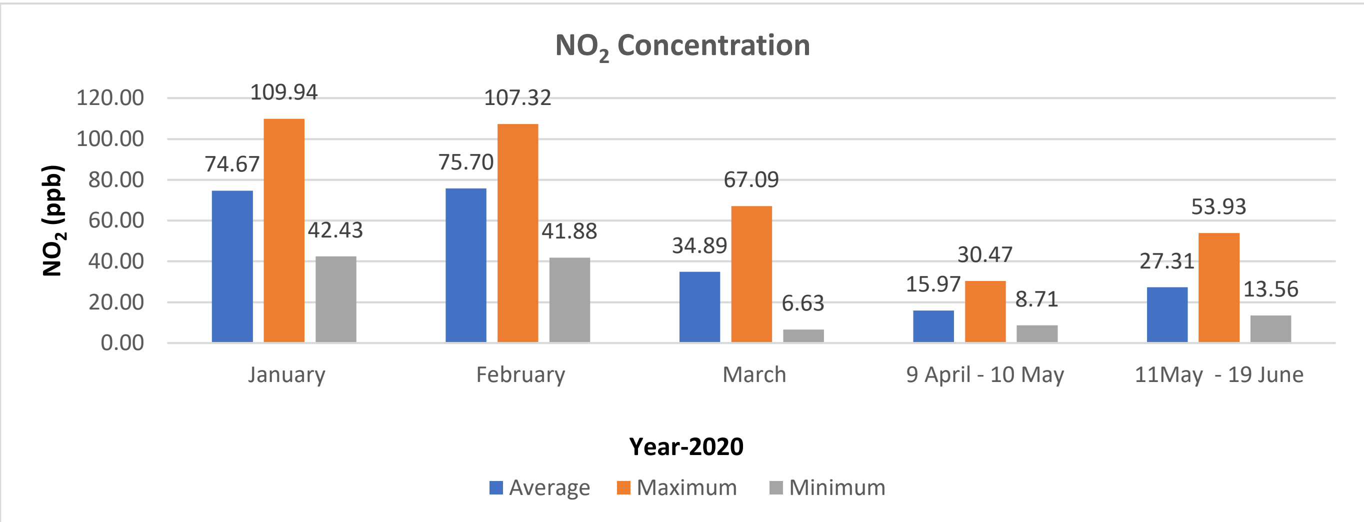

Fig. 3(C). The average NO_2 concentrations of Delhi during five phases of COVID-19 outbreak.

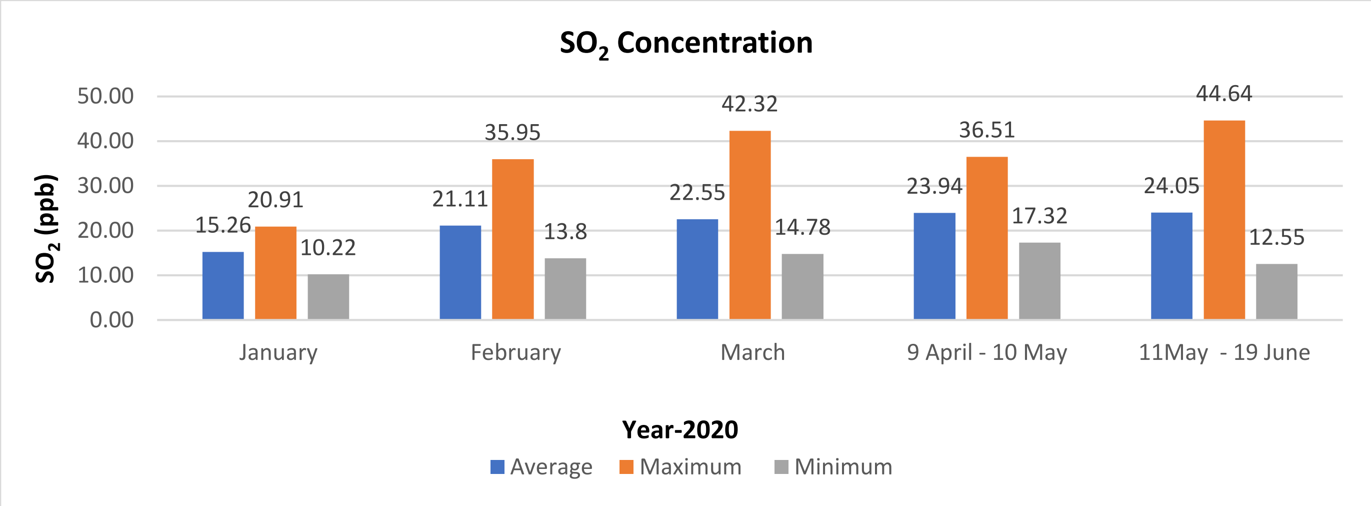

Fig. 3(D). The average SO_2 concentrations of Delhi during five phases of COVID-19 outbreak.

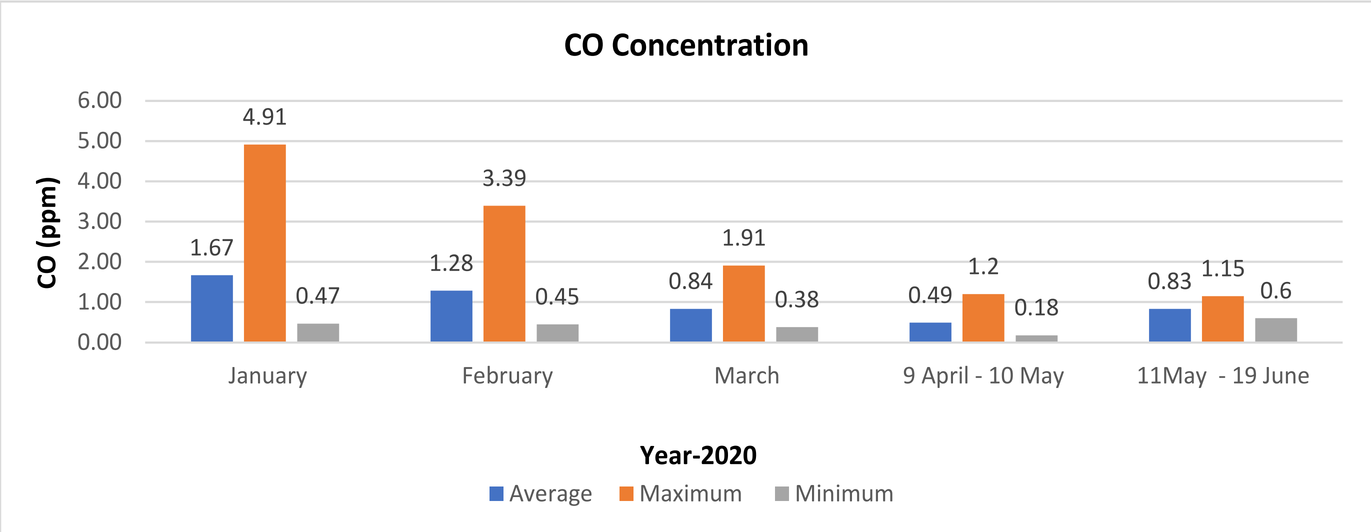

Fig. 3(E). The average CO concentrations of Delhi during five phases of COVID-19 outbreak.

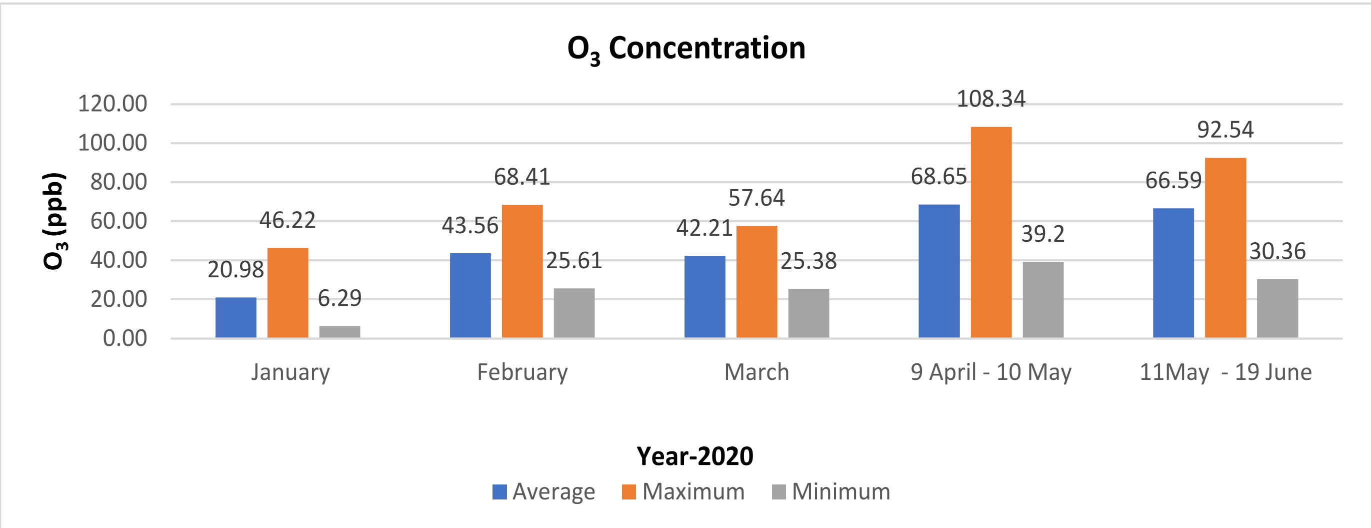

Fig. 3(F). The average O_3 concentrations of Delhi during five phases of the COVID-19 outbreak.

strict epidemic control period (9 April–10 May) with an average of only 37.51 µg m^{-3} where maximum and minimum were 58.79 µg m^{-3} and 18.33 µg m^{-3} respectively. With the initiation of 'unlock' operation, from 11 May-19 June 2020, the average $PM_{2.5}$ concentration level somewhat increased to 42.15 µg m^{-3} with a maximum and minimum of 76.1 µg m^{-3} and 15.41 µg m^{-3} respectively. After the epidemic control measures in the form of lockdown enforced during March, the average $PM_{2.5}$ concentration level decreased and came down within the National Ambient Air Quality Standard (NAAQS).

The Fig. 3(B) indicates that during January 2020, the average PM_{10} concentration was 240.44 µg m^{-3} in Delhi with a maximum as high as 573.04 µg m^{-3} and a minimum of 125.26 µg m^{-3}. During February, Delhi recorded a maximum PM_{10} concentration of 341.67 µg m^{-3}, a minimum of 89.01 µg m^{-3} with averages of 217.92 µg m^{-3}. During March 2020, the PM_{10} concentration went further low of a maximum of 196.12 µg m^{-3} and a minimum of 29.22 µg m^{-3} with an average of 113.86 µg m^{-3}. Interestingly, there was further lowering of PM_{10} in Delhi during the days of strict epidemic control measure (9 April–10 May) with a maximum of 190.72 µg m^{-3}, a minimum of 49.39 µg m^{-3} while average stood at only 104.86 µg m^{-3}. During the initiation of the 'unlocking' operation phase (11 May–19 June 2020), there was a slight increase in the average value of PM_{10} as 128.68 µg m^{-3} in the city. It may be noted here that even after the lockdown policy, the average PM_{10} concentration level remained higher than the NAAQS.

The Fig. 3(C) indicates that during January 2020, the average NO_2 concentration was recorded as 74.67 ppb with a maximum of 109.94 ppb and a minimum of 42.43 ppb in the city of Delhi. During February, Delhi recorded an average NO_2 concentration of 75.7 ppb with a maximum of 107.32 ppb and a minimum of 41.88 ppb. During the onset of the COVID-19 epidemic (March 2020), the NO_2 average concentration made a nosedive to 34.89 ppb with a maximum of 67.09 ppb and a minimum of 6.63 ppb. Interestingly, there was further lowering of NO_2 in Delhi during the peak COVID-19 period (9 April–10 May) with maximum, minimum, and average of only 30.47 ppb, 8.71 ppb, and 15.97 ppb respectively. As the data reveals, in percentage term, the average NO_2 concentration increased first between January to February marginally by 1.38% followed by a considerable reduction of 53.91% and 54.22% between February to March and March to 9 April–10 May period respectively. With the initiation of the unlocking operation, during 11 May–19 June, the NO_2 concentration made a steady recovery with an average stood at 27.31 ppb.

It can be seen from Fig. 3(D) that during January 2020, the average SO_2 concentration was recorded as 15.26 ppb (maximum 20.91 ppb and a minimum of 10.22 ppb) for the city of Delhi. During February, Delhi recorded a higher SO_2 average concentration of 21.11 ppb (maximum 35.95 ppb, minimum as 13.8 ppb). During March 2020, the average SO_2 concentration jumped up further with 22.55 ppb (maximum 42.42 ppb and a minimum of 14.78 ppb). Interestingly, though there was a marginal decrease of the maximum level of SO_2 in Delhi to 36.51 ppb during the peak COVID-19 period (9 April–10 May) in comparison to March 2020 value, both minimum and average level had risen to 17.32 ppb and 23.94 ppb respectively. In percentage terms, the average SO_2 concentration increased substantially by 38.29 % first between January to February followed by a marginal increase of 6.85% and 6.16% between February to March and March to 9 April–10 May period respectively. From 11 May–19 June, the average value of SO_2 was 24.05 which was only 0.5% higher than that of 9 April-10 May value.

Fig. 3(E) reveals that during January 2020, the maximum CO concentration was recorded as 4.91 ppm and a minimum of 0.47 ppm, with an average of 1.67 ppm for the city of Delhi. During February, Delhi recorded a maximum CO concentration of 3.39 ppm, a minimum of 0.45 ppm with an average of 1.28 ppm. During March 2020, the maximum CO concentration was recorded as 1.91 ppm and a minimum of 0.38 ppm with an average of 0.84 ppm. Interestingly, the maximum, minimum, and average CO concentration further decreased to 1.2 ppm, 0.18 ppm, and 0.49 ppm respectively during the 9 April–10 May period. In percentage terms, the average CO concentration decreased by 23% first between January to February and followed by a decrease of 34.86% and 41.6% between February to March and March to 9 April–10 May period respectively. However, with the initiation of unlocking operation, the average concentration of CO made a marginal recovery with an average 0.83 ppm during the 11 May–19 June period.

January 2020 recorded the maximum O_3 concentration of 46.22 ppb and a minimum of 6.29 ppb with an average of 20.98 ppb in Delhi which indicates substantial air presence of ground-level O_3

in the pre-COVID-19 period as shown in Fig. 3(F). During February, Delhi recorded a further rise with maximum O_3 concentration to 68.41 ppb with a minimum of 25.61 ppb and averages of 43.56 ppb. Interestingly, during March 2020, the maximum, minimum, and average O_3 concentration was reduced to 57.64 ppb, 25.38 ppb, and 42.21 ppb respectively. However, again during the peak COVID-19 period (9 April–10 May), there was a substantial increase in the maximum, minimum, and average level of O_3 in Delhi. In percentage term, the average O_3 concentration was increased by about 63.64% in between January to February 2020 while in between March and 9 April–10 May period, the rise was of 107.63%. However, during the 11 May–19 June period, there was a marginal decrease of 3% in the average O_3 concentration level than that of the 9 April–10 May period.

4.3 Effect of COVID-19 on PM and Gaseous Elements: Possible Reasons

The average concentrations of criteria pollutants varied during all the five phases considered in the study. In percentage term, the reductions of the average concentration of $PM_{2.5}$ in-between phase 1 to phase 2, phase 2 to phase 3, phase 3 to phase 4, and overall phase 1 to phase 5 were 28.73%, 56.21%, 25.42%, and 73.85% respectively as shown in Table 3 below. The downturn of $PM_{2.5}$ level in the capital city during phase 1 to phase 2 was due to the reinforcement of odd-even traffic rule from November 2019 onwards and closure of office and factories during mid of January 2020 due to festivals like Makar Sankranti and Pongal (Singh *et al*., 2011). The $PM_{2.5}$ level also abruptly came down during phase 3 and phase 4 due to a complete lockdown enforced by the central government from the morning of 23 March 2020 onwards to prevent the spread of the COVID-19 epidemic. A marginal increase of $PM_{2.5}$ level by 12.23% during phase 4 was due to the relaxation of lockdown initiated in the city. In totality, this study reveals an unprecedented 73.85 % reduction of $PM_{2.5}$ in the sixth most polluted city of the world during phase 1 to phase 5. The primary identified sources of $PM_{2.5}$ in Delhi were secondary aerosols (23.2%), soil dust (22.5%), vehicle emissions (18.5%), fossil fuel burning (13.1%), biomass burning (12.3%), industrial emissions (6.3%) and sea salts (4.1%) (Sharma and Mandal, 2017). Therefore, the steep reduction in $PM_{2.5}$ may be due to the substantial reduction of vehicle emissions, soil dust, and industrial emissions because of the complete lockdown enforced during the epidemic outbreak. Table 3 further reveals that, in percentage terms, the reductions of the average concentration of PM_{10} during phase 1 to phase 5 was about 46.48%. Possible reasons for the reduction of PM_{10} almost to half were the complete shutdown of construction activities and industrial production activities in the entire national capital region of Delhi due to the epidemic prevention and control actions.

From phase 1 to phase 2, the average NO_2 concentration increased marginally by 1.38% showing that the industrial production and traffic activities did take time to get reduced as the importance of economic activities was put in the forefront and fear of COVID-19 related epidemic was yet to get into the people. However, once the government machinery was in action to invoke lockdown, the fall in the average level of NO_2 concentration was the sharpest. From phase 2 to

Table 3. Increase/decrease in the average concentration level in Delhi.

Time periods*	Average concentration level: Increase/decrease					
	$PM_{2.5}$ (μg m^{-3})	PM_{10} (μg m^{-3})	NO_2 (ppb)	SO_2 (ppb)	CO (ppm)	O_3 (ppb)
Phase 1	161.17	240.44	74.67	15.26	1.67	20.98
Phase 2	114.87	217.92	75.70	21.11	1.28	43.56
Phase 3	50.30	113.86	34.89	22.55	0.84	42.21
Phase 4	37.51	104.86	15.97	23.94	0.49	68.65
Phase 5	42.15	128.68	27.31	24.05	0.83	66.59
Phase 1 to Phase 2	28.73% ↓	9.37% ↓	–1.38% ↑	38.29% ↑	22.99% ↓	107.57% ↑
Phase 2 to Phase 3	56.21% ↓	47.75% ↓	53.91% ↓	6.85% ↑	34.86% ↓	3.09% ↑
Phase 3 to Phase 4	25.42% ↓	7.91% ↓	54.22% ↓	6.16% ↑	41.60% ↓	62.62% ↑
Phase 4 to Phase 5	12.23 ↑	22.71 ↑	70.97% ↑	0.46% ↑	70% ↑	3% ↓
Phase 1 to Phase 5	73.85 ↓	46.48 ↓	63.43 ↓	57.58 ↑	50.18 ↓	217.33 ↑

* Phase 1 (January, 2020), Phase 2 (February, 2020), Phase 3 (March 2020), Phase 4 (9 April–10 May, 2020), Phase 5 (11 May–19 June, 2020).

phase 3 and phase 3 to phase 4, the average NO_2 level fell by 53.91% and 54.22% respectively. While the origin of SO_2 predominantly from natural sources worldwide, but in urban and industrial areas like Delhi, the manmade sources also prevail. The previous studies have shown that during the winter months (December–January), SO_2 gets into the Delhi atmosphere through long-distance transfer from western Asia, northwestern Pakistan, Rajasthan, and Punjab provinces. Besides, coal-based thermal power plants at Panipat (in the northwestern side of Delhi) and Faridabad (in the southeastern side of Delhi), local industries, soil erosion, and biomass burning also contributes to the accumulation of SO_2 in Delhi air (Goyal and Sidhartha, 2002; Datta *et al.*, 2010). As shown in Table 3, the rise of SO_2 concentration level during phase 1 to phase 5 by 57.58% was possibly due to a combination of long-distance transfer, power plant emissions in the vicinity, and biomass burning. Though local industries were closed, agriculture activities were allowed to continue in the periphery of Delhi to a great extent during the lockdown period also. Delhi usually experiences high CO concentration in the atmosphere because of sources like long-distance transfer over the Bay of Bengal from the Indo-Gangetic plains as well as local sources like the burning of firewood and emissions from the transport sector. This study records that from phase 3 to phase 4; there was about a 40.6% drop in the CO average concentration in Delhi. It indicates that neither the local sources could be active nor the long-distance transfer of CO was possible because of pan India lockdown which affected the running of motor vehicles to a great extent (Tyagi *et al.*, 2016).

Table 3 also reveals that the average concentration of O_3 had a massive increase of 217.33% during the period of phase 1 to phase 5, which was significantly high and alarming for a city like Delhi. The rise in O_3 was a concern for Delhi during the non-COVID-19 time also and the authority, i.e., CPCB even initiated action to control the health effect caused by this dominant pollutant. Ozone is a reactive form of oxygen that is not directly emitted from any sources but formed with a reaction between nitrogen oxides (composed of nitrogen and oxygen) and hydrocarbons in the presence of sunlight. There may be two possible reasons for the significant rise of O_3 during the outbreak of COVID-19 in Delhi. First, vehicular and industrial fumes gave rise to NO_x, and a higher level of NO_x contributed towards the forming of NO_2. NO_2 then dissociated to form NO, and O in the presence of sunlight. Further, O combined with atmospheric O_2 to form O_3 in the atmosphere. Hence, under this process, the levels of O_3 and NO_2 are inextricably linked (Han *et al.*, 2011). Second, when urban VOC emissions from a complex mix of sources like traffic, industry, solvents, and waste burning were not possible due to the lockdown effect, a new inverse relationship between O_3 concentration and NO_2 concentration emerged. The second possible reason seems to be relevant for high ground-level O_3 in Delhi air where lower NO_2 rather contributed more O_3 to accumulate in the atmosphere as not enough NO was there in the air to react with O_3 to form O_2 (Chameides *et al.*, 1992; Biswas *et al.*, 2019).

4.4 AQI Distribution

India has its own national air quality indices (AQIs), corresponding to different national air quality standards. The AQI was launched by the Indian government to make India pollution-free. The AQI for a given pollutant concentration (Cs) is based on a linear segmented principle (Nigam *et al.*, 2015). The AQI Eqs. (1) and (2), as shown below, are based on dose-response relationships of pollutants to obtain breakpoint concentration which is considered to be most robust for decision making (CPCB, 2014).

$$I_P = \left[\left\{ \frac{I_{HI} - I_{LO}}{B_{HI} - B_{LO}} \right\} \times \left(C_P - B_{LO} \right) \right] + I_{LO} \quad (1)$$

AQI = Max (I_P) (where p = 1, 2, 3, …, n; denotes n pollutants) (2)

where,
I_P - Air quality sub-index for air pollutant p;
B_{HI} - Breakpoint concentration greater or equal to given Concentration;
B_{LO} -Breakpoint concentration smaller or equal to given Concentration;
C_P - Concentration of pollutant p;

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I_{HI} - AQI value corresponding to B_{HI};
I_{LO} - AQI value corresponds to B_{LO}.

India had six AQI categories, namely Good, Satisfactory, Moderately polluted, Poor, Very Poor, and Severe. The different ranges of each category are as shown in Table 4 below along with the color codes for each category.

The outbreak of COVID-19 had its impact on the AQI values of Delhi too. The AQIs of Delhi during the five phases considered in this study were calculated out and shown in Figs. 4(A)–4(E), respectively. As shown in Fig. 4(A), during January 2020, the AQIs in Delhi ranged from a minimum of 120 to a maximum of 579, with an average of 310.03 and a standard deviation of 94.93. Fig. 4(B), indicates that the AQI values fell substantially during February and ranged between a minimum of 89 to a maximum of 361 with an average value of 250.57 and a standard deviation of 82.02. The minimum, maximum, and average values of February AQIs were 37.67%. 25.83%, 19.3% lower than the corresponding values recorded during January 2020.

The AQI values of Delhi further tumbled down during March to a new low as shown in Fig. 4(C). During March, the maximum AQI was 212 with a minimum of 29 and an average 109.58 with a

Table 4. National Air Quality standard of India.

Class	AQI Range	Air Quality effects on health
Class I	Good (0–50)	Minimal Impact
Class II	Satisfactory (51–100)	Minor breathing discomfort to sensitive people
Class III	Moderate (101–200)	Breathing discomfort to people with lung, heart disease, children, and older adults
Class IV	Poor (201–300)	Breathing discomfort to people on prolonged exposure
Class V	Very Poor (301–400)	Respiratory illness to the people on prolonged exposure
Class VI	Severe (> 401)	Respiratory effects even on healthy people

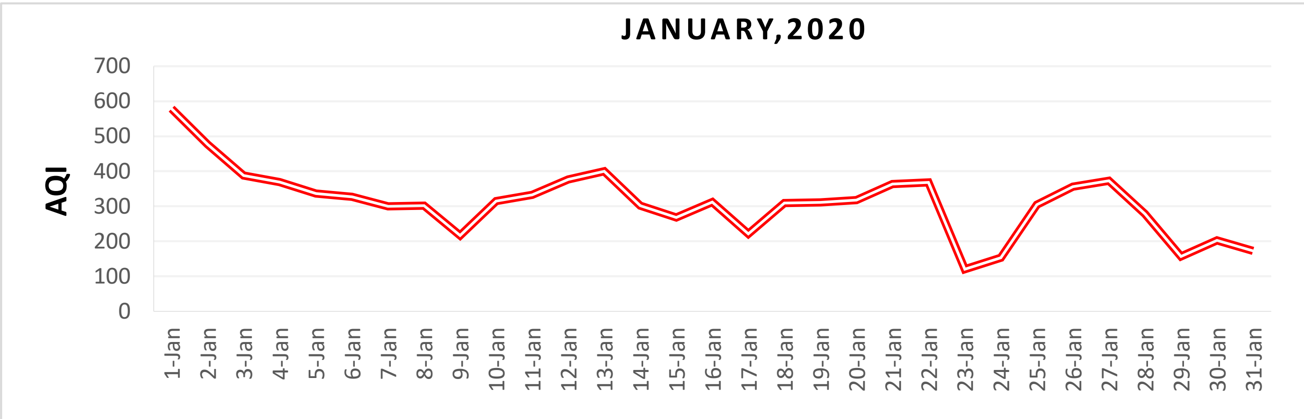


Fig. 4(A). AQI for Delhi during January 2020.

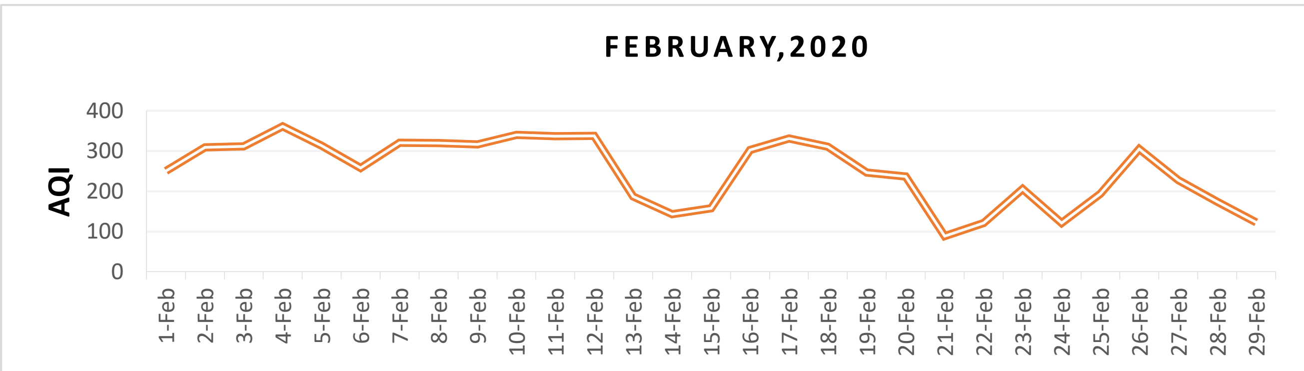


Fig. 4(B). AQI for Delhi during February 2020.

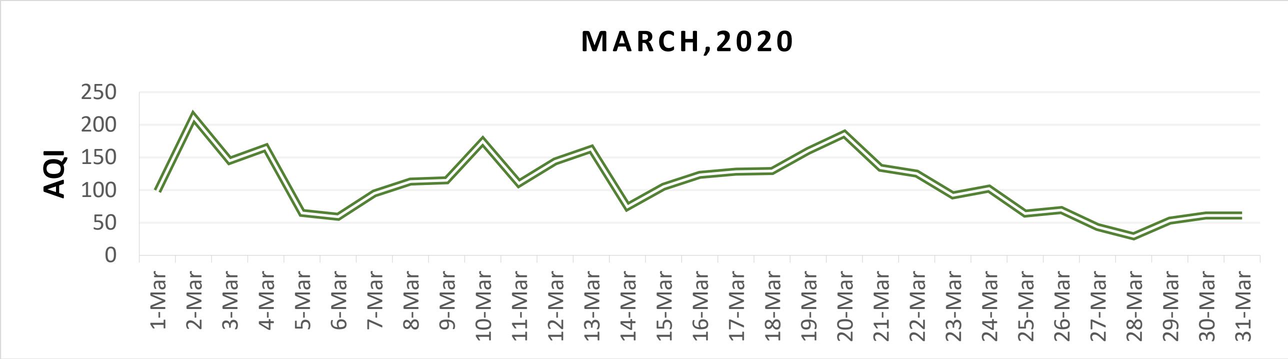


Fig. 4(C). AQI for Delhi during March 2020.

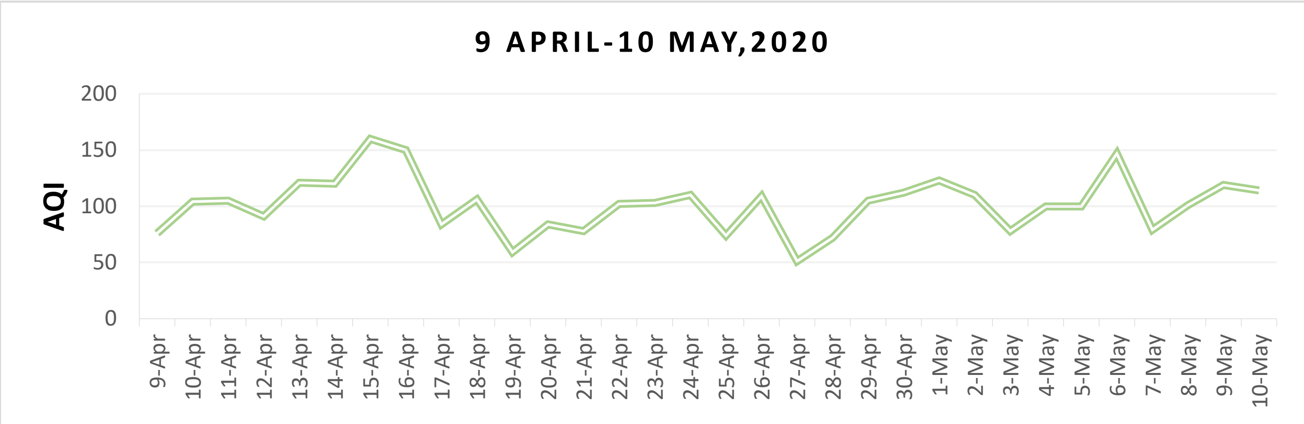


Fig. 4(D). AQI for Delhi during 9 April–10 May 2020.

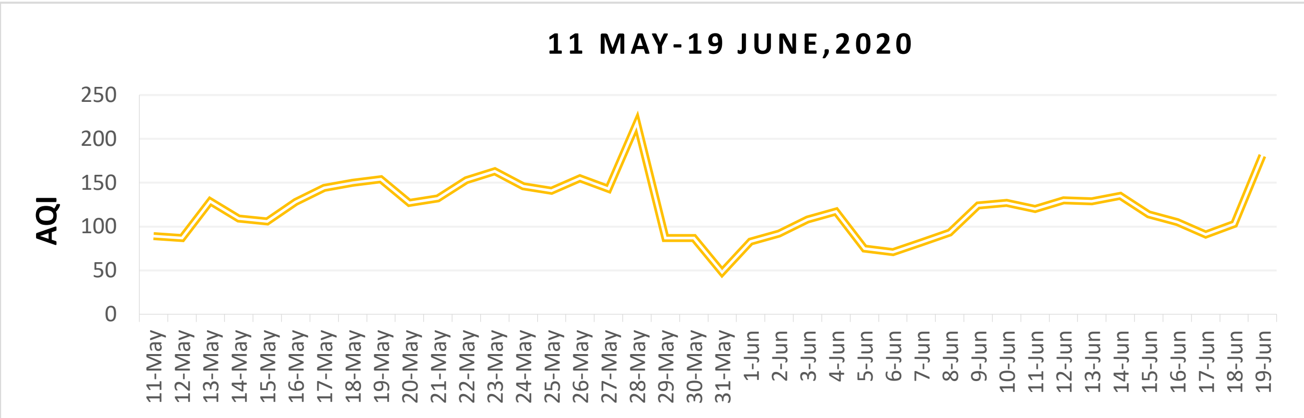


Fig. 4(E). AQI for Delhi during 11 May–19 June 2020.

standard deviation of 45.61. The maximum, minimum, and average values of March AQIs were 58.73%, 32.58%, 43.8% lower than the corresponding values of February 2020.

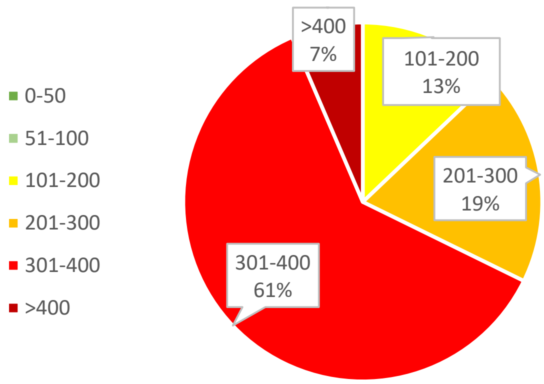
As shown in Fig. 4(D), the maximum AQI value recorded during the period 9 April–10 May 2020 was 160 while the minimum value was 59 and the average value was 101.46 with a standard deviation of 24.64 for the city of Delhi. In comparison with the maximum, minimum, and average values of AQIs of March 2020, the corresponding values of AQIs recorded from 9 April–10 May were 24.52% lower, 3.5% higher, and 7.4% lower.

As shown in Fig. 4(E), the maximum AQI value recorded in Delhi for the period 11 May–19 June 2020 was 218 while the minimum value was 48 and the average value was 119.4 with a standard deviation of 33.04. In comparison with the maximum, minimum, and average values of AQIs of 9 April–10 May 2020 period, the corresponding values of AQIs recorded during 11 May–19 June values were 36.25% higher, 18.64% lower, and 17.68% higher. The relaxation in the epidemic prevention and control actions during 9 April–10 May 2020 led to the weakening of air quality in Delhi vis-à-vis the upward movement of average AQI.

4.5 AQI Class Distribution: Delhi

As a result of the change in the concentrations of the different pollutants, the AQI classes prevailed in Delhi during the periods January, February, March, 9 April–10 May, and 11 May–19 June 2020 had shown a new pattern as evident from Figs. 5(A), 5(B), 5(C), 5(D) and 5(E). This

(5.A)

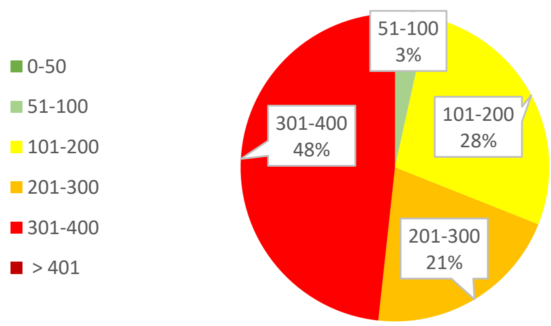


January 2020

AQI Distribution: January, 2020

0–50	51–100	101–200	201–300	301–400	> 401
0%	0%	13%	19%	61%	7%

(5.B)

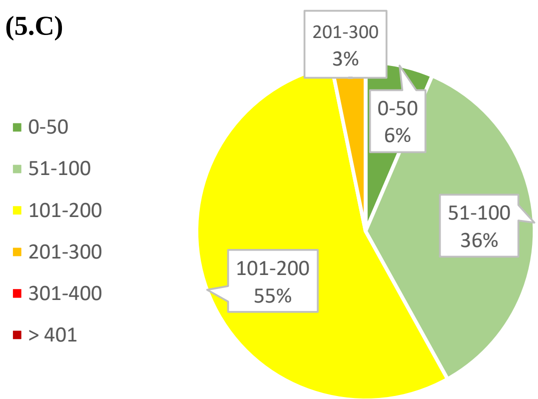


February 2020

AQI Distribution: February, 2020

0–50	51–100	101–200	201–300	301–400	> 401
0%	3%	28%	21%	48%	0%

(5.C)



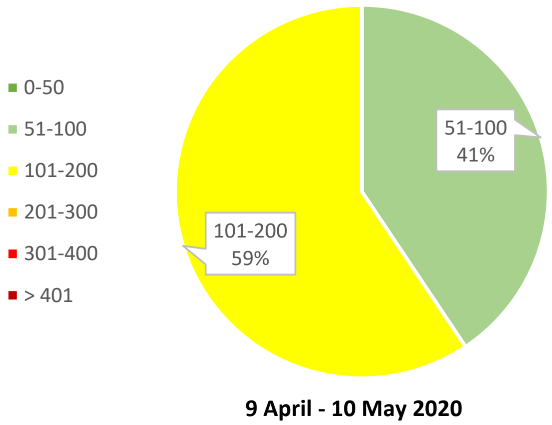
March 2020

AQI Distribution: March, 2020

0–50	51–100	101–200	201–300	301–400	> 401
6%	36%	55%	3%	0%	0%

Fig. 5. The distribution of six AQI classes of Delhi.

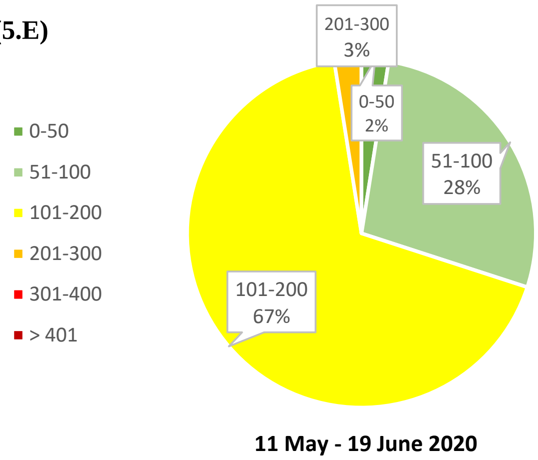
(5.D)



AQI Distribution: 9 April–10 May, 2020

0–50	51–100	101–200	201–300	301–400	> 401
0%	41%	59%	0%	0%	0%

(5.E)



AQI Distribution: 11 May–19 June, 2020

0–50	51–100	101–200	201–300	301–400	> 401
2%	28%	67%	3%	0%	0%

Fig. 5. (*continued*).

study found that Delhi experienced AQI classes I, II, III, IV, V, and VI in the proportion of 0%, 0%, 13%, 19%, 61%, and 7% respectively during January 2020 as indicated in Fig. 5(A). The January distribution of AQIs indicates a severe air quality problem for the city as 87% of the time the city found itself in the IV, V, and VI classes of AQI. The distribution of AQI classes in Delhi underwent further changes in February with 0%, 3%, 28%, 21%, 48%, and 0% in the classes I, II, III, IV, V, and VI respectively indicating somewhat betterment in the air pollution status as shown in Fig. 5(B). Fig. 5(C) indicated that during March 2020 there were AQI classes I, II, III, IV, V, and VI in the proportion of 6%, 36%, 55%, 3%, 0%, and 0% respectively. In other words, 97% of the time the city found itself in the AQI classes I, II, and III only. During the peak COVID-19 period (9 April–10 May), the AQI classes I, II, III, IV, V, and VI were distributed in the proportion of 0%, 41%, 59%, 0%, 0%, and 0% respectively for Delhi city as indicated in Fig. 5(D). It can be understood, therefore, that during the peak COVID-19 period there were only two AQI classes, i.e., class II and class III which covered the whole AQIs of Delhi indicating a marked improvement in the city level pollution standard. Further, during 11 May–19 June period, AQI classes I, II, III, IV, V, and VI were in the proportion of 2.5%, 27.5%, 67.51%, 2.5%, 0%, and 0% respectively indicating that the combined proportions of classes I, II and III decreased from previous 100% to 97.5% in the current period as shown in Fig. 5(E). In a sense, it indicates the beginning of air quality deterioration with somewhat corresponding relaxation in the strict epidemic prevention and control actions.

4.6 AQI Level and Air Pollutants

The proportion of the cumulative contribution of different pollutants in respective AQI classes prevailed in Delhi during different phases of the COVID-19 outbreak, which have been calculated out and placed in Tables 5(A) and 5(B) below. Table 5(A) indicates that during January 2020, Delhi

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Table 5(A). Contribution of different pollutants in AQI in Delhi: January and February 2020.

AQI	January 2020 (in %) (31 days)							February 2020 (in %) (28 days)						
Class	Days	$PM_{2.5}$	PM_{10}	NO_2	SO_2	CO	O_3	Days	$PM_{2.5}$	PM_{10}	NO_2	SO_2	CO	O_3
I	0	0%	0%	0%	0%	0%	0%	0	0%	0%	0%	0%	0%	0%
II	0	0%	0%	0%	0%	0%	0%	1	20%	33%	21%	6%	0%	20%
III	4	23%	42%	19%	5%	0%	11%	8	20%	44%	16%	6%	0%	14%
IV	6	29%	44%	18%	4%	0%	5%	6	22%	48%	17%	4%	0%	9%
V	19	32%	47%	14%	3%	0%	3%	14	27%	46%	16%	4%	0%	7%
VI	2	38%	49%	9%	2%	0%	2%	0	0%	0%	0%	0%	0%	0%

Table 5(B). Contribution of different pollutants in AQI in Delhi: March, 9 April–10 May and 11 May–19 June, 2020.

AQI	March, 2020 (in %) (31 days)							9 April–10 May, 2020 (in %) (30 days)							11 May–19 June, 2020 (in %) (40 days)						
Class	Days	$PM_{2.5}$	PM_{10}	NO_2	SO_2	CO	O_3	Days	$PM_{2.5}$	PM_{10}	NO_2	SO_2	CO	O_3	Days	$PM_{2.5}$	PM_{10}	NO_2	SO_2	CO	O_3
I	2	17	32	6	17	0	28	0	0	0	0	0	0	0	1	12	27	11	13	0	37
II	11	17	36	15	11	0	21	13	14	36	6	11	0	33	11	14	36	10	10	0	30
III	17	20	46	13	8	0	14	19	16	44	6	9	0	25	27	15	46	10	8	0	21
IV	1	22	45	16	6	0	11	0	0	0	0	0	0	0	1	7	66	4	5	0	17
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

had four days of class III AQIs, six days of IV AQIs, nineteen days of class V AQIs, and two days of VI AQIs while classes I and II did not occur. The predominant air pollutants for the AQI class III, in order of their contributions, were PM_{10} (42%), $PM_{2.5}$ (23%), NO_2 (19%), O_3 (11%), and SO_2 (5%). The predominant air pollutants for the AQI class IV, in order of their contributions, were PM_{10} (44%), $PM_{2.5}$ (29%), NO_2 (18%), O_3 (5%), and SO_2 (4%). Contribution of pollutants for the AQI class VI, under which the city spent the lowest number of days, i.e., two days were (in order of contribution) PM_{10} (49%), $PM_{2.5}$ (38%), NO_2 (9%), O_3 (2%), and SO_2 (2%). The critical point to be noticed that PM_{10} and $PM_{2.5}$ were the pivotal pollutants in terms of their cumulative contribution to the AQI classes before the onset of the COVID-19 epidemic.

Table 5(A) further reveals that during February 2020, Delhi experienced fifteen days of class I to IV AQI levels which were ten days during January 2020, indicating an improvement in air quality. The predominant indicatory air pollutants for each of AQI were Class I: $PM_{2.5}$ (4.8%) (followed by PM_{10} (4.4%), O_3 (0.8%), and CO (0.4%)), Class II: PM_{10} (33.%) (followed by $PM_{2.5}$ (20%), NO_2 (21%), O_3 (20%) and SO_2 (6%)), Class III: PM_{10} (44%) (followed by $PM_{2.5}$ (20%), NO_2 (16%), O_3 (14%) and SO_2 (6%)), Class IV: PM_{10} (48%) (followed by $PM_{2.5}$ (22%), NO_2 (17%), O_3 (9%) and SO_2 (4%)), respectively. The Class I and VI AQIs did not occur. Interesting to note that, PM_{10} and O_3 contributions to AQIs comparatively increased and strengthened during February than in January 2020.

Table 5(B) reveals the change Delhi experienced in terms of the indicatory air pollutants constituting the AQIs at the introduction of lockdown during March 2020 and after that. The city witnessed, possibly after many years, class I AQI level of 2 days followed by 11 days of class II AQI level, 17 days of class III AQI level, and only one day of class IV AQI level during March 2020 while classes V and VI did not occur. The predominant indicatory air pollutants for the class I AQIs, in order of their contributions, was PM_{10} (32%), O_3 (28 %), $PM_{2.5}$ (17%), SO_2 (17%), and NO_2 (6%). Almost the same pattern followed for AQI class II and III of March but with increased contribution of PM_{10} to the tune of 36% and 46% respectively and decreased contribution of O_3 of 21% and 14% respectively. Interesting to note here that as NO_2 contributions maintained a somewhat increasing trend and O_3 contributions had a decreasing trend as AQI classes moved from I to IV showing the inverse relationship between NO_2 and O_3 in the absence of sufficient VOC in the environment of Delhi under lockdown condition (Guo *et al.*, 2019).

Table 5(B) also reveals the behavior of different pollutants during the peak of the COVID-19 period, i.e., 9 April–10 May 2020 in Delhi. The city witnessed a long stretch of 13 days under class II AQI level followed by 19 days under class III level while classes I, IV, V, and VI did open their account at all. The predominant air pollutants for the AQI class II, in order of their contributions, were PM_{10} (36%), O_3 (33%), $PM_{2.5}$ (14%), SO_2 (11%), and NO_2 (6%). Again, the predominant air pollutants for the AQI class III, in order of their contributions, were PM_{10} (44%), O_3 (25%) $PM_{2.5}$ (16%), SO_2 (9%), and NO_2 (6%). The pattern indicates that for 30 days (9 April–10 May), though Delhi was experiencing comparatively favorable AQI classes (class II and III only) the dominance of PM_{10} in general and O_3, in particular, had the potential to create health hazards. This point is distinguished from the point of view that O_3 induced health effects include chest pain, coughing, throat irritation, and airway inflammation, which in turn could enhance COVID-19 induced criticalities as well.

The Table 5(B) also shows that during 40 days (11 May–19 June), which include the time of initiation of unlocking operation, Delhi had four AQI classes, i.e., class I (1 day), class II, (11 days), class III (27 days) and class IV (1 day). The predominant air pollutants for the AQI class I, in order of their contributions, were O_3 (37%), PM_{10} (27%), SO_2 (13%), $PM_{2.5}$ (12%), and NO_2 (11%). The predominant air pollutants for the AQI class II, in order of their contributions, were PM_{10} (36%), O_3 (30%), $PM_{2.5}$ (14%), NO_2 (10%), and SO_2 (10%). Contributions of pollutants for the AQI class III, in order of contribution, were PM_{10} (46%), O_3 (21%), $PM_{2.5}$ (15%), NO_2 (10%), and SO_2 (8%). Contributions of pollutants for the AQI class IV, in order of contribution, were PM_{10} (66%), O_3 (17%), $PM_{2.5}$ (7%), SO_2 (5%) and NO_2 (4%). An important point to be noticed here that during 40 days (11 May–19 June), accommodating the AQI class of 1, II, III, and IV, the O_3 contributions were 37%. 30%, 21%, and 17% respectively showing the dominance of O_3 as the indicatory air pollutants in these AQIs.

4.7 COVID-19 and its Interactions with Environmental Parameters of Delhi

At the inception of the COVID-19 outbreak, without any availability of vaccination or medication, countries resorted to a lockdown strategy to break down the COVID-19 infection cycle through social distancing. Entering into the community transmission phase, characterized by infections spreading in public without easy detection of source, highly polluted city like Delhi would require a more in-depth understanding of the behavior of criteria pollutants ($PM_{2.5}$, O_3, NO_2, and SO_2) and meteorological parameters (temperature and RH) concerning the spread of infection. Two different periods have been analyzed here, one; from 1 March to 10 May marked by inception and rapid increase of disease with strict enforcement of epidemic control measures, and two; from 11 May–19 June 2020 marked by a rapid increase of the diseases but with 'unlock' operation in force. The descriptive statistics of COVID-19 daily infection cases, the air pollutants, and the meteorological variables during these two periods can be seen in Table 6.

The correlations among the data variables are shown in Table 7. New COVID-19 cases per day maintained negative correlations with variables like $PM_{2.5}$, NO_2, and RH but positive correlations with O_3 and temperature during the 1 March–10 May 2020 period. During the 11 May–19 June period, only RH had a positive correlation with COVID-19 cases per day while O_3 and SO_2 had negative correlations as can be seen from Table 7.

4.8 Relative Humidity, Temperature and COVID-19

Recent research has highlighted that environmental factors, especially temperature and RH, are essential factors in responding to viral infections in the respiratory tract through activating

Table 6. Descriptive Statistics of the data variables of Delhi (N = 111).

Variables	1 March–10 May			11 May–19 June, 2020		
	Min	Max	Mean	Min	Max	Mean
$PM_{2.5}$ (µg m^{-3})	15.2	93.6	42.4	15.41	76.10	42.15
NO_2 (ppb)	6.5	67.1	23.9	13.56	53.93	27.31
SO_2 (ppb)	14.8	42.3	23.3	12.55	44.64	24.05
O_3 (ppb)	25.4	108.3	56.3	30.36	92.54	66.59
Temperature (°C)	15.7	33.6	25.4	25.94	38.44	33.21
RH (%)	25	90.3	53.5	17.1	73.5	42.85
COVID-19 cases/day	0	448	98	299	3137	1157

Table 7. Correlations among the data variables of Delhi.

COVID-19/day	Pearson Correlation	$PM_{2.5}$	NO_2	SO_2	O_3	Temperature (°C)	RH (%)
1March–10 May,	Coefficient	−0.301*	−0.472**	0.133	0.670**	0.548**	−0.341**
2020	N	71	71	71	71	71	71
11 May–19 June,	Coefficient	−0.245	−0.091	−0.674**	−0.402*	0.098	0.476**
2020	N	40	40	40	40	40	40

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

the immune system of human beings (Falagas *et al*., 2008; Makinen *et al*., 2009). More importantly, studies have also revealed the role of temperature and humidity on respiratory virus stability and transmission rates (Moriyama *et al*., 2020). Fig. 6 below indicates that Delhi had an average RH of around 53.5% during 1 March–10 May 2020 while the maximum recorded as 90.3% and a minimum of 25%. During this phase, the COVID-19 infection cases were also in the low ebb (average 98 cases per day) as can be seen from Fig. 6 and Table 6. The higher humid condition prevailed from 1 March–10 May also maintained a negative correlation with the daily COVID-19 cases, as indicated in Table 7. However, from 11 May–19 June 2020, when the average RH level in Delhi air was down to an average 42.85% with the maximum level stood at 73.5%, and the minimum level as low as 17.1%, it had a positive correlation with the COVID-19 infection cases. Fig. 6 and Table 6 also indicate that the COVID-19 infection increased to an average of 1157 cases per day during the 11 May–19 June 2020 period. Table 7, therefore, indicates the existence of a positive correlation between RH and daily COVID-19 infection cases when humidity level was comparatively low. Several studies in the past confirmed that air with low humidity levels might be an essential risk factor for respiratory infection diseases vis a vis increase in mortality rates (Barreca, 2012; Davis *et al*., 2016; Sajadi *et al*., 2020).

Fig. 7 indicates that Delhi had an average temperature of around 25.4°C during 1 March–10 May, with a maximum recorded as 33.6°C and a minimum of 15.7°C. Again, from 11 May–19 June, the average temperature level went up to 33.21°C with the maximum level stood at 38.44°C and the minimum level as 25.94°C. The comparatively low-temperature situation during 1 March–10 May 2020 was found to have a positive correlation (0.548) with the daily COVID-19 cases in Delhi while the comparatively high-temperature situation during 11 May–19 June found no significant correlation with the daily COVID-19 infection cases as revealed from Table 7. Therefore, in the case of Delhi, comparatively low RH and the low-temperature situation is found to be positively correlated with COVID-19 infection cases. However, it requires more studies to understand whether high RH and high temperature that prevails in other cities of India like Kolkata or Thai city Bangkok had any deterrent effect in the COVID-19 infection spread as the correlation analysis used here does not indicate any causality (Chan *et al*., 2011).

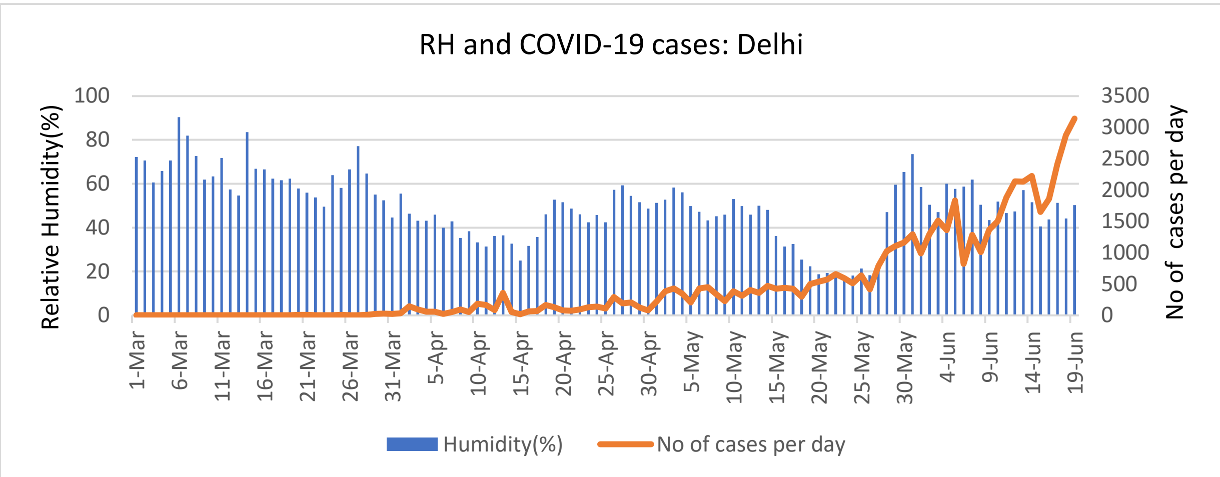

Fig. 6. RH of Delhi and confirmed cases.

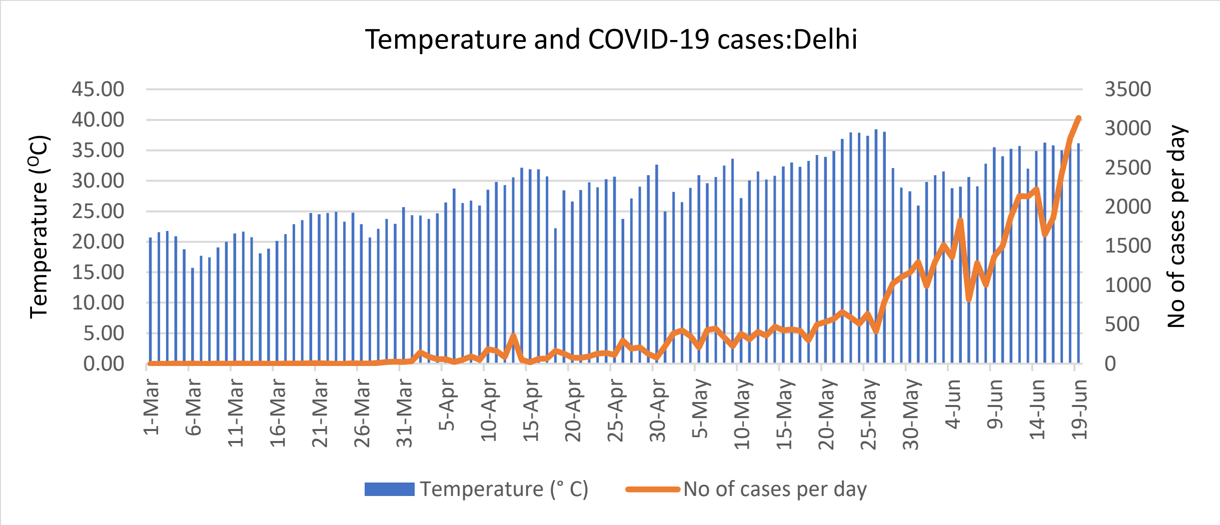

Fig. 7. Temperature of Delhi and confirmed cases.

4.9 Nitrogen Dioxide and COVID-19

As can be seen in Table 6 and Fig. 8 below that Delhi had an average NO_2 of around 23.9 ppb during1 March–10 April with a maximum recorded as 67.09 ppb and a minimum of 6.5 ppb. After that, from 11 May–19 June, the city of Delhi had a marginal rise in NO_2 level with an average of 27.31 ppb while the maximum was 53.93 ppb and the minimum was 13.56 ppb. Fig. 8 and Table 7 indicate that during phase 11 May–19 June, there was also a considerable rise of COVID-19 cases in Delhi. However, no significant correlation between NO_2 and COVID-19 cases in Delhi could be established. However, a comparatively lower NO_2 level from 1 March–10 April demonstrated a significant negative correlation with COVID-19 cases in Delhi, indicating lower NO_2 presence in the air could be a COVID-19 deterrent. Earlier studies found that chronic exposure to high NO_2 levels in the environment caused inflammation in the lungs, which could be a vital contributor to the high COVID-19 fatality rates (Ogen *et al.*, 2020). Therefore, the non-significant correlation between the comparatively higher NO_2 level and COVID-19 cases in the city of Delhi, as indicated in Fig. 8, opens a new area for further exploration.

4.10 Sulphur Dioxide and COVID-19

Delhi had an average SO_2 level of 23.3 ppb in the air from 1 March–10 May 2020 with maximum recoded as 67.1 ppb and a minimum of 6.5 ppb as can be seen from Table 6 and Fig. 9. For the period 11 May to 19 June, the average SO_2 level marginally increased to 24.05 ppb with a maximum of 44.64 ppb and a minimum of 12.58 ppb which shows a marginal change in the average SO_2 concentration level in the city during the two phases under consideration. Therefore, it will be complicated to assess the role of SO_2 with the number of daily COVID-19 confirmed cases found in Delhi at a comparative level between the two periods under consideration. However, the present study found that when the SO_2 level marginally increased from 11 May–19 June, it had a significant negative correlation with (–0.402) COVID-19 cases in Delhi (Table 7 and Fig. 9). This finding is in alignment with an earlier study of 120 Chinese cities which found a negative association of SO_2 with the number of daily COVID-19 confirmed cases (Zhu *et al*., 2020).

4.11 Ozone and COVID-19

As can be seen in Table 6 and Fig. 10 that Delhi had an average O_3 level of 56.3 ppb in the air from 1 March–10 May with a maximum recoded as 108.3 ppb and a minimum of 25.4 ppb. During May 11–June 19, the average O_3 level shot up to 66.59 ppb while maximum and minimum level recorded as high as 92.54 ppb and 30.36 ppb respectively. As shown in Fig. 10 and Table 7 that daily new COVID-19 cases for the period 1 March–10 May exhibited significant positive correlations (0.670) with O_3 but inverse correlations from 11 May–19 June, when O_3 concentration was comparatively higher. Zoran *et al*. (2000) indicated that O_3 had shown positive correlations with daily new COVID-19 cases in Milan, Italy while this study indicates that O_3 possibly exhibits a positive correlation with new COVID-19 cases under the condition of comparatively low temperature and low humidity.

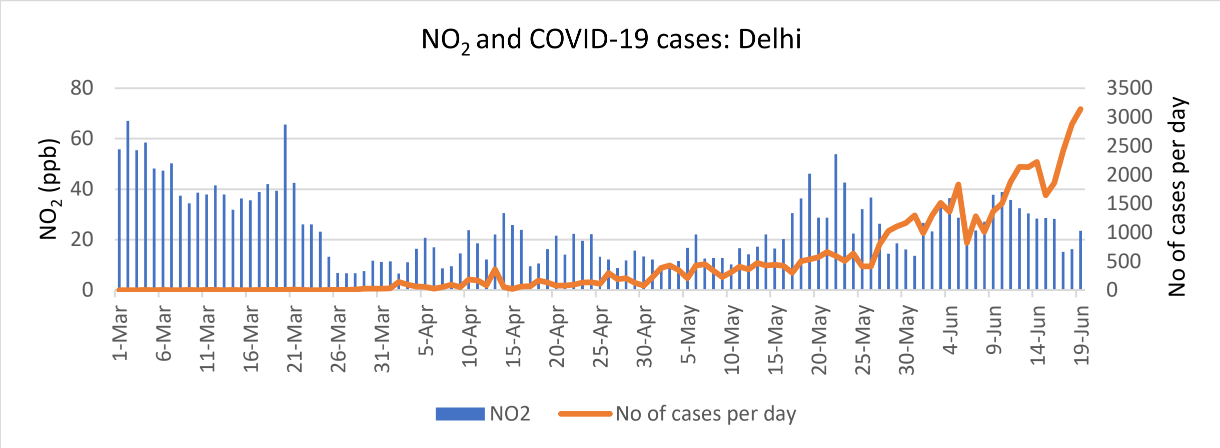

Fig. 8. NO_2 of Delhi and confirmed cases.

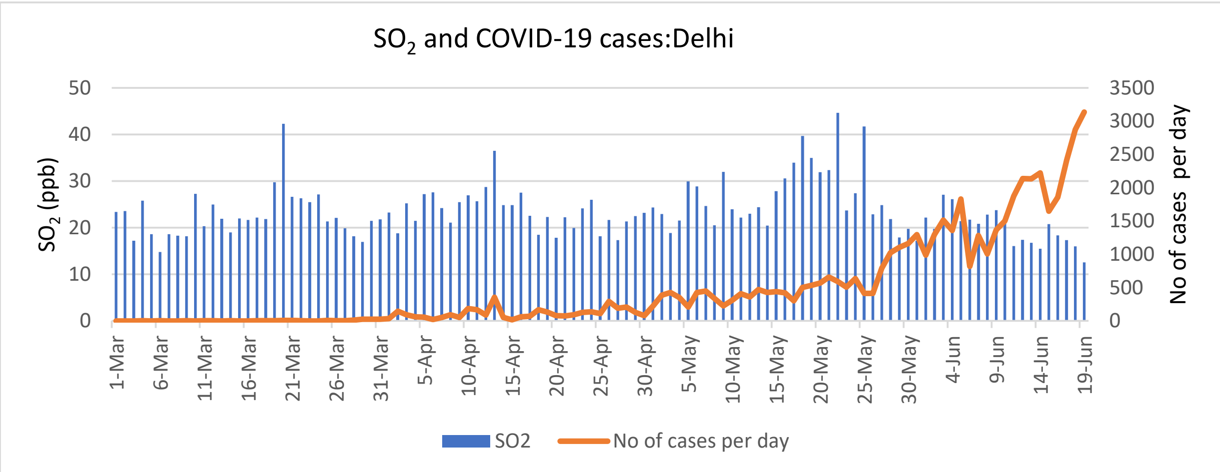

Fig. 9. SO_2 of Delhi and confirmed cases.

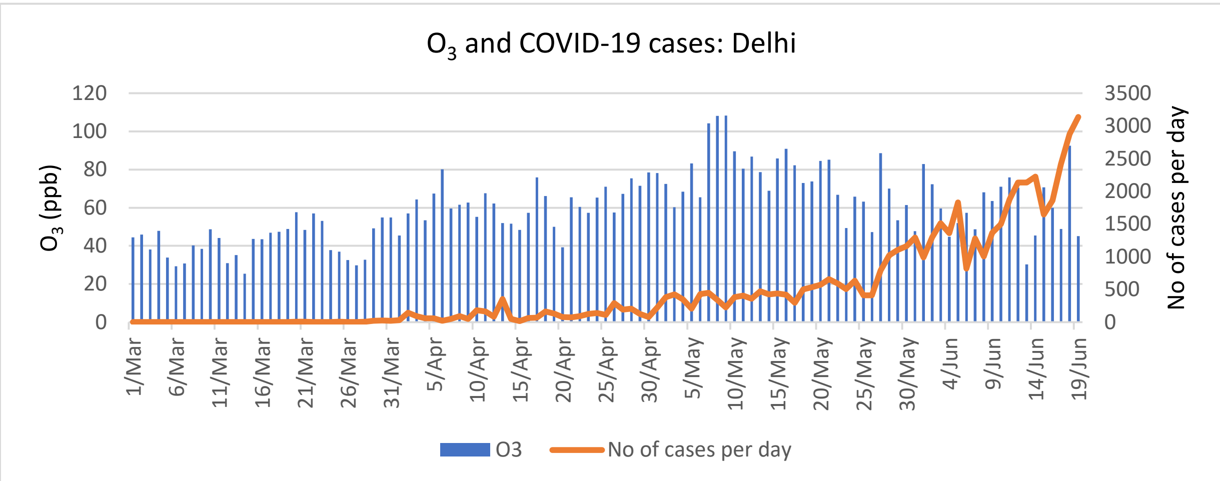

Fig. 10. O_3 of Delhi and confirmed cases.

5 CONCLUSION AND POLICY IMPLICATIONS

India is fighting hard to restrain and control the outbreak of COVID-19 in the country. Delhi is the frontrunner with the most infected cases per million population in the country. COVID-19 positive cases steadfastly increased from the first case surfaced on 4 March 2020 to 53,116 cases as of 19 June 2020 in the city with the coefficient of variation as high as 142.76%.

Based on a time series analysis of the criteria pollutants, meteorological parameters, and COVID-19 data, covering five different periods of COVID-19 outbreak in Delhi, this study found that in-between January to 11 May–19 June 2020 period, the average concentration of air pollutants like $PM_{2.5}$, PM_{10}, NO_2, and CO reduced drastically by 73.85%, 46.48%, 63.43%, and 50.18% respectively. However, air pollutants like O_3 and SO_2 increased significantly by 217.33% and 57.58 % respectively from January to 11 May–19 June 2020 period.

Just before the onset of the COVID-19 epidemic in Delhi (January and February 2020), the concentration level of the primary pollutants from vehicle emission (PM, NO_2, and CO) in the air was very high. After the lockdown policy, these pollutants decreased, but PM_{10} was still at a higher level than the NAAQS. SO_2 concentration level, before and after the lockdown policy continued to rise in Delhi. The rise of PM_{10} could be due to open burning sources, from biomass, solid waste, and domestic cooking while the rise of SO_2 could be attributed to a combination of long-distance transfer, power plant emissions in the vicinity, and biomass burning allowed even during the lockdown. The sharp rise of O_3 in Delhi was due to accumulation in the atmosphere as not enough NO was there in the air to react with O_3 to form O_2.

The ups and downs of pollutants in the atmosphere had its effects on AQI levels experienced by the city and in the proportional cumulative contribution of different pollutants constituting the AQIs of Delhi. During January 2020, i.e., before the onset of the COVID-19 epidemic, Delhi had 61.29 % of the days under AQI class V thereby indicating high air pollution with possible respiratory illness to the people on prolonged exposure. PM_{10} and $PM_{2.5}$ were pivotal pollutants in terms of their cumulative contribution to the AQI classes before the onset of the COVID-19 epidemic. During the peak COVID-19 phase (9 April–10 May 2020), though Delhi had improved AQI classes of II and III only, the pivotal pollutants in terms of their cumulative contribution to the AQI classes were PM_{10} and O_3 indicating possible health hazards mainly due to higher level of O_3 in air.

The study found that comparatively low RH and the low-temperature situation was significantly and positively correlated with the new COVID-19 infection cases in Delhi. However, it requires more studies to understand whether high RH and high temperature that prevails in other cities of the world had any deterrent effect in the COVID-19 infection spread. Comparatively lower NO_2 levels in the air demonstrated a significant negative correlation with new COVID-19 cases in Delhi. In a similar line, when the average SO_2 level in the air was marginally increased to 24.05 ppb, it had a significant negative correlation (–0.402) with new COVID-19 cases in Delhi. Daily new COVID-19 cases of Delhi exhibited significant positive correlations (0.670) with O_3 at around 56.3 ppb level, but inverse correlations during when average O_3 concentration was comparatively higher at 66.59 ppb. Possibly O_3 exhibits a positive correlation with new COVID-19 cases under the condition of comparatively low temperature and low humidity. Delhi and other cities of India are currently at a challenging phase of community transmission, and a full understanding of the association between COVID-19 and climate indicators will help them to check the diffusion of the disease by positioning correct counter-strategy in place. In this respect, some practical implications are coming out of the findings of the study. Firstly, during the winter months, Delhi's temperature comes down as low as 3 to 4 degrees Celsius. As low temperatures and low RH found to supportive of COVID-19 infection spread, the authority must prepare an anti-epidemic plan for the city if the disease continues to exist till the end of the current year and beyond. Secondly, the study has indicated that during a period (say, fortnight or month) the city can have a different combination of AQI classes based on different levels of stringency on mobility restrictions enforced. In addition, the predominance of different indicatory air pollutants also varied for the different combinations of AQIs. The authority now can selectively use lockdown as a strategy to have a desired pattern of AQIs which will be beneficial for restricting the disease to spread during different climatic conditions. Our findings have a few limitations as well. Further research, in this line, should consider data for criteria pollutants from all the ambient air quality monitoring stations of Delhi and for an extended period to have a better predictive effect of the findings. Finally, the study findings related to the correlation of air pollutants and meteorological variables with COVID-19 infection in the city are derived from statistical analysis and some amount of causal inference.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at https://doi.org/10.4209/aaqr.2020.07.0417

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