



# Did unprecedented air pollution levels cause spike in Delhi's COVID cases during second wave?

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## Abstract

The onset of the second wave of COVID-19 devastated many countries worldwide. Compared with the first wave, the second wave was more aggressive regarding infections and deaths. Numerous studies were conducted on the association of air pollutants and meteorological parameters during the first wave of COVID-19. However, little is known about their associations during the severe second wave of COVID-19. The present study is based on the air quality in Delhi during the second wave. Pollutant concentrations decreased during the lockdown period compared to pre-lockdown period (PM<sub>2.5</sub>: 67  $\mu\text{g m}^{-3}$  (lockdown) versus 81  $\mu\text{g m}^{-3}$  (pre-lockdown); PM<sub>10</sub>: 171  $\mu\text{g m}^{-3}$  versus 235  $\mu\text{g m}^{-3}$ ; CO: 0.9  $\text{mg m}^{-3}$  versus 1.1  $\text{mg m}^{-3}$ ) except ozone which increased during the lockdown period (57  $\mu\text{g m}^{-3}$  versus 39  $\mu\text{g m}^{-3}$ ). The variation in pollutant concentrations revealed that PM<sub>2.5</sub>, PM<sub>10</sub> and CO were higher during the pre-COVID-19 period, followed by the second wave lockdown and the lowest in the first wave lockdown. These variations are corroborated by the spatiotemporal variability of the pollutants mapped using ArcGIS. During the lockdown period, the pollutants and meteorological variables explained 85% and 52% variability in COVID-19 confirmed cases and deaths (determined by General Linear Model). The results suggests that air pollution combined with meteorology acted as a driving force for the phenomenal growth of COVID-19 during the second wave. In addition to developing new drugs and vaccines, governments should focus on prediction models to better understand the effect of air pollution levels on COVID-19 cases. Policy and decision-makers can use the results from this study to implement the necessary guidelines for reducing air pollution. Also, the information presented here can help the public make informed decisions to improve the environment and human health significantly.

**Keywords** COVID-19 · Second wave · Lockdown · Air pollution · Meteorological factors · New Delhi

## Abbreviations

COVID-19	Coronavirus disease 2019
CO	Carbon monoxide
CPCB	Central pollution control board, India
DPCC	Delhi pollution control committee
GLM	General linear models
IITM	Indian institute of tropical meteorology
IMD	Indian meteorological department
MERS	Middle East respiratory syndrome
MoHFW	Ministry of health and family welfare, India
NO <sub>x</sub>	Nitrogen oxides
O <sub>3</sub>	Ozone
PM	Particulate matter
RH	Relative humidity

SARS	Severe acute respiratory syndrome
SARS-CoV-2	Severe acute respiratory syndrome coronavirus 2
VOCs	Volatile organic compounds

## 1 Introduction

In the twenty-first century, COVID-19 is the new coronavirus that was acknowledged as a pandemic after the two coronaviruses which resulted in severe acute respiratory syndrome (SARS) and Middle East Respiratory Syndrome (MERS), also declared as a pandemic in the years 2003 and 2012, respectively (Ramadan and Shaib 2019; Zhong et al. 2003). These coronaviruses relate to the Coronaviridae family. These viruses are typically between 65–125 nm in

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diameter, 26–32 kbs in length (Shereen et al. 2020). COVID-19 is caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) which spread across the globe quickly, forcing the WHO to announce it as a global pandemic on 11 March 2020. The SARS-CoV-2 is a highly transmissible virus that has catastrophic effects on the world's demographics accounting for more than 4.5 million deaths worldwide (as of 06 September 2021) (<https://covid19.who.int/>). As of 22 June 2021, four variants have been identified as variants of concern: (1) Alpha (B.1.1.7)—initially reported in December 2020 in the United Kingdom; (2) Beta (B.1.351)—also reported in December 2020 at South Africa; (3) Gamma (P.1)—reported in early January 2021 at Brazil; and (4) Delta (B.1.617.2)—reported in December 2020 in India (Casella et al. 2021).

In India, the first reported coronavirus case was from persons who returned from Wuhan, China to Kerala on 30 January and 03 February 2020. A month later, two cases were reported from the travelers who had visited Italy and Dubai on 03 March 2020. A few more cases were reported in Jaipur on the same day (Patrikar et al. 2020). The Ministry of Health and Family Welfare (MoHFW) of India issued several travel advisory restrictions including a self-quarantine of 14 days to all international travelers returning to the country. Further, on 24 March 2020, the first phase of national lockdown was announced, which was further extended by several phases till 31 May 2020 (Saha et al. 2020). At the end of the lockdown, India recorded 1,90,648 confirmed cases and 5407 deaths. Metropolitan cities like Delhi were identified as COVID-19 hotspots where ~ 40% of total cases in India were reported.

India became the third most infected country during the first wave with 2,92,258 active cases, 22,674 deaths with a recovery rate of 60.86% (Ghosh et al. 2020). After several months of lockdown, the daily confirmed cases and deaths were reduced across the country. The emergence of the second wave in early March 2021 resulted in the surge in daily cases which rose rapidly in April 2021 and was responsible for about 21,077,410 cases and 2,22,000 deaths (Lancet 2021). The number of active cases and deaths during the second wave COVID-19 were approximately 72 times and 10 times higher respectively compared to first wave in India. During the second wave, Delhi was the most affected among other cities. On average, there were 8500 daily confirmed cases between March–May 2021 with the highest number of cases on 19 April 2021 (20,395 confirmed cases). Witnessing the high daily cases, the Government of Delhi announced a lockdown on 20 April 2021 and it continued till 07 June 2021. During the second wave, hospitals were overwhelmed, and healthcare workers were exhausted. There were severe shortages of hospital beds, medical oxygen cylinders, and other necessities. The

cremation sites were being overflowed with bodies (Chakraborty et al. 2021). By the starting week of June 2021, the daily active cases were reduced, and the unlock phase started on 08 June 2021 in Delhi.

Previous studies in several countries observed the interrelation of PM, CO, and O<sub>3</sub> with the COVID-19 confirmed cases and deaths (Thapliyal et al. 2022; Naqvi et al. 2022; Kumar et al. 2022; Chelani and Gautam 2022; Bherwani et al. 2021). A recent review also concluded that there was a strong correlation between chronic exposure to outdoor air pollutants with the likelihood of developing COVID-19 instances as well as its severity and fatality during the second wave (Marquès and Domingo 2022). Despite the fact that the scientific evidence is significantly more sparse, several research suggest that PM<sub>2.5</sub> and PM<sub>10</sub> are potential airborne transmitters of the virus in connection to the impact of outdoor air pollution on the transmission of SARS-CoV-2 (Fattorini and Regoli 2020). Previous studies also indicated that meteorological parameters can have the ability to influence the spread and thriving of multiple viruses. Temperature, relative humidity, and wind speed are considered as the crucial factors for the spread of COVID-19 (Ahmadi et al. 2020; Auler et al. 2020; Iqbal et al. 2020; Şahin 2020; Xie and Zhu 2020; Wu et al. 2020; Gautam et al. 2021; Chelani and Gautam 2021). Nonetheless, it was also observed that the pollutant concentration levels decreased across different countries during the lockdowns (Ravina et al. 2021). A study conducted in 44 Chinese cities at the lockdown concluded that the concentrations of PM (2.5 and 10) and CO levels were reduced by 5.9%, 13.6%, and 4.5% respectively (Bao and Zhang, 2020). A similar study during the lockdown period on air quality in Spain found a considerable reduction of air pollutant concentrations (Tobías et al. 2020). Singh et al. (2020) reported that there were reductions in PM<sub>2.5</sub>, PM<sub>10</sub> (~ 40–60%), and CO levels (~ 20–40%) during lockdown at 134 locations across India. They also found that air quality levels in Delhi had enhanced significantly at the time of lockdown. Many studies across the capital city Delhi reported better air quality levels during the lockdown period (Dhaka et al. 2020; Kolluru et al. 2021; Mahato et al. 2020; Maji et al. 2021; Shehzad et al. 2020; Srivastava et al. 2020; Vadrevu et al. 2020). All these studies were carried out during the COVID-19 first wave. During the second wave, rather than nationwide lockdown, the decision was left upon individual states to implement their own lockdowns depending upon the severity of the cases. Operationally, the second wave lockdown in New Delhi (and across India) was lenient. The people did not follow social distancing rules, avoided wearing masks and neglected relevant COVID-19 protocols. Most people came on roads for attending their jobs in industries and for their daily needs causing rise in the vehicle density across the

city. Due to these consequences combined with severity of the mutated virus, huge population were highly affected causing a greater number of deaths.

Most of the studies observing the relationship of air pollution and COVID-19 were conducted during the first wave. However, very few studies were conducted on air quality during the second wave lockdown in India. This forms the basis of our study. The study's main aim is to understand the influence of air pollution combined with meteorology during the second wave COVID-19 in Delhi. The specific goals are to (a) evaluate the pollutant concentrations during the second wave and compare them to the first wave; (b) observe the second wave's spatiotemporal variability of pollutants across Delhi; and (c) determine the relationship between the second wave's confirmed cases, deaths and the pollutant concentrations and meteorological variables. This study reports the missing knowledge on air pollution and COVID-19 interaction during the second wave and adds the information about the spatiotemporal variability of the air pollutants in Delhi. The remainder of the article is structured as follows: the methodology is discussed in detail in Sect. 2, along with the study area's description, the data collection methods, and the techniques used for data analysis. The results and observations are discussed in Sect. 3, and the study is concluded in Sect. 4.

## 2 Materials and methods

### 2.1 Study area

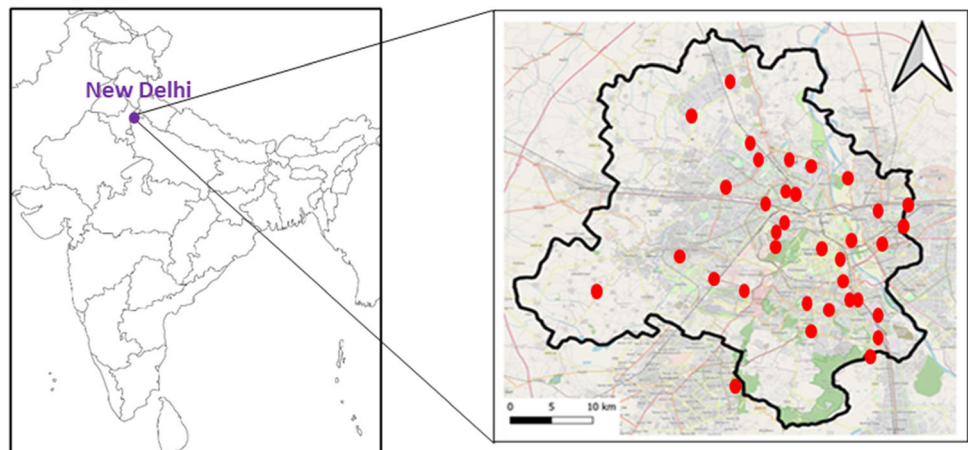
Delhi is the administrative capital of India. With a total area of 1484 km<sup>2</sup>, it is the largest city in India (Fig. 1) and the second-largest megacity in the world. The city has a population of 16.78 million with a density of 11,297 persons/km<sup>2</sup> which is the highest in the country (<https://cen.susindia.gov.in/>). The city lies between 28°24'17"N and

28,053'00"N latitude and 76°50'24"E and 77°20'37"E longitude. Delhi is located at an elevation of 216 m above Main Sea Level (MSL) within the Indo-Gangetic alluvial plains (Sahay, 2018). The city has semi-arid climatic conditions and is distinguished by four distinct seasons: summer (March–May); monsoon (June–August); post-monsoon (September–November); and winter (December–February) (Kumar et al. 2017). During summer, the temperature peaks at 48 °C with dry weather conditions. The city receives 80% of the total annual rainfall during the monsoon. Most of the year, the winds are westerly except during monsoon when the direction is reversed (Gurjar et al. 2016). About 90% of the city population resides in urban settings, which is way higher than the national average of 31% (SAD, 2014). The city is characterized by high vehicle density. In 2015 alone, the city witnessed 8.8 million vehicle registrations (including transport and non-transport vehicle categories) (<http://mospi.nic.in/statistical-year-book-india/2017/189>). The on-road vehicles are projected to increase up to 25 million by 2030 from 6.9 million vehicles registered during 2011. It is the most polluted city in India and the world with an annual mean PM<sub>2.5</sub> concentration of 153 µg m<sup>-3</sup> (<http://edition.cnn.com/2014/05/08/world/asia/india-pollution-who/>). The children and women in Delhi are affected by asthma and lung cancer due to the dangerously high concentration levels of air pollutants (Manisalidis et al. 2020; Sharma et al. 2013).

### 2.2 Data collection

To study the short-term variability of the air pollution levels during the second wave of COVID-19, the ambient concentration of four pollutants such as PM<sub>2.5</sub>, PM<sub>10</sub>, CO, and O<sub>3</sub> were collected. According to previous studies (Jain and Sharma 2020; Kumar et al. 2020; Mahato et al. 2020; Sharma et al. 2020), these pollutants were mostly affected during COVID-19 in India. The meteorological variables that were

**Fig. 1** Study area including the locations of air quality monitoring stations



considered for this study included temperature, relative humidity, and wind speed. All these pollutants and meteorological parameters are regularly monitored by the central and state governments of India using a network of monitoring stations (<https://app.cpcbcr.com/ccr/#/caaqm-dash-board-all/caaqm-landing/data>). The data were collected from all monitoring stations operating in Delhi (Table 1). Data of the second wave of COVID-19 cases and deaths were compiled from the Health Ministry of India and a private volunteer-driven network (<https://www.covid19india.org/>).

### 2.3 Data analysis

To determine the variability in the concentration of the pollutants during the COVID-19 s wave, two time periods were considered: pre-lockdown period (18 March 2021–19 April 2021) and lockdown period (20 April 2021–07 June 2021). By following the outlier removal protocol described in Spinazzè et al. (2015), the outliers present in the data (data were hourly averaged) were removed. Data greater than the ninety-nine percentile and lower than first percentile were omitted from the final datasets. It was observed that there were approximately 5% missing data for each variable. Descriptive statistics were calculated for the pollutant concentrations and meteorological variables during pre-lockdown and lockdown periods. Non-parametric

statistical tests such as the Kruskal Wallis H test and Mann–Whitney U test were conducted to identify the significant differences in the pollutant concentrations and meteorological variables during the two periods.

Additionally, the pollutant concentrations obtained during the second wave lockdown period (2021) were compared with the first wave lockdown (2020) and pre-COVID period (2019) for the same months March–May. Pollutant's spatiotemporal variability during these periods are mapped for all the pollutants using the Kriging method in ArcGIS. Spearman's correlations were used to identify the associations of air pollutant levels and meteorological variables with COVID-19. General Linear Models (GLM) were utilized to determine the variables that may demonstrate the variations in confirmed cases and deaths. These models were run separately for two different periods. IBM SPSS Statistics 25.0 was used for all the statistical tests.

## 3 Results and discussion

### 3.1 Pollutants concentration during the second wave of COVID-19

The descriptive of the pollutant concentrations during the pre-lockdown (18 March 2021–19 April 2021) and the

**Table 1** List of air quality monitoring stations operating in Delhi

Sl. no.	Station name	Operating agency	Sl. no.	Station name	Operating agency
1	Alipur	DPCC	21	Mandir Marg	DPCC
2	Anand Vihar	DPCC	22	Mundka	DPCC
3	Ashok Vihar	DPCC	23	NSIT Dwarka	CPCB
4	Aya Nagar	IMD	24	Najafgarh	DPCC
5	Bawana	DPCC	25	Narela	DPCC
6	Burari Crossing	IMD	26	Nehru Nagar	DPCC
7	CRRI Mathura road	IMD	27	North Campus-DU	IMD
8	Chandni Chowk	IITM	28	Okhla Phase 2	DPCC
9	DTU	CPCB	29	Patparganj	DPCC
10	Dr. Karni Singh Shooting Range	DPCC	30	Punjabi Bagh	DPCC
11	Dwarka-Sector 8	DPCC	31	Pusa	DPCC
12	East Arjun Nagar	CPCB	32	Pusa	IMD
13	IGI Airport (T3)	IMD	33	RK Puram	DPCC
14	IHBAS, Dilshad Garden	CPCB	34	Rohini	DPCC
15	ITO	CPCB	35	Shadipur	CPCB
16	Jahangirpuri	DPCC	36	Siripuri	CPCB
17	Jawaharlal Nehru Stadium	DPCC	37	Sonia Vihar	DPCC
18	Lodhi Road	IITM	38	Sri Aurobindo Marg	DPCC
19	Lodhi Road	IMD	39	Vivek Vihar	DPCC
20	Major Dhyan Chand National Stadium	DPCC	40	Wazipur	DPCC

\*CPCB Central Pollution Control Board, DPCC Delhi Pollution Control Committee, IMD Indian Meteorological Department, IITM Indian Institute of Tropical Meteorology

lockdown periods (20 April 2021–07 June 2021) during the second wave of COVID-19 in Delhi are shown in Table 2. It was observed that, except O<sub>3</sub>, the lockdown period mean pollutant concentrations were comparatively lesser than the pre-lockdown mean concentrations. For instance, mean PM<sub>2.5</sub> concentrations at the time of lockdown were  $67.2 \pm 12.3 \mu\text{g m}^{-3}$ , about 0.8 times lower, compared to  $81.7 \pm 17.5 \mu\text{g m}^{-3}$  obtained during the pre-lockdown period (Table 1). Similarly, the mean concentration levels of PM<sub>10</sub> and CO in pre-lockdown were 1.3 and 1.1 times the lockdown period concentrations, respectively. However, the mean O<sub>3</sub> concentrations were higher during the lockdown period ( $57.6 \pm 20.6 \text{ mg m}^{-3}$ ) in comparison to the pre-lockdown period ( $39.1 \pm 16.5 \text{ mg m}^{-3}$ ). Mann–Whitney U test was performed to evaluate the similarity in these scenarios. The test showed that the pollutant levels were dissimilar during the two lockdown periods ( $p \leq 0.05$ ). In summary, concentrations of PM<sub>2.5</sub>, PM<sub>10</sub>, and CO followed the trend: lockdown < pre-lockdown, and O<sub>3</sub> concentrations followed the trend: lockdown > pre-lockdown period.

The lower concentrations of PM<sub>2.5</sub>, PM<sub>10</sub>, and CO during the lockdown period compared to the pre-lockdown period in our study were similar to several earlier studies which were conducted during the first wave (Kumar et al. 2022; Kolluru et al. 2021; Mahato et al. 2020; Sharma et al. 2020) and second wave of COVID-19 (Shukla et al. 2021). During the lockdown, several restrictions were imposed on personal travel, economic and outdoor activities. Due to the restrictions on vehicular traffic in the city, the concentrations of PM and CO which are considered as the tracers of the tailpipe emissions, were less during the lockdown period (Kolluru et al. 2020; Kumar et al. 2020). Conversely, the O<sub>3</sub> concentrations increased. Several studies in India, Mexico, Ecuador, China, and many European cities reported a comparable increase in ozone concentrations during the first wave of COVID-19 (Grange et al. 2021; Kolluru et al. 2021; Peralta et al. 2021; Zhao et al. 2021). There may be several reasons for the increase in the O<sub>3</sub> concentrations during the lockdown period. Stagnant weather conditions of Delhi city coupled with higher temperatures might have favored the production rates and

photochemical reactions of ozone. Near-surface O<sub>3</sub> concentrations can also be increased due to the property changes in warm and polluted air masses (Garrido-Perez et al. 2019; Sun et al. 2017). Additionally, anthropogenic emissions, VOCs combined with meteorology may also play a significant role in ozone generation (Kolluru et al. 2021).

### 3.2 Summary of meteorological parameters during the second wave of COVID-19

The variations in the meteorological parameters at the time of study are summarized in Table 3. A marginally higher temperature was observed during the pre-lockdown (33.5 °C) with respect to the lockdown period (32.5 °C). Humidity (44.8%) and wind speed ( $0.9 \text{ m s}^{-1}$ ) were higher during the lockdown period. The weather was relatively stable during these periods with temperature, RH, and wind speed varying between 30.6 and 34.4 °C, 20.6–72.1%, and  $0.5\text{--}1.7 \text{ m s}^{-1}$  respectively. Nevertheless, the differences observed in these meteorological parameters between the pre-lockdown and lockdown periods were significant (Mann–Whitney U test,  $p \leq 0.05$ ).

### 3.3 Variation in pollutant levels during COVID-19 lockdowns

The mean pollutant concentrations during pre-lockdown (normal) times (during the same months as lockdown) and during first wave and second wave lockdowns are shown in Fig. 2. PM<sub>2.5</sub>, PM<sub>10</sub>, and CO concentrations were higher during the pre-lockdown period (2019) when compared to first wave (2020) and second wave (2021) lockdowns due to no restrictions during the pre-lockdown period. The highest increase in the mean concentrations of  $52 \mu\text{g m}^{-3}$  was observed for PM<sub>10</sub> that increased from  $119 \mu\text{g m}^{-3}$  during the first wave lockdown to  $171 \mu\text{g m}^{-3}$  during the second wave lockdown. For PM<sub>2.5</sub>, the mean concentrations increased by  $14 \mu\text{g m}^{-3}$  during the second wave lockdown. Similarly, the CO and O<sub>3</sub> concentrations during the second wave lockdown increased by  $0.1 \text{ mg m}^{-3}$  and

**Table 2** Descriptive of pollutants concentrations during the second wave of COVID-19

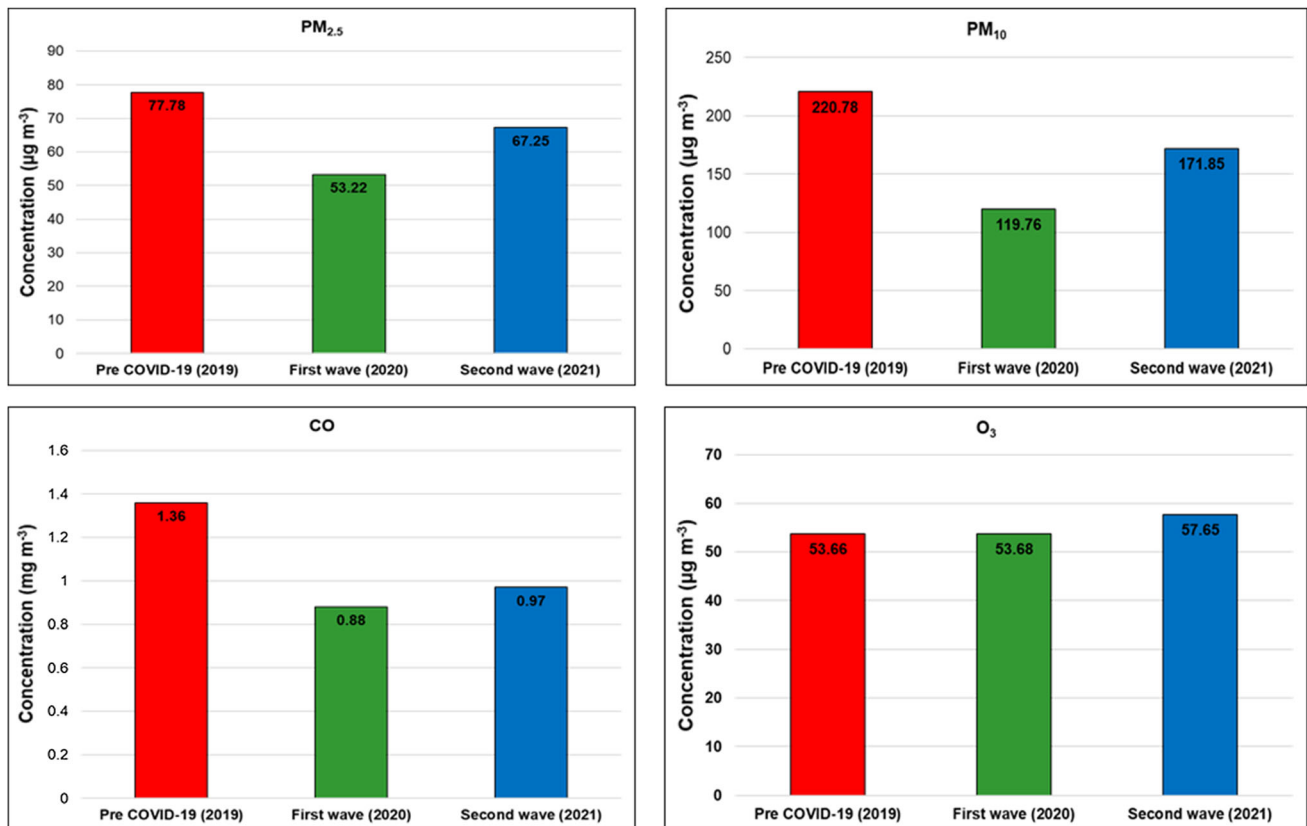
Pollutants	Pre-lockdown				Lockdown			
	Mean	SD	Median	95% CI	Mean	SD	Median	95% CI
PM <sub>2.5</sub> ( $\mu\text{g m}^{-3}$ )	81.7*	17.5	78.8	78.2–88.1	67.2*	12.3	67.8	62.7–71.7
PM <sub>10</sub> ( $\mu\text{g m}^{-3}$ )	235.7*	45.1	231.3	219.1–252.2	171.8*	29.7	16.1	160.9–182.7
CO ( $\text{mg m}^{-3}$ )	1.1*	0.3	0.9	0.9–1.2	0.9*	0.3	0.8	0.8–1.1
O <sub>3</sub> ( $\mu\text{g m}^{-3}$ )	39.1*	16.5	36.9	33.1–45.2	57.6*	20.6	41.9	37.9–53.1

\*All pollutants vary significantly across the two lockdown periods ( $p \leq 0.05$ )

**Table 3** Meteorological parameters during the second wave of COVID-19

	Temperature (°C)			Relative humidity (%)			Wind speed (m s <sup>-1</sup> )		
	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max
Pre lockdown	33.5 ± 0.4*	33.1	34.4	35.6 ± 8.4*	20.6	48.6	0.9 ± 0.2*	0.7	1.5
Lockdown	32.5 ± 1.1*	30.6	34.3	44.8 ± 11.8*	29.8	72.1	0.9 ± 0.2*	0.5	1.7

\* Meteorological variables during two study periods vary significantly ( $p \leq 0.05$ )

**Fig. 2** Mean pollutant concentrations during the first wave and the second wave lockdown periods

4  $\mu\text{g m}^{-3}$  respectively, compared to the first wave lockdown.

The mean concentrations of all pollutants were higher during the second wave lockdown than during the first wave lockdown. The nationwide lockdown in India during the first wave was the strictest lockdown in the world (Hale et al. 2021). Strict restrictions were imposed on every sector of the country during the first wave lockdown that severely impacted the transport, business, and manufacturing sectors. Due to the country's restrictions on industrial, commercial, and personal activities, the overall pollutant concentration decreased. However, during the second wave, a nationwide lockdown was not implemented as in the case of the first wave. The Union Government of India permitted to individual States to implement their lockdown as and when required. Based on the seriousness of COVID cases in Delhi, the local government imposed

the lockdown on 20 April 2021. During the second wave, the Delhi government was conscious of maintaining a stable economy in addition to the restriction on people's mobility during the second wave. It can be understood by the several relaxations granted by the local government which includes running of the industries, interstate and air travel, etc. (<https://www.indiatoday.in/coronavirus-outbreak/story/lockdown-in-delhi-2021-rules-timings-duration-everything-you-need-to-know-1792528-2021-04-19>). Due to these relaxations, emission-intensive activities were ongoing during the second wave lockdown. As a result, the pollutant concentrations across the city were higher than that was recorded during the first wave lockdown.

The variability in the pollutant concentrations during the first wave (2020) and second wave (2021) is shown in Fig. 3. The analysis is based on the data for the whole year 2020 and up to June 2021. The 2020 data shows how the

pollutant concentrations declined during the lockdown and escalated during the unlock periods. It can be observed that  $PM_{2.5}$ ,  $PM_{10}$ , and CO concentrations decreased gradually from April 2020 (the first wave lockdown was imposed on March 24, 2020) and were very less until August 2020. With the gradual lifting of the lockdown, the pollution levels started increasing from September 2020 and reached the highest concentrations during October–November 2020. The variability of these pollutants' concentrations followed an approximate U shape during the year 2020. On the contrary, the  $O_3$  concentrations followed an inverted V shape (Fig. 3). Ozone concentrations peaked during April–May 2020, which are the months of the first wave lockdown, and the concentrations declined during July–August 2020 (unlock period). A similar increase in  $O_3$  concentrations during the lockdown period was observed in several previous studies (Grange et al. 2021; Kolluru et al. 2021; Peralta et al. 2021; Zhao et al. 2021). Due to the strong reduction in  $NO_x$  emissions due to reduced road travel during the lockdown, the ozone concentrations might have increased due to the lower titration of  $O_3$  by NO (Sicard et al. 2020). The second wave's data was only considered until the end of June 2021. The gradual decrease of PM and CO concentrations and increase of  $O_3$  concentrations during the year 2021 was similar to the pattern observed in 2020.

To check the similarities in the pollutant concentrations, the percentage variability in the concentrations was calculated for two time periods: January–March (pre-lockdown period) and April–May (lockdown period) for the years 2020 and 2021. It can be seen from Table 4 that the highest percentage change in pre-lockdown period concentrations was observed for CO and  $PM_{10}$  (28%), followed by  $PM_{2.5}$  (23%). The least change was observed for  $O_3$  concentrations (3.6%). Therefore, the  $O_3$  concentrations were almost similar during the pre-lockdown periods of 2020 and 2021. During the lockdown periods of 2020 and 2021, the highest percentage change was observed for CO (36%), followed by  $PM_{10}$  (30%) and  $PM_{2.5}$  (23%). However, for  $O_3$  concentrations, the percentage change obtained was  $-22\%$ , which indicates that the mean concentrations were higher in the year 2020 when compared to 2021. Due to the severity of the nationwide lockdown during the first wave, the pollutant concentrations were lower compared to the second wave lockdown implemented in 2021.

### 3.4 Spatiotemporal variability of the pollutants during the second wave

The spatiotemporal variability in the pollutant concentrations was mapped for Delhi city by Kriging method in

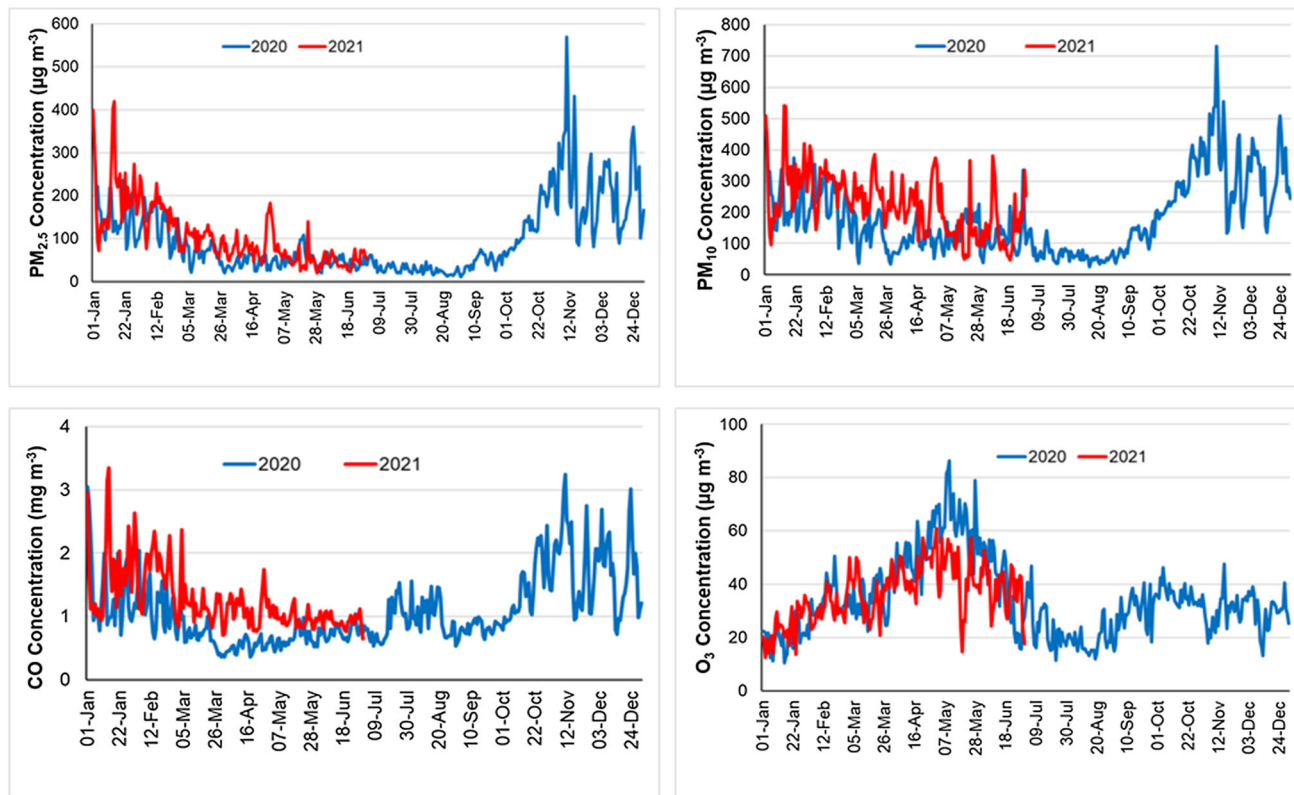


Fig. 3 Variations in pollutant concentrations during the first wave (2020) and second wave (2021) COVID-19

**Table 4** Percentage changes in mean pollutant concentrations during the two lockdowns

Pollutants	Pre lockdown (Jan–Mar) 2021	Pre lockdown (Jan–Mar) 2020	% Change in concentration	Lockdown (Apr–May) 2021	Lockdown (Apr–May) 2020	% Change in concentration
PM <sub>2.5</sub> ( $\mu\text{g m}^{-3}$ )	152.4	116.4	23.5	62.2	47.6	23.5
PM <sub>10</sub> ( $\mu\text{g m}^{-3}$ )	278.5	200.2	28.1	175.3	123.4	29.6
CO ( $\text{mg m}^{-3}$ )	1.5	1.1	28.2	1.0	0.6	36.0
O <sub>3</sub> ( $\mu\text{g m}^{-3}$ )	30.3	29.2	3.6	42.1	51.4	– 22.4*

\*Negative percentage change indicates that the concentrations were higher during the year 2020

ArcGIS. Figure 4 depicts the variations of all pollutants during the pre-lockdown and lockdown period. During the pre-lockdown period, PM<sub>2.5</sub> and PM<sub>10</sub> concentrations were higher in northern and central parts of Delhi (Fig. 4a and c). The northern and central parts of Delhi are characterized by high population and important business centers. Major pollution hotspots such as Mundka, Jahangirpuri, Chandni Chowk and Karol Bagh are in the northern and central parts of Delhi. CO concentrations were higher in the eastern to southern part of Delhi (Fig. 4e). Some of the important areas with high vehicle densities such as Lajpat Nagar, Ashram Chowk, Saket, Yusuf Sarai etc. located in these areas. Similar observations of higher concentration of pollutants in these areas were found in earlier studies (Jain and Sharma 2020; Singh and Kumar 2021). However, the concentrations of these pollutants decreased due to restrictions on the people's movement. These reduced concentrations are evident in the maps with lower concentration indicating green (Fig. 4b, d and f). On the contrary, the ozone concentrations were higher during the lockdown period (Fig. 4h).

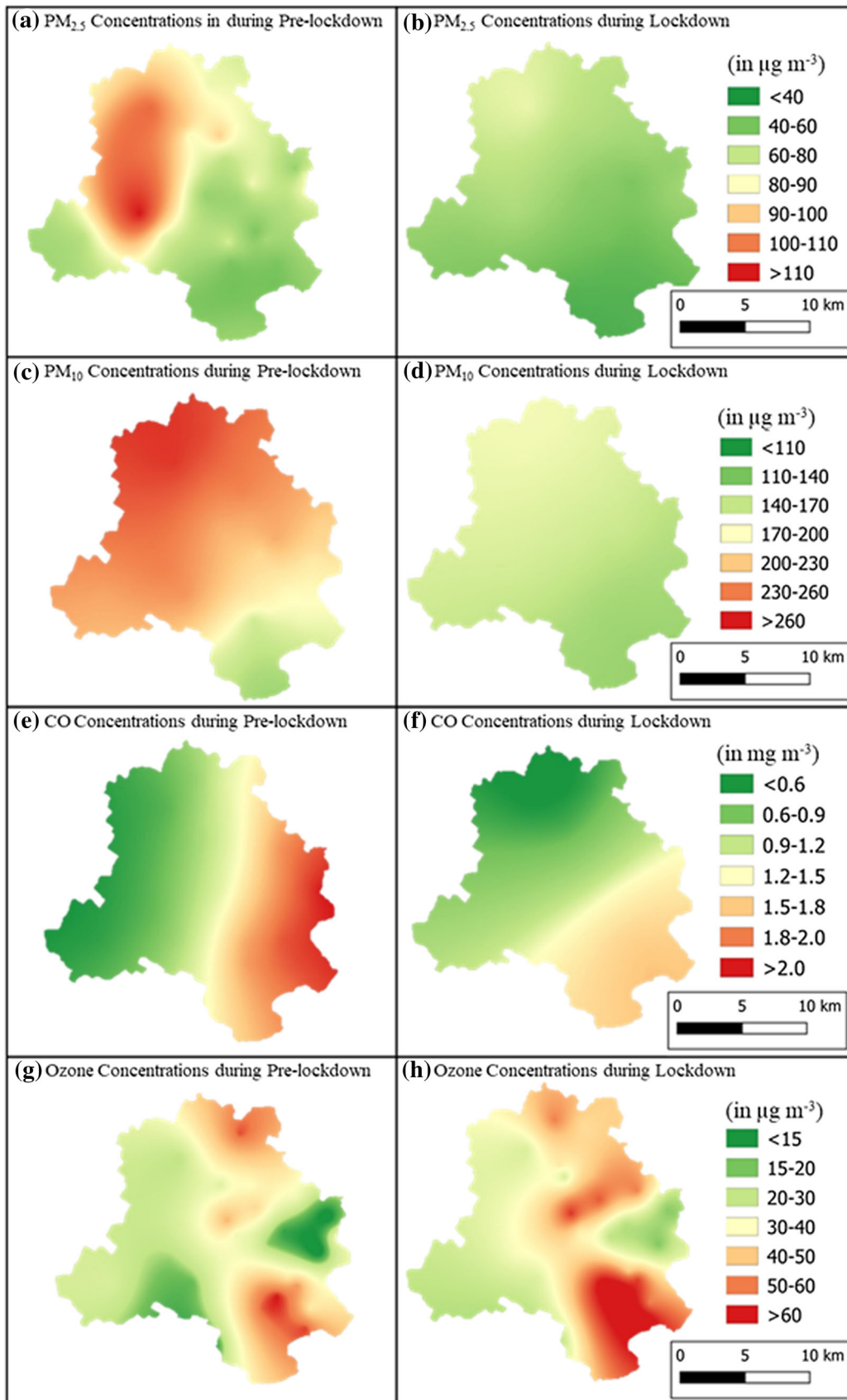
### 3.5 Confirmed cases and deaths of second wave COVID-19

Figure 5 depicts the trends of daily confirmed cases and deaths during the two waves of COVID-19. The data considered was for the months March–May 2020, and 2021. These months represent the rise and fall of COVID-19 in India during both the waves as seen from the figure. There was an immense rise in the number of daily confirmed cases and deaths during the second wave than in the first wave. During the three months of first wave (March–May), a total of 19,849 cases and 473 deaths recorded. During the second wave, however, the number of cases were 786,951 and the 13,327 total deaths. This is a ~ 40-fold increase for confirmed cases and ~ 28-fold increase of death during the second wave. On average, there were 218 daily cases and 5 deaths throughout the first wave and 8554 cases and 145 deaths during the second wave. During the second wave, the daily cases peaked from mid-April to

**Fig. 4** Spatiotemporal variability in pollutant concentrations across Delhi during pre-lockdown and lockdown periods

the first week of May. However, by the end of May, there was a drastic fall in the number of cases and deaths (Fig. 4). The virulence of the second wave COVID-19 was higher than the first wave in India. In addition to high population density, the evolution of the virus with varied pathogenicity and transmissibility increased chances of mutation, replication of the virus (Asrani et al. 2021). Previous studies have identified various SARS-CoV-2 multiple mutant strains. These strains were reported to be more infectious than the strains identified in the first wave. The highly contagious double mutant strain B.1.617 with the key structural mutations Glu484Gln and Leu452Arg is less influenced by the current vaccine doses and is responsible for the second wave COVID-19 in India (Cherian et al. 2021). Additionally, the presence of the triple mutant strain B.1.618, along with B.1.351, B.1.1.7, and P.1 which are discovered in other countries are the major reasons for the deteriorating COVID-19 situation in India (Boehm et al. 2021; Sahoo et al. 2021). The first wave infected the population aged > 60 years more, with an increased risk of death who had comorbid conditions. However, the second wave infected more the younger population aged 25–60 years (Asrani et al. 2021). Due to the higher proportion of the younger population in India, the daily confirmed cases are way higher than the first wave. A major observation during the surge of the second wave was that the patients with a rapid decrease in oxygen saturation levels mostly expired. Moreover, after the first wave, the people became more negligent in dealing with the virus. Most people avoided social distancing norms and face masks. Several national movements such as farmers' rallies, election campaigns, and religious events like Kumbh Mela where thousands of people gathered, might have increased the risk of COVID-19 transmissibility during the second wave (Kar et al., 2021; Thiagarajan, 2021).





### 3.6 Association of meteorology, pollutants with the cases during second wave COVID-19

Spearman’s correlations were conducted to ascertain the influence of meteorology and pollutant levels on the second wave confirmed cases and deaths (Tables 5 and 6). During the pre-lockdown period, the confirmed cases and deaths were correlated strongly ( $r = 0.7$ ;  $p \leq 0.01$ ) (Table 5).  $PM_{2.5}$  and  $PM_{10}$ , and CO were positively correlated with the COVID-19 cases and deaths, and these correlations were significant. Among the three pollutants, higher correlations were identified for  $PM_{2.5}$  followed by  $PM_{10}$ , and CO concentrations. On the contrary, the ozone concentrations were negatively associated with the COVID-19 cases and deaths. Among the meteorological variables considered, the temperature has shown the highest correlation coefficients with the confirmed cases ( $r = 0.5$ ;  $p \leq 0.01$ ) and deaths ( $r = 0.5$ ;  $p \leq 0.01$ ). Wind speed and RH did not significantly correlate with COVID-19 cases and deaths. Temperature has shown strong positive associations with the confirmed cases ( $r = 0.5$ ;  $p \leq 0.01$ ) and deaths ( $r = 0.4$ ;  $p \leq 0.01$ ) (Table 6). RH was negatively

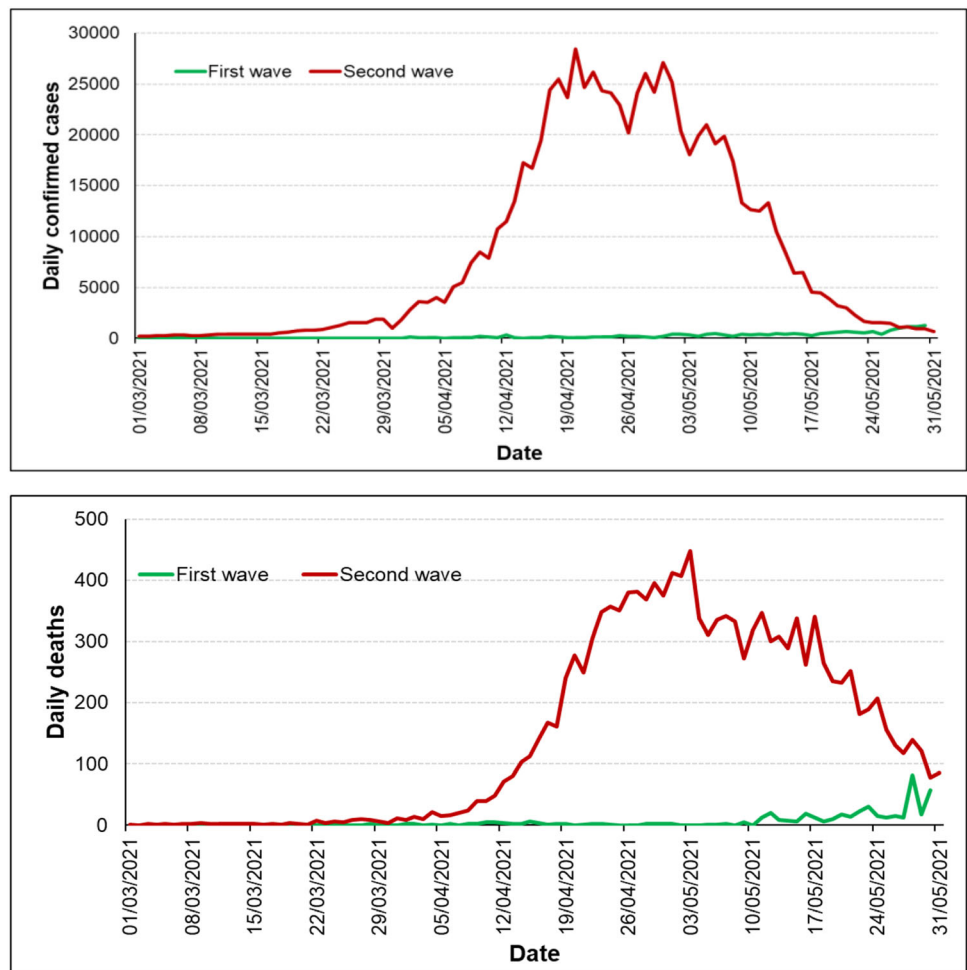
**Table 5** Association of pollutants and COVID-19 during the second wave pre-lockdown period

	Confirmed cases	Deaths
Confirmed cases	1	
Deaths	0.7**	1
$PM_{2.5}$	0.5**	0.5**
$PM_{10}$	0.3**	0.3**
CO	0.3**	0.2**
$O_3$	- 0.1*	- 0.1*
T	0.5**	0.5**
RH	- 0.4	- 0.2
WS	- 0.0	- 0.1

\* $p \leq 0.05$ ; \*\* $p \leq 0.01$

associated. As a comparison, temperature also showed positive associations with confirmed cases ( $r = 0.3$ ;  $p \leq 0.05$ ) and deaths ( $r = 0.1$ ;  $p \leq 0.05$ ) during the first wave lockdown period in Delhi (Kolluru et al. 2021).  $PM_{2.5}$ ,  $PM_{10}$ , and CO concentrations were significantly

**Fig. 5** Daily trends of COVID-19 cases and deaths during first wave and second wave COVID-19



**Table 6** Association pollutants and COVID-19 during the second wave lockdown period

	Confirmed cases	Deaths
Confirmed cases	1	
Deaths	0.9**	1
PM <sub>2.5</sub>	0.3**	0.3**
PM <sub>10</sub>	0.3*	0.1*
CO	0.2**	0.2**
O <sub>3</sub>	− 0.1*	− 0.1
T	0.5**	0.4**
RH	− 0.2	− 0.2
WS	− 0.2	0.0

\* $p \leq 0.05$ ; \*\* $p \leq 0.01$

correlated with COVID-19 cases and deaths. Similar to the pre-lockdown period, O<sub>3</sub> was negatively correlated with confirmed cases ( $r = -0.1$ ;  $p \leq 0.05$ ) and deaths ( $r = 0.2$ ;  $p > 0.05$ ). However, these associations were weak. It is observed that in both periods, all pollutant concentrations (except O<sub>3</sub>) were positively associated. This implies that when the PM<sub>2.5</sub>, PM<sub>10</sub>, and CO levels increased, there was a surge in the COVID-19. The correlations obtained in this study were similar to the studies conducted in Italy, Germany, the USA, China, Spain, and Netherlands (Bashir et al. 2020a, b; Briz-Redon et al. 2021; Cole et al. 2020; Zhang et al. 2021). As the COVID-19 mainly affects the respiratory system in a manner similar to the exposure to pollutants (PM and CO), the rise in level of these pollutants aggravates the COVID-19 susceptibility. It is also observed that when the temperature increases, there is an increment in COVID-19 during the two different periods.

On the contrary, RH was negatively associated. This means that the hot and dry climate favored the rate of COVID-19 transmission in Delhi. Further, it is found that the trends of association of the variables with the COVID-19 cases and deaths were similar in both periods, although the extent of association was different. This variability may be due to the change in the meteorology and the lockdown conditions. During the pre-lockdown period, the degree of association of the pollutant levels with the confirmed cases and deaths was higher than in the lockdown period. Due to several restrictions during the lockdown period, the pollutant concentrations were minimized reducing the association with the confirmed cases and deaths.

### 3.7 Influence of meteorology, pollutant levels on the second wave COVID-19

GLM was used to estimate the variability in COVID-19 cases and deaths during the pre-lockdown (Table 7) and

lockdown periods (Table 8). For this modeling, COVID-19 cases and deaths were treated as dependent variables. The remaining variables such as PM<sub>2.5</sub>, PM<sub>10</sub>, CO, O<sub>3</sub>, temperature, RH, and wind speed were treated as covariates. During the pre-lockdown period, temperature (22%) substantially determined the highest variability, succeeded by PM<sub>2.5</sub> (8%), CO (3%), and ozone (3%) for the confirmed cases. Further, temperature (14%) followed by ozone concentrations (10%) explained the highest variability for COVID-19 deaths (Table 6). The total models were responsible for 61% and 35% variability in the confirmed cases and deaths during the pre-lockdown period, respectively. And during the lockdown, temperature (41%) and PM<sub>2.5</sub> (8%) explained the highest variability in confirmed cases. Additionally, temperature explained (39%) variability in deaths. The total model explained 85% and 51% variability in COVID-19 confirmed cases and deaths, during the lockdown period.

It can be noticed here that only temperature among the meteorological variables has shown significant variation in COVID-19 related cases and deaths during both periods. Several previous studies have shown a positive association of temperature with the COVID-19 cases. A study conducted in 219 Chinese cities concluded that temperature has accelerated COVID-19 transmissibility (Zhang et al. 2020a, b). A Brazilian study conducted in most infected cities observed that extreme temperatures accelerated the spread of COVID-19 (Auler et al. 2020). A study in different provinces of Iran found that temperature is a sensible factor that might have impacted the COVID-19 outcomes (Jahangiri et al. 2020). A study performed in 122 Chinese cities found that there was a ~ 5% increase in the daily confirmed cases when there was a rise in temperature of 1 °C (Xie and Zhu 2020). It was also observed that the temperature positively correlated with COVID-19 related mortalities in Wuhan, China (Jiang and Xu 2021). In this

**Table 7** Explained variability during the second wave pre-lockdown

Parameters	Confirmed cases			Deaths		
	R <sup>2</sup> = 61.3%			R <sup>2</sup> = 34.5%		
	B	p	R <sup>2</sup>	B	p	R <sup>2</sup>
PM <sub>2.5</sub>	24.8	0.01*	0.08	0.1	0.89	0.00
PM <sub>10</sub>	21.7	0.60	0.01	0.1	0.67	0.00
CO	11.0	0.04*	0.03	22.8	0.11	0.03
O <sub>3</sub>	− 29.2	0.03*	0.03	− 1.9	0.05*	0.10
T	29.8	0.00**	0.22	11.2	0.01**	0.14
RH	− 38.4	0.83	0.00	− 0.5	0.69	0.00
WS	− 2.4	0.74	0.00	− 27.3	0.61	0.01

\* $p \leq 0.05$ ; \*\* $p \leq 0.01$

**Table 8** Explained variability during the second wave lockdown

Parameters	Confirmed cases			Deaths		
	R <sup>2</sup> = 84.8%			R <sup>2</sup> = 51.4%		
	B	<i>p</i>	R <sup>2</sup>	B	<i>p</i>	R <sup>2</sup>
PM <sub>2.5</sub>	8.0	0.05*	0.08	0.0	0.97	0.00
PM <sub>10</sub>	5.1	0.71	0.00	0.1	0.71	0.00
CO	7.7	0.04*	0.01	5.7	0.48	0.01
O <sub>3</sub>	− 1.3	0.01**	0.07	− 1.9	0.11	0.07
T	22.0	0.00**	0.41	16.2	0.00**	0.39
RH	− 1.7	0.28	0.03	− 0.4	0.28	0.03
WS	− 5.2	0.33	0.02	− 11.2	0.33	0.02

\* $p \leq 0.05$ ; \*\* $p \leq 0.01$

study, negative association is observed between RH, wind speed and confirmed cases and deaths. On the contrary, several previous studies observed that RH influences COVID-19 cases (Ali and Alharbi 2020; Bashir et al. 2020a, b), regardless of the argument that RH and COVID-19 spread were negatively associated (Ahmadi et al. 2020; Wu et al. 2020). Wind can also influence the spread of various pathogens (Ellwanger and Chies 2018). However, several studies have shown an insignificant negative association between wind speed and COVID-19 (Ahmadi et al. 2020; Bashir et al. 2020a, b).

As observed in this study, air pollution increased the spread of COVID-19. The positive association of it with COVID-19 implies that when the pollution levels increase, the spread of COVID-19 increases which was also reported in earlier studies (Collivignarelli et al. 2020; Ricco et al. 2020; Travaglio et al. 2020). Airborne particles (especially PM<sub>2.5</sub>) travel longer distances, can penetrate deeper regions of the respiratory system and have been observed to proliferate viruses such as measles and influenza (Andree 2020). A similar phenomenon can be thought of for the spread of COVID-19 as this virus also primarily affects the respiratory system and can attach to the surface of the aerosols that remain airborne for hours (Van Doremalen et al. 2020). It is a well-known fact that severe air pollution reduces the lung capacity making them vulnerable to respiratory infections such as Chronic Obstructive Pulmonary Disease (COPD) and asthma (Kim et al. 2018). Since COVID-19 primarily targets the lungs and the viral spikes attach to the lung's cell receptors, it increases the chances of infection if the person is exposed to higher air pollution (Ali and Alharbi 2020). In addition to PM<sub>2.5</sub>, CO also positively influenced the confirmed cases during both waves of COVID-19. Similar observations were found in earlier studies in China where influenza and COVID-19 cases increased when there was an increase in CO

concentrations (Li et al. 2020). A similar association was observed for a study in London between CO and SARS-CoV-2 related mortality (Meo et al. 2021). Earlier studies reported that exposure to CO causes several respiratory diseases (Zhao et al. 2019; North et al. 2019). Therefore, higher CO levels lead to weaker respiratory systems making a person more susceptible to the COVID-19 viral infection.

Our study observed the negative influence of O<sub>3</sub> concentrations on the confirmed cases and deaths. Similar observations have also been found in earlier studies (Ran et al. 2020; Wiśniewski et al. 2021). Studies conducted by various research groups concluded that ozone gas can be effective against most parasites such as viruses, and a relatively low level of ozone gas can inactivate them (Blanchard et al. 2020; Hudson et al. 2007). Several earlier studies such as Yano et al. (2020) reported that the ozone doses can have the virucidal effect of up to 120 min for the range up to 6 ppm. Ozone generators showed antiviral efficiency at 10–20 ppm (Dennis et al. 2020). Zhang et al. (2004) demonstrated that aqueous ozone could inactivate SARS-CoV-1 (which caused SARS in 2003) which is identical form to SARS-CoV-2. Ozone can damage the viral capsids through pre-oxidation of phospholipids and affect its reproductive cycle through interaction with proteins (Elvis and Ekta 2011). Ozone primed immunity against viruses might have played a crucial role in reducing COVID-19 infectivity. Overall findings suggest that ozone acts as a powerful disinfectant at low concentrations (up to 99% reduction), which can kill airborne viruses (Grignani et al. 2021).

## 4 Conclusions

The current study investigated the variability in the air pollution levels in Delhi city, India, during the COVID-19 s wave. This is one of the few studies investigating the role of air pollutant levels on the COVID-19 confirmed cases and deaths during the second wave in India. Overall, a considerable reduction in the concentration of the pollutants (PM<sub>2.5</sub>, PM<sub>10</sub>, CO) is observed in the lockdown period compared to the pre-lockdown period, except for ozone levels which slightly increased during the lockdown period. Due to the restrictions imposed during the lockdown period, PM<sub>2.5</sub>, PM<sub>10</sub> and CO concentrations decreased by 15  $\mu\text{g m}^{-3}$ , 64  $\mu\text{g m}^{-3}$  and 0.1  $\text{mg m}^{-3}$  respectively during the lockdown period compared to the pre-lockdown period. The O<sub>3</sub> concentrations, however, increased by 18  $\mu\text{g m}^{-3}$  during the lockdown period, possibly due to high temperatures that promoted photochemical reactions leading to increased ozone production. The variation in pollutant levels during the first wave

(2020) and second wave (2021) lockdowns were compared with the concentrations before COVID-19. The pollutant concentrations were higher before COVID-19 followed by the second wave lockdown and the lowest in the first wave lockdown. The difference in the severity of the restrictions during the first and second wave is responsible for the variation in the pollutant levels during the lockdown periods. More remarkable percentage changes in the concentration levels during both lockdown periods are observed in PM<sub>10</sub> and CO followed by PM<sub>2.5</sub>. The change in the pollutant levels is also identified by mapping the spatiotemporal variabilities for the entire city. Pollutant concentrations and meteorological parameters associated with COVID-19 (cases and deaths) revealed that temperature, PM<sub>2.5</sub>, PM<sub>10</sub> and CO are positively associated. Moreover, O<sub>3</sub> levels are negatively associated with COVID-19. Further, during the two different lockdown periods, the total GLM models explained 61% and 85% variability in COVID-19 confirmed cases. Similarly, the models explained a total of 35% and 51% variability in deaths during the two lockdowns. This indicates that temperature, PM<sub>2.5</sub>, PM<sub>10</sub> and CO, besides other factors such as quarantine and healthcare facilities, acted as precursors in excess confirmed cases and deaths.

Overall, it can be deduced that air pollution is a silent agent in increasing the spread of COVID-19. It is therefore becoming important for the people residing in the world's most polluted city to be very vigilant about the rising pollutant levels and their association with COVID-19 cases and deaths. During the lockdowns, the air pollution levels have reduced, only to again increase with the start of the unlock phases. To better understand the factors associated with the spreading of COVID-19, the present study could be used as a reference. The governments should focus on reducing the air pollution levels which might lessen the mortalities and morbidities linked with COVID-19. The companies should focus on implementing strategies such as work from home which enable the peoples' safety without mingling with others and to reduce the city's on-road vehicle emissions drastically. The positive results evident during the lockdown periods of air pollution can serve as the basis for governments and regulatory agencies that strict air quality policies can significantly improve the environment and human health. An integrated strategy where the medical science includes the environmental considerations to prevent the airborne infectious diseases, can be incorporated into the planning for dealing with future spread of SARS type epidemics. Also, getting vaccination doses and maintaining several rules and protocols like social distancing can eradicate COVID-19 not only in India but from the world.

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**Data Availability** The datasets generated during and/or analyzed during the current study are available in the <https://app.cpcbcr.com/ccr/#/caaqm-dashboard-all/caaqm-landing/data>

## Declarations

**Conflict of interest** The authors declare no competing interests.

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