Association of air pollution and meteorological variables with COVID-19 incidence: Evidence from five megacities in India

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ARTICLE INFO

ABSTRACT

Although lockdown of the industrial and transport sector and stay at home advisories to counter the COVID-19 pandemic have shown that the air quality has improved during this time, very little is known about the role of ambient air pollutants and meteorology in facilitating its transmission. This paper presents the findings from a study that was conducted to evaluate whether air quality index (AQI), three primary pollutants (PM$_{2.5}$, PM$_{10}$ and CO), Ground level ozone (O$_3$) and three meteorological variables (temperature, relative humidity, wind speed) have promoted the COVID-19 transmission in five megacities of India. The results show significant correlation of PM$_{2.5}$, PM$_{10}$, CO, O$_3$ concentrations, AQI and meteorological parameters with the confirmed cases and deaths during the lockdown period. Among the meteorological variables considered, temperature strongly correlated with the COVID-19 cases and deaths during the lockdown ($r = 0.54; 0.25$) and unlock period ($r = 0.66; 0.25$). Among the pollutants, ozone, and among the meteorological variables, temperature, explained the highest variability, up to 34% and 30% respectively, for COVID-19 confirmed cases and deaths. AQI was not a significant parameter for explaining the variations in confirmed and death cases. WS and RH could explain 10–11% and 4–6% variations of COVID-19 cases. A GLM model could explain 74% and 35% variability for confirmed cases and deaths during the lockdown and 66% and 19% variability during the unlock period. The results suggest that meteorological parameters may have promoted the COVID-19 incidences, especially the confirmed cases. Our findings may encourage future studies to explore more about the role of ambient air pollutants and meteorology on transmission of COVID-19 and similar infectious diseases.

1. Introduction

COVID-19, a novel coronavirus disease caused by SARS CoV-2 (severe acute respiratory syndrome coronavirus-2) was first identified in the Wuhan city of Hubei Province, China in December 2019. Due to widespread human-to-human transmission, significant number of deaths, higher number of infection and mortality rate, WHO declared the COVID-19 as global pandemic on March 11, 2020 (WHO, 2020a). After SARS (Severe acute respiratory syndrome) in 2003 and MERS (Middle East Respiratory Syndrome coronavirus) in 2012, the COVID-19 is the third coronavirus to be declared as pandemic in the 21st century (Bashir et al., 2020). Since the outbreak of COVID-19, the lives of billions of people have been disrupted and it caused more than 2,014,729 deaths worldwide as of January 17, 2021 (WHO 2020b). This has forced the governments of many nations to enforce strict lockdown. In India,

the first case of COVID-19 was detected on January 30, 2020 in Kerala state. Since then, there has been an exponential growth of active cases and deaths in India. As per Government of India (GoI), there are 205,109 active cases and 152,456 deaths as on January 17, 2021, attributed to COVID-19 (https://www.mohfw.gov.in/). In response to the global pandemic, the GoI announced "janata (people) curfew" on March 22, 2020 from 7 a.m. to 9 p.m. Soon after, the GoI announced nationwide complete lockdown for next 21 days, starting from March 24, 2020, imposing restrictions on all transportation and industrial activities. Later, the lockdown was extended four times till May 31, 2020, due to an increased number of cases on a daily basis. During these lockdowns, almost all industrial activities, domestic and international flights, trains and vehicular transport were suspended. All the states in India strictly followed the lockdown and social distancing rules.

India faces the challenge of dealing with poor air quality, especially

in big cities. Nearly, 1 million deaths occurred in 2015 were attributed to ambient particulate matter (PM) in India (Guo et al., 2017). In 2017, it was estimated that around 77% of Indian population were exposed to $PM_{2.5}$ concentration levels of more than 40 µg m^{-3} (ICMR-PHFI-IHME, 2017). Past studies have revealed that Indian cities made the top 20 most polluted cities of the world that has exceeded the ambient air quality standard recommended by WHO (World Health Organisation) and CPCB (Central Pollution Control Board) (Garaga et al., 2018; Mukherjee and Agarwal et al., 2018). The lockdowns resulted in closure of all the emission intensive sources. Several studies have reported the reduction of air pollutants during COVID-19 pandemic in many countries, including India. For example, Wang et al. (2020 a, b) carried out the analysis for major cities of China (Beijing, Shanghai, Guangzhou and Wuhan) and found the substantial reduction in air pollution could be attributed to reduction in emissions from industrial and transportation sectors. In another study, approximately 20–30% reduction in NO_2 emission was observed in countries like China, USA, Spain, France and Italy during the lockdown (Muhammad et al., 2020). During one-month lockdown period in Barcelona, Spain, the highest reduction in pollutant concentrations were observed for NO_2 (51%), followed by PM_{10} (45%), SO_2 (31%), and black carbon (19%) (Tobías et al., 2020). Similarly, in India, a 43% reduction in $PM_{2.5}$ levels compared to previous year was found using WRF-AERMOD modelling system during the lockdown period (Sharma et al., 2020). Kumar et al. (2020) revealed that cities with larger traffic volume showed greater reduction in $PM_{2.5}$ concentrations and for five major Indian cities (Delhi, Mumbai, Kolkata, Hyderabad and Chennai), he estimated that the lower $PM_{2.5}$ level in air due to the lockdown prevented 630 deaths. Further, Mahato et al. (2020) reported 50% decline in PM_{10} and $PM_{2.5}$ during the lockdown, and Venter et al. (2020) showed a strong relation between lockdown period and reduction of $PM_{2.5}$ related premature deaths. Srivastava et al. (2020) reported gradual reduction of $PM_{2.5}$, NO_2, and CO levels during the 21 days' lockdown period (March 25, 2020 to April 14, 2020) compared to pre lockdown in Lucknow and Delhi. Using aerosol optical depth (AOD) as a measure of air pollution level, especially for $PM_{2.5}$ and PM_{10} concentration, a recent study reported that AOD levels over the Indian Territory reduced by ~45% during the lockdown periods (25th March to May 15, 2020) as compared to the mean AOD level during 2000–2019 (Ranjan et al., 2020). A summary of a few important Indian studies are presented in Table 1.

The review shows that the lockdown due to COVID-19 pandemic has resulted in reduction of pollution across the globe confirming the natural processes like deposition, diffusion and dispersion of airborne particles and gases are effective enough to clear the atmosphere of the pollutants when anthropogenic emissions are restricted. However, the society needs to come back to pre-pandemic normal situation and that started with limited easing of the travel and business restrictions, termed as "unlock". The unlock period therefore comes with switching on the emission sources which were shut during the lockdown, and therefore it is important to see how the air quality is changing subsequent to unlock and how long is it taking to come back to the pre lockdown level. This will give an idea how fast the pollution emissions from anthropogenic activities can exceed the natural cleansing process of the atmosphere. The other objective was to assess if level of pollutants and meteorological parameters are associated with COVID-19 confirmed cases and deaths. To fill this research gap, we conducted this study during the lockdown and unlock periods. The aim of this paper was to assess the influence of lockdown and unlock periods on the PM_{10}, $PM_{2.5}$, CO and O_3 concentrations in five megacities of India: Bangalore, Chennai, Delhi, Kolkata and Mumbai. Additionally, the concentrations levels were also compared with the previous year (2019). We then examined the role of different determinants (pollutant concentrations, air quality index, and meteorological variables) on COVID-19 daily confirmed cases and deaths. To our knowledge, this is the first study to evaluate the different determinants of COVID-19 confirmed cases and deaths in India.

Table 1
Summary of the recent studies conducted in India.

Authors	Pollutants	Study period	Study areas	Major findings
Sharma et al. (2020)	PM_{10}, $PM_{2.5}$, CO, NO_2, O_3 and SO_2	16 March-14 April (2017–2020)	22 Indian cities	During the lockdown period, concentrations were reduced up to 43% in $PM_{2.5}$, 31% in PM_{10}, 10% in CO, and 18% NO_2 when compared with the previous years' concentrations (2017–2019).
Kumar et al. (2020)	$PM_{2.5}$	January 2015–May 2020	Delhi, Kolkata, Chennai, Mumbai, Hyderabad	Reduction in $PM_{2.5}$ concentrations during the lockdown period ranged from 41% to 53% in Delhi, 24%–36% in Kolkata, 19%–43% in Chennai, 10%–39% in Mumbai and 26%–54% in Hyderabad.
Singh et al. (2020)	$PM_{2.5}$, NO_2 and AQI	March 2019 and March 2020	Delhi, Mumbai, Hyderabad, Kolkata, and Chennai	During March 2020, the highest percentage reductions in $PM_{2.5}$ were observed in Kolkata (34.52%) followed by Delhi (27.57%) and the lowest in Hyderabad (3.99%).
Jain and Sharma (2020)	PM_{10}, $PM_{2.5}$, NO_2, O_3 and CO	March–April (2019 and 2020); 10–20 March 2020 (before lockdown); and 25 March-6 April 2020 (during lockdown)	Delhi, Mumbai, Chennai, Kolkata and Bangalore	The highest reduction was reported in PM_{10} (52%), followed by NO_2 (51%), $PM_{2.5}$ (41%) and CO (28%) during the lockdown in Delhi.
Mahato et al. (2020)	PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, O_3 and NH_3	2–21 March 2020 (before lockdown); and 25 March-14April 2020 (during the lockdown	Delhi	The highest decline in concentrations were observed in PM_{10} (60%),NO_2 (53%), $PM_{2.5}$ (39%), and CO levels (30%) compared to the previous year.
Srivastava et al. (2020)	$PM_{2.5}$, NO_2, SO_2 and CO	25th March to April 14, 2020 (21-day lockdown period)	Lucknow and Delhi	NO_2 and CO concentrations were reduced in Lucknow; and $PM_{2.5}$, NO_2 and CO concentrations were reduced in Delhi during the 21 days lockdown.
Mitra et al. (2020)	CO_2	April 2019 and April 2020	Kolkata	CO_2 level decreased up to

Table 1 (*continued*)

Authors	Pollutants	Study period	Study areas	Major findings
Ranjan et al. (2020)	Aerosol optical depth	25 March – 15 May (2000–2019); and 25 March – 15 May (2020)	Delhi, Kolkata, Bengaluru, and Mumbai	30–40% with temporal variation with $p < 0.01$ during April 2020. AOD level reduced up to 37% in these cities during the lockdown period compared to mean AOD level during 2000–2019.

2. Materials and methods

2.1. Study areas

The present study has been focused on five megacities in India (Bangalore, Chennai, Delhi, Kolkata and Mumbai) (Fig. 1).

Bangalore is the capital city of Karnataka state located on the Deccan plateau of southern India. The total area of the city is 709 km^2. Chennai (13.08° N, 80.27° E) is the capital city of the Tamil Nadu state in southern India, which spread across 426 km^2. New Delhi is the capital city of India. It is the largest city in the world after Tokyo, Japan and is the largest megacity in Asia. The area of the city is 1484 km^2 which is nearly two times of the size of the second largest megacity Bangalore and two and half times that of Mumbai. Kolkata is the capital city of West Bengal state which is located on the Ganges delta of the northeastern part of India. Among the five megacities it is the smallest in size with a total area of 205 km^2. However, it has the highest population

Fig. 1. Megacities in India.

density of 72,440 persons per km^2, which is 2–3 times the population density of the remaining four megacities. Mumbai is the capital city of Maharashtra state, which is the financial capital of India and the sixth-largest metropolitan city in the world with a total area of 603 km^2 (Pacione, 2006). Chennai, Kolkata and Mumbai are the coastal cities having an elevation <20 m above the mean sea level (MSL). On the other hand, Bangalore city is located at an elevation >900 m above MSL. The dominant wind directions are southerly and easterly in coastal cities located at the east (Kolkata and Chennai), westerly and northerly for cities in west and peninsular India (Mumbai and Bangalore) and westerly and easterly for Delhi (Kumar et al., 2020). All cities typically have three seasons: summer (March–May/June); monsoon (June–August/September); and winter (November/December–February) except Delhi which has a distinct post-monsoon period (September–November) in addition to the above three seasons (Shukla et al., 2020) and Chennai that experiences a prolonged monsoon period that continues until winter (June–December) (Kumar et al., 2020). Table 2 showed the total population, population density, latitude and longitude of these megacities.

Delhi is ranked as the most polluted city in the world with Kolkata and Mumbai also coming among the highly polluted cities (Scroll, 2019). Vehicular emissions are the major source of the PM in ambient air in these megacities. In 2017, the total number of registered on-road vehicles were highest in Delhi (10.26 million), followed by Chennai (5.3 million), Mumbai (3.05 million) and Kolkata (0.8 million) and Bangalore (0.7 million) (Kumar et al., 2020). Bangalore is mainly characterized by commercial activities rather than industrial activities. It was found that vehicular emissions and associated road re-suspended dust as the major contributors of PM emissions in the city (Gargava and Rajagopalan, 2016). However, Bangalore is less polluted in comparison with other megacities (Devaraj et al., 2019). The source apportionment studies in Chennai clearly indicated that crystal dust and vehicular emissions as the principal sources of air borne particles followed by marine and secondary aerosols (Banerjee et al., 2016; Mohanraj et al., 2011; Srimuruganandam and Nagendra, 2011). Central and southern parts of the city receive the pollutants carried by winds from the industrial suburbs located in the northern parts of the city. In Delhi, vehicular and industrial emissions, and biomass burning are the major sources of the PM (Banerjee et al., 2016; Sharma et al., 2014). Fossil fuel combustion and biomass burning are the dominant sources of airborne PM in Kolkata (Banerjee et al., 2016; Chowdhury et al., 2007). Ambient PM level in Mumbai is dominated by anthropogenic sources which includes coal and biomass combustion, fuel combustion, road traffic and emissions from metal industries (Police et al., 2018).

2.2. Data collection

To study the influence of the COVID-19 pandemic on the lockdown and unlock period air quality, PM$_{2.5}$, PM$_{10}$, CO and O$_3$ concentration levels in ambient air of the five megacities (Bangalore, Chennai, Delhi, Kolkata and Mumbai) of India were analyzed. These are the four out of twelve criteria pollutants that are included in Indian National Ambient Air Quality Standards (NAAQS), and therefore these are regularly monitored through a wide network of automatic and manual weather stations (www.cpcb.nic.in). Meteorological parameters such as temperature (T), relative humidity (RH) and wind speed (WS) were also collected. Additionally, Air Quality Index (AQI) values were included in this study. In each megacity, the above mentioned variables data were collected from one of the several Continuous Ambient Air Quality Monitoring Stations (CAAQMS) installed and maintained by the Central Pollution Control Board, India (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing). The list of the monitoring stations considered in these cities were indicated in Table 3. The monitoring stations were selected based on the criteria that these stations are located at the middle of these cities, which indicates the approximate air quality of these cities. If the particular data is found missing in these

Table 2
Description of the study areas.

Megacities	Elevation above MSL[x] (m)	Total population (millions)[y]	Population density (persons per km^2)[y]	Weather[z]	Dominant wind directions[x]	Location
Bangalore	920	12	20,000	Summer (March–May) Monsoon (June–September) Winter (November–February)	West (26%) North (18%)	12.97° N 77.59° E
Chennai	16	10.9	25,800	Summer (March–June) Monsoon (June–December) Winter (December to March)	South (21%) East (15%)	13.08° N 80.27° E
Delhi	216	30.3	20,415	Summer (March–May) Monsoon (June–August) Post monsoon (September–November) Winter (December–February)	West (34%) East (19%)	28.65° N 77.22° E
Kolkata	6.1	14.8	72,440	Summer (February–April) Monsoon (May–October) Winter (November–January)	South (34%) East (13%)	22.56° N 88.36° E
Mumbai	12.2	20	33,850	Summer (March–June; September–November) Monsoon (June–August) Winter (November–February)	West (36%) North (20%)	19.07° N 72.88° E

[x] https://skyvector.com/.
[y] http://www.populationu.com/.
[z] (Kumar et al., 2020).

Table 3
Monitoring stations and their location in the megacities.

Megacities	Monitoring station	Location
Bangalore	Silk Board	12.91°N, 77.62°E
Chennai	Velachery residential area	13.00°N, 80.23°E
Delhi	Major Dhyan Chand National Stadium	28.61°N, 77.23°E
Kolkata	Rabindra Bharati University	22.62°N, 88.38°E
Mumbai[a]	Bandra	19.06°N, 72.84°E
	Kurla	19.08°N, 72.88°E

[a] The station considered for this study was Kurla. Missing data at Kurla was obtained from Bandra station.

stations, then the appropriate data is collected from the stations which are located nearest to it. Data of COVID-19 daily confirmed cases and deaths in these megacities were collected from the Ministry of Health and Family Welfare, Government of India (https://www.mohfw.gov.in/) and volunteer driven crowd sourced network (https://www.covid19india.org/).

2.3. Data analysis

The hourly averaged data for PM$_{10}$, PM$_{2.5}$, CO, O$_3$, AQI, T, RH and WS were collected at these monitoring stations. It was observed that the missing data were approximately 3% of the total data. Outliers were removed following the procedure mentioned in Spinazzè et al. (2015). The concentrations data above 99th percentile and below 1st percentile were trimmed to remove extreme high and low values. To detect the variation of the pollutants concentration in the year 2020, three different time periods were considered during the COVID-19 pandemic: pre lockdown period (February 2020); lockdown period (May 2020); and unlock period (June 2020). ANOVA was used to check the concentration variations across the three lockdown periods. Additionally, the pollutants concentrations during the pandemic (May and June 2020) were also compared with the concentrations obtained in the previous year (May and June 2019). Timelines of the total confirmed cases and deaths in all megacities were shown. Pearson correlation analyses were conducted for lockdown and unlock period separately to find out the association of pollutant concentrations, AQI, meteorological variables and COVID-19 confirmed cases and deaths. To identify the determinants that may explain the variability in the COVID-19 cases and deaths, General Linear Models for lockdown and unlock periods were applied. In the statistical analyses, if the level of significance was at $p \leq 0.05$, then the tests were considered significant. All the statistical analyses were conducted using IBM SPSS Statistics 26.0 (IBM, Armonk, NY, USA).

3. Results and discussion

3.1. Pollutant levels during COVID-19 pandemic

The mean PM$_{10}$, PM$_{2.5}$, CO and O$_3$ concentrations during the pre-lockdown period (February 2020), lockdown period (May 2020), and unlock period (June 2020) in five megacities were shown in Table 4. It was observed that during the lockdown period, the PM$_{10}$, PM$_{2.5}$, and CO concentrations were lower compared to concentrations during the pre-lockdown period in all the megacities. In the lockdown period, the highest reduction in PM$_{10}$ concentrations was observed in Kolkata (234 µg m^{-3}), followed by Mumbai (128 µg m^{-3}) and New Delhi (95.1 µg m^{-3}) compared with the pre lockdown period. The PM$_{2.5}$ concentrations during the lockdown period reduced by 85% in Kolkata, followed by 84% in Mumbai and 65% in New Delhi compared with the pre lockdown period. Similarly, the CO concentrations during the lockdown period reduced by 58% in Bangalore, 38% in New Delhi, and 14.2% in Kolkata. The O$_3$ concentrations during the lockdown period in Bangalore and Chennai were lower by approximately 4 µg m^{-3} and 2 µg m^{-3}, respectively, compared with the concentrations during the pre-lockdown period. However, surprisingly in Delhi and Kolkata, the lockdown period concentrations increased by 25 µg m^{-3} and 12 µg m^{-3} respectively, compared to pre lockdown period. During the unlock period, there were inconsistencies in the variation of the pollutant concentrations in megacities. PM$_{10}$, PM$_{2.5}$ concentrations in Chennai, New Delhi and Kolkata, and CO concentrations in Chennai, New Delhi, Kolkata, and Mumbai were marginally higher during the unlock period in comparison with the lockdown period. The maximum incremental concentrations during the unlock period were observed for PM$_{10}$ in Kolkata (10 µg m^{-3}), PM$_{2.5}$ in New Delhi (4.3 µg m^{-3}) and CO in Mumbai (0.8 mg m^{-3}). For O$_3$, except in Bangalore, the concentrations during the unlock period increased in all megacities.

In summary, the mean pollutant concentrations in each megacity showed the following trends: PM$_{10}$ in Bangalore and Mumbai - pre lockdown > lockdown > unlock period and in New Delhi and Kolkata - pre lockdown > unlock > lockdown period; PM$_{2.5}$ in Chennai, New Delhi, Kolkata and Mumbai - pre lockdown > unlock > lockdown period and in Bangalore - pre lockdown > lockdown > unlock period; except Chennai, CO in all megacities: pre lockdown > unlock > lockdown period; O$_3$ in Delhi and Kolkata: pre lockdown < lockdown < unlock period, in Bangalore: pre lockdown > lockdown > unlock, and in Chennai: unlock > pre lockdown > lockdown period.

To evaluate the role of different lockdown periods on the pollutant concentrations in each megacity, ANOVA was performed. It showed that PM$_{10}$, PM$_{2.5}$, CO and O$_3$ concentrations varied significantly across the three lockdown periods ($p \leq 0.05$). As observed in previous studies (Li et al., 2020; Mahato et al., 2020; Sasidharan et al., 2020; Sharma et al.,

Table 4

Mean pollutant concentrations in Indian megacities during the COVID-19 pandemic.

Megacities	Pollutants	Pre lockdown period (Feb 2020) [AM±SD]	Lockdown period (May 2020) [AM±SD]	Unlock period (June 2020) [AM±SD]
Bangalore	PM_{10} (μg m^{-3})	97.1 ± 30.2* (n = 679)	57.0 ± 14.1* (n = 725)	52.3 ± 32.1* (n = 704)
	$PM_{2.5}$ (μg m^{-3})	42.0 ± 13.9* (n = 687)	19.4 ± 4.9* (n = 739)	11.8 ± 4.9* (n = 709)
	CO (mg m^{-3})	1.1 ± 0.4* (n = 672)	0.6 ± 0.1* (n = 729)	0.6 ± 0.3* (n = 696)
	O_3 (μg m^{-3})	36.5 ± 7.8* (n = 567)	32.4 ± 10.9* (n = 740)	20.7 ± 9.5* (n = 613)
Chennai	PM_{10} (μg m^{-3})	[a]	[a]	[a]
	$PM_{2.5}$ (μg m^{-3})	32.5 ± 16.7* (n = 681)	12.2 ± 5.7* (n = 729)	16.5 ± 12.5* (n = 714)
	CO (mg m^{-3})	0.8 ± 0.2* (n = 691)	0.8 ± 0.1* (n = 736)	1.0 ± 0.1* (n = 707)
	O_3 (μg m^{-3})	32.3 ± 29.9* (n = 689)	30.8 ± 26.1* (n = 744)	46.1 ± 23.6* (n = 713)
Delhi	PM_{10} (μg m^{-3})	202.2 ± 83.3* (n = 689)	107.1 ± 61.7* (n = 727)	109.1 ± 42.1* (n = 699)
	$PM_{2.5}$ (μg m^{-3})	113.7 ± 56.3* (n = 686)	39.8 ± 15.6 (n = 731)	43.0 ± 16.3* (n = 701)
	CO (mg m^{-3})	1.3 ± 1.1* (n = 692)	0.5 ± 0.1* (n = 741)	0.6 ± 0.2* (n = 706)
	O_3 (μg m^{-3})	19.3 ± 12.3* (n = 654)	45.7 ± 42.4* (n = 698)	67.1 ± 54.2* (n = 664)
Kolkata	PM_{10} (μg m^{-3})	260.0 ± 122.3* (n = 675)	26.0 ± 9.2* (n = 736)	36.1 ± 12.4* (n = 697)
	$PM_{2.5}$ (μg m^{-3})	101.3 ± 43.2* (n = 679)	14.5 ± 5.1* (n = 741)	14.9 ± 6.4* (n = 702)
	CO (mg m^{-3})	0.7 ± 0.6* (n = 676)	0.1 ± 0.1* (n = 729)	0.3 ± 0.1* (n = 711)
	O_3 (μg m^{-3})	32.3 ± 22.9* (n = 508)	44.5 ± 17.4* (n = 263)	53.5 ± 23.4* (n = 640)
Mumbai	PM_{10} (μg m^{-3})	208.4 ± 80.5* (n = 689)	80.8 ± 20.0* (n = 731)	55.5 ± 45.9* (n = 706)
	$PM_{2.5}$ (μg m^{-3})	75.1 ± 28.9* (n = 684)	11.7 ± 4.4* (n = 737)	13.7 ± 7.2* (n = 703)
	CO (mg m^{-3})	2.9 ± 0.7* (n = 678)	0.2 ± 0.1* (n = 731)	1.0 ± 0.1* (n = 698)
	O_3 (μg m^{-3})	51.4 ± 41.2 (n = 596)	[a]	[a]

*$PM_{2.5}$, PM_{10}, CO and O_3 concentrations vary across the three lockdown periods significantly in each city (ANOVA, $p \le 0.05$).

[a] Data not available.

2020), our study also showed that the concentrations of PM_{10}, $PM_{2.5}$, CO in all megacities and O_3 in Bangalore and Chennai were lower during the lockdown period. Due to the seriousness of the COVID-19 pandemic in India, a nationwide lockdown was enforced on March 24, 2020. Severe restrictions on personal travel, economic, industrial, and outdoor activities were imposed. This scenario had led to shutting down of all emission-intensive sources, which in turn reduced the pollutant concentrations during the lockdown period (May 2020). On average, in all the megacities, the PM_{10}, $PM_{2.5}$, and CO concentrations during the lockdown period is reduced by 65%, 73%, and 67%, respectively when compared with the pre lockdown period. Since $PM_{2.5}$ and CO are mostly the tracers for vehicle tailpipe emissions (Kolluru et al., 2018; Kolluru et al., 2019a,b; Kolluru et al., 2020; Kumar et al., 2020), the highest reduction in $PM_{2.5}$ and CO can be attributed to the very low vehicular traffic in megacities during the lockdown period. On the contrary, during the unlock period (June 2020), the private/limited public travel was resumed, and all the industrial and economic activities (with restrictions) restarted from June 8, 2020. This has led to a slight increase in the overall PM_{10}, $PM_{2.5}$, and CO concentrations in Chennai, New Delhi, and Kolkata. However, in Bangalore and Mumbai, despite restarting all the activities, PM_{10} and $PM_{2.5}$ concentrations during the

unlock period decreased in comparison with the lockdown period. This reduction can be attributed to the heavy rainfall events occurring during the unlock period (Indian monsoon) in these cities. According to the Indian Meteorological Department, these two cities received excessive rainfall in June 2020, due to which the PM has been cleared from the environment (https://mausam.imd.gov.in/). Conversely, the CO concentration in these two cities has significantly increased due to the increase in traffic and industrial emissions during the unlock period. However, the O_3 concentrations increased in Delhi and Kolkata during the lockdown period. Similar increase in O_3 concentrations during the COVID-19 lockdown were observed in several cities across the globe. In Mexico City, the O_3 concentrations increased during the lockdown period and the concentration profile were similar to the past years in the same time span (Peralta et al., 2021). A study in Quito, Ecuador observed that NO_x concentrations reduced during the morning rush hours as opposed to increase in the production rates of ozone (Cazorla et al., 2021). A study by Zhao et al. (2021) reported that there is 47% increase in the ozone concentrations during the lockdown period in the mainland China. Similar increase in the ozone concentrations were observed in many European cities (Grange et al., 2021). Production of the ozone depends on several factors. Anthropogenic emissions and VOCs are the major precursors for the ozone generation. In addition to these pollutants, the meteorological parameters also play an important role in the production of ozone. Advection of warm and polluted air masses can also raise the near surface ozone concentrations (Sun et al., 2017; Garrido-Perez et al., 2019; Ordonez et al., 2020). Higher temperatures and stagnant conditions at Delhi and Kolkata are likely to have favored the photochemical reactions and increase the production rates of O_3.

To understand the effect of COVID-19 pandemic on pollutants better, the concentration of the pollutants obtained during the pre-lockdown, lockdown, and unlock periods were compared with the concentrations obtained during the same periods during the previous year 2019. The descriptive summary of the pollutants in all megacities for the years 2019 and 2020 were shown in Fig. 2. During the pre-lockdown period (February 2019 vs. February 2020), the mean concentrations of PM_{10} (178.8 ± 115.3 μg m^{-3} in 2019 and 185.8 ± 100.7 μg m^{-3} in 2020), $PM_{2.5}$ (76.7 ± 68.4 μg m^{-3} in 2019 and 71.7 ± 47.7 μg m^{-3} in 2020), CO concentrations (1.3 ± 1.0 mg m^{-3} in 2019 and 0.9 ± 0.6 mg m^{-3} in 2020) and O_3 concentrations (40.2 ± 27.1 μg m^{-3} in 2019 and 34.1 ± 22.8 μg m^{-3} in 2020) were almost similar. However, during the lockdown (May 2019 vs. May 2020) and unlock periods (June 2019 vs. June 2020), large variations were observed in the pollutant concentrations. In the lockdown period, PM_{10}, $PM_{2.5}$, and CO concentrations were reduced up to 51%, 54%, and 58% respectively compared with the previous year (May 2019). Because of the nationwide lockdown, the reduction in pollution concentrations during May 2020 is expected. However, we observed that ozone concentrations were similar (37.9 ± 22.4 μg m^{-3} in 2019 and 38.3 ± 24.2 μg m^{-3} in 2020). Moreover, during the unlock period (June 2020), PM_{10}, $PM_{2.5}$, and CO concentrations decreased up to 62%, 51% and 49% respectively, compared to the previous year (June 2019). Despite the resumption of all activities in the unlock period, the pollutant concentrations did not reach the levels reported during the same month in the previous year, except the ozone concentrations during the unlock period in 2020. Ozone concentration during unlock period increased by 17% when compared with the previous year concentrations and the reasons for it have been discussed earlier. People voluntarily avoiding public and private travels, gatherings in public places due to the fear of the COVID-19 pandemic could be one of the reasons for the reduced concentrations.

3.2. COVID-19 confirmed cases, deaths, air quality index and meteorological variables

Fig. 3 shows the total COVID-19 daily confirmed cases and deaths in lockdown and unlock periods in the five megacities. It can be seen that
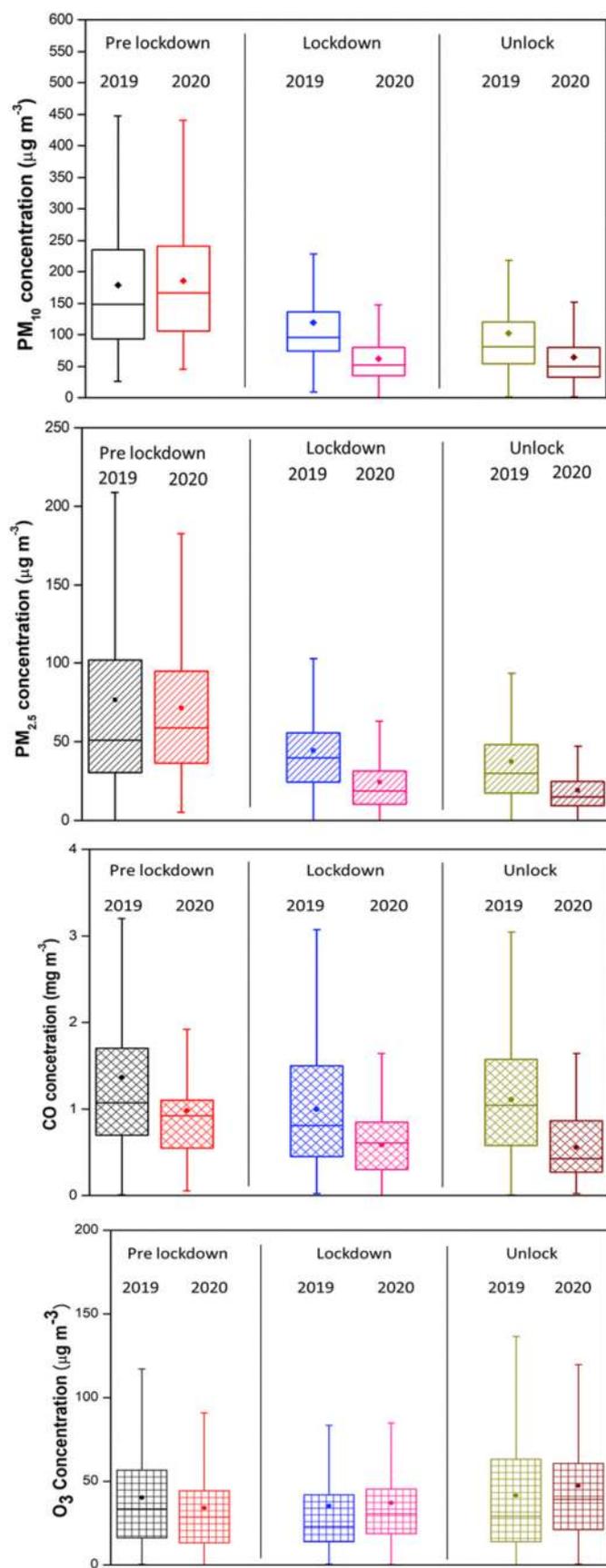
Fig. 2. Boxplots of pollutant concentrations for all megacities combined during years 2019 and 2020. Boxes represent data between 25th and 75th percentile, the dot inside the box is the mean, the central line represents the median, whiskers represent data under 1.5 times the interquartile range.

daily confirmed cases and deaths increased from the beginning of May to the end of June 2020. During the first week of May, ~1000 daily confirmed cases were reported, which increased gradually up to ~3500 confirmed cases by the end of the month. Similarly, the COVID-19 pandemic led to ~50 daily deaths at the start of May, and it increased up to ~100 deaths at the end of May 2020. Likewise, during June, daily confirmed cases and deaths have increased from ~3000 to ~7000 and ~100 to ~200, respectively.

Table 5 shows the total confirmed cases and deaths that occurred in each city during May and June 2020. The highest number of confirmed cases has been reported in New Delhi (82,632), followed by Mumbai (68,433) and Chennai (56,274). The highest number of deaths occurred in Mumbai (4220), followed by New Delhi (2631) and Chennai (860). COVID-19 has been responsible for a total of 217,475 confirmed cases and 8174 deaths in the five megacities. It is evident that the confirmed cases and deaths have increased from May to June in each megacity. The highest increase in confirmed cases from May to June has been reported in Bangalore (19 times), followed by New Delhi (4.1 times) and Chennai (3.1 times). Similarly, the highest increase in deaths count occurred in Bangalore (16 times), followed by Chennai (6.5 times) and New Delhi (5.3 times). During the unlock period, the Indian government allowed limited resumption of many activities including opening up of shopping malls and restaurants and running of road and rail transport on a few selected routes. People came out of their homes and got involved in many activities, which includes the public gatherings. Most of the people also came out of their homes without any reason after being locked up in their homes for two months. During the lockdown period, the virus transmission was controlled because of strict lockdown implications. However, a significant number of mildly symptomatic or asymptomatic cases that remained undetected due to the limitation of testing and unawareness of the population during the lockdown period led to increasing spread of the virus during the unlock period resulting in higher confirmed cases and deaths in June 2020. The European countries, especially in Italy and Spain, where the first outbreak was reported and therefore large scale testing and tracing were deployed, were able to reduce the undetected cases and thus were able to control the spread. But the numbers continued to increase in India and USA because the number of testing as percentage of the population was far less than the countries in Europe (Paul et al., 2020).

Fig. 4 shows the Air Quality Index (AQI) for lockdown (May 2020) and unlock period (June 2020) in each megacity. There is an increment of AQI values in Chennai (from 49 to 54), New Delhi (119–125), and Kolkata (39–42) from lockdown to unlock period suggesting air quality was better during the lockdown period. This is expected since the personal/private transport, industrial and economic activities restarted during the unlock period. However, the AQI values in Bangalore (57–52) and Mumbai (80–55) decreased which suggests that air quality continued to improve in spite of the resumption of industrial activities in the unlock phase. As previously mentioned, the wet scavenging of the particulates and less road dust resuspension during the rain events in Bangalore and Mumbai are the reasons for this improvement in air quality.

The variations in meteorological parameters during the study duration are summarized in Table 6. The month of February marks the last phase of winter in India and month of May and until mid-June is the peak of the summer season. Therefore, temperature has increased over the time from pre lockdown to unlock period across all cities. From middle of June the monsoon rain starts which brings down the temperature, as can be seen in case of Mumbai, where mean temperature during unlock period was ~2.5 °C less than the temperature during lockdown period. Coastal cities reported higher RH and it was highest in the month of June, primarily due to monsoon rain. Chennai was the windy city among others with mean wind speed of 3.5 m s^{-1} in February, 4.65 m s^{-1} in May and 4.77 m s^{-1} in June 2020. All other cities reported a wind speed of <2.0 m s^{-1} throughout the study period, except in Bangalore where wind speed in June 2020 was marginally
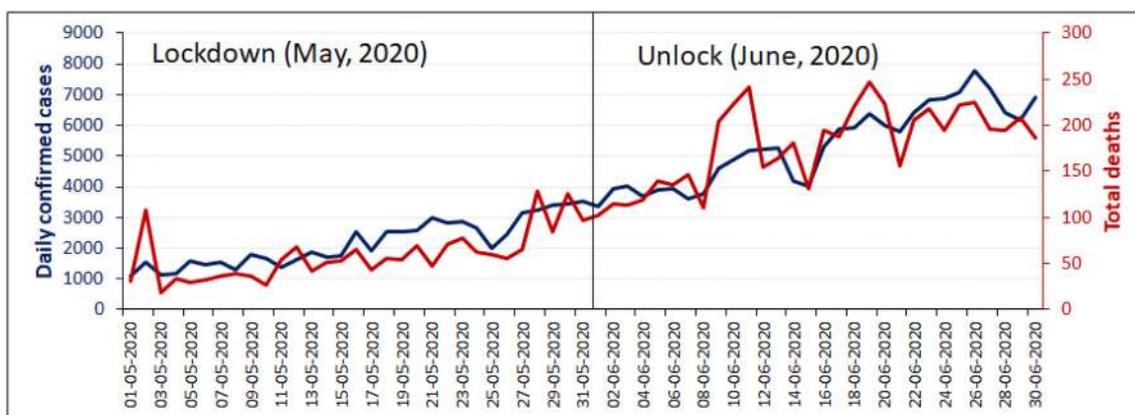
Fig. 3. Total COVID-19 daily confirmed cases and deaths during the lockdown and unlock periods in all megacities.

Table 5
Total COVID-19 confirmed cases and deaths in May and June 2020. The values represent the total count as on 31 May and June 30, 2020.

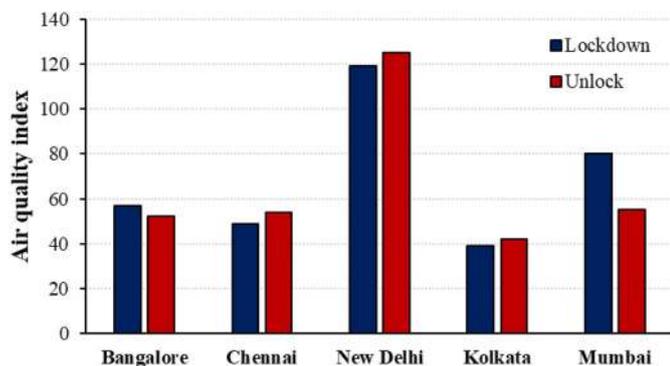|	Bangalore		Chennai		New Delhi		Kolkata		Mumbai	
	May	June	May	June	May	June	May	June	May	June
Confirmed cases	218	4172	13,713	42,561	16,106	66,526	1941	3805	31,874	36,559
Deaths	5	84	116	744	412	2219	209	165	983	3237

Fig. 4. Air quality index during lockdown and unlock periods (source: https ://app.cpcbccr.com/).

higher than it (2.18 m s^{-1}).

3.3. Association of COVID-19 confirmed cases, deaths and all variables

Pearson correlations were used to evaluate the relationships of the COVID-19 confirmed cases, deaths, pollutant concentrations, AQI, and meteorological variables in all megacities during May and June 2020 (Tables 7 and 8). It is observed that during the lockdown and the unlock periods, the death count is significantly correlated with the confirmed cases ($p \leq 0.05$). However, the correlation is lower in June (correlation coefficient $r = 0.27$) when compared with May ($r = 0.76$). Among the meteorological variables considered, temperature strongly correlated with the COVID-19 cases and deaths during the lockdown ($r = 0.54; 0.25$) and unlock period ($r = 0.66; 0.25$). Temperature was also correlated with PM$_{2.5}$, PM$_{10}$, CO, O$_3$, wind speed, AQI during the lockdown and unlock period. PM$_{2.5}$, PM$_{10}$, CO and O$_3$ concentrations and AQI were also significantly correlated with confirmed cases and deaths during the lockdown. However, during the unlock period, only PM$_{2.5}$ and AQI were associated with both confirmed cases and deaths, and PM$_{10}$, CO and O$_3$ were only correlated with confirmed cases. The air pollutants primarily affect our respiratory system and weakens it. SARS-COV-2 is also a respiratory disease and thus the synergy of high pollution

Table 6
Descriptives of the meteorological variables during the COVID-19 pandemic.

Megacities	Pollutants	Pre lockdown period (Feb 2020) AM±SD [Max-Min]	Lockdown period (May 2020) AM±SD [Max-Min]	Unlock period (June 2020) AM±SD [Max-Min]
Bangalore	Temperature (°C)	23.9 ± 3.5* [17.3–29.8]	24.4 ± 1.8* [28.9–23.1]	27.6 ± 1.2* [25.6–28.1]
	RH (%)	54.9 ± 18.5* [19.5–85.5]	59.2 ± 7.5* [47.2–74.2]	71.4 ± 4.8* [62.3–86.8]
	WS (m s^{-1})	1.7 ± 1.2* [0.23–2.9]	1.5 ± 0.3* [0.9–2.5]	02.1 ± 0.3* [1.3–2.9]
Chennai	Temperature (°C)	[a]	31.6 ± 0.9* [30.5–34.1]	31.1 ± 1.2* [27.5–33.3]
	RH (%)	66.9 ± 10.0* [36.4–86.1]	67.2 ± 6.3* [47.3–75.0]	69.1 ± 7.7* [56.7 ± 84.5]
	WS (m s^{-1})	3.5 ± 1.0* [0.9–6.6]	4.6 ± 0.8* [3.1–6.1]	4.7 ± 0.8* [1.6–6.0]
Delhi	Temperature (°C)	[a]	30.13 ± 2.32* [26.7–34.8]	32.05 ± 2.58* [25.2–35.5]
	RH (%)	66.6 ± 16.4* [34.3–89.9]	48.03 ± 9.10* [34.3–61.5]	57.6 ± 4.5* [48.±67.6]
	WS (m s^{-1})	0.9 ± 0.5* [0.1–3.1]	0.9 ± 0.2* [0.6–1.9]	0.6 ± 1.2* [0.6–1.2]
Kolkata	Temperature (°C)	22.1 ± 3.6* [13.1–30.3]	27.4 ± 2.1* [23.7–31.5]	28.9 ± 1.2* [26.9–31.6]
	RH (%)	58.0 ± 18.2* [23.9–99.6]	75.6 ± 8.5* [62.6–94.6]	82.6 ± 7.7* [68.3–97.1]
	WS (m s^{-1})	0.3 ± 0.3* [0.0 ± 1.7]	0.9 ± 1.0* [0.2–4.1]	1.2 ± 0.6* [0.3–2.6]
Mumbai	Temperature (°C)	28.2 ± 3.8* [19.4–39.3]	32.6 ± 0.5* [31.3–33.6]	30.2 ± 1.4* [25.1–32.0]
	RH (%)	57.6 ± 14.2* [18.0–91.7]	73.2 ± 2.0* [66.3–76.7]	84.3 ± 5.0* [76.6–98.53]
	WS (m s^{-1})	0.2 ± 0.3* [0.0–2.3]	1.5 ± 0.1* [1.3–2.0]	1.4 ± 0.5* [0.6–3.7]

*Temperature, RH and wind speed vary across the three lockdown periods significantly in each city (ANOVA, $p \leq 0.05$).
[a] Data not available.

with presence of SARS-COV-2 aggravates the COVID-19 infections. Recent studies in China, USA, Germany, and Italy also observed the association of PM$_{2.5}$ and PM$_{10}$ with SARS-COV-2 related cases and

Table 7
Pearson correlation coefficients during May 2020.

	Confirmed cases	Death	T	WS	RH	AQI	PM$_{2.5}$	PM$_{10}$	CO	O$_3$
Confirmed cases	1									
Death	.76**	1								
T	0.54**	0.25**	1							
WS	0.23**	−0.16	0.28**	1						
RH	−0.16**	0.01	−0.14	0.28**	1					
AQI	0.45**	0.38**	0.23**	−0.30**	−0.62**	1				
PM$_{2.5}$	0.21**	0.12**	0.00	−0.40**	−0.75**	0.73**	1			
PM$_{10}$	0.40**	0.29**	0.50**	0.61**	0.25**	-.17**	0.68**	1		
CO	0.31**	0.50**	0.01	0.60**	−0.30**	0.14	0.18*	0.46**	1	
O$_3$	−0.56**	−0.50**	−0.05	−0.87	−0.30	0.25**	0.18**	0.20*	0.02	1

**p < 0.05.

Table 8
Pearson correlation coefficients during June 2020.

	Confirmed cases	Death	T	WS	RH	AQI	PM$_{2.5}$	PM$_{10}$	CO	O$_3$
Confirmed cases	1									
Death	0.27**	1								
T	0.66**	0.25**	1							
WS	0.01	−0.18**	0.13	1						
RH	−0.42**	0.00	−0.47**	−0.13	1					
AQI	0.46**	0.24**	0.46**	−0.26**	−0.54**	1				
PM$_{2.5}$	0.56**	0.16**	0.43**	−0.29**	−0.62**	0.71**	1			
PM$_{10}$	0.55**	0.17	0.58**	−0.24**	−0.64**	0.71	0.74**	1		
CO	0.28**	0.11	0.22**	0.75**	−0.53**	0.15	0.19	0.45**	1	
O$_3$	−0.24**	−0.90	0.27**	−0.07	−0.50**	0.27**	0.54**	−0.22	0.17*	1

**p < 0.05.

deaths (Bashir et al., 2020; Hendryx and Luo, 2020; Liang et al., 2020; Sanità di Toppi et al., 2020; Yao et al., 2020). AQI, which is derived from different pollutant levels in air, is also therefore correlated with confirmed cases. The correlations of temperature with other variables suggest that the combinations of these variables may play an important role in the spread of COVID-19.

It can be observed here that there are no uniform patterns of correlations were observed in May and June 2020. This is due to two different scenarios for the two different months. May represents the lockdown period, where all the services were closed. People stayed inside their homes and there were no active emission sources were operated. However, June represents the unlock period, where essential services were opened up gradually. The central government gave powers to the individual state governments to regulate the opening up of services based on the COVID-19 situations locally. Therefore, there were also some inconsistencies among the services opened in different states. These scenarios lead to the different emission patterns in different megacities. So, the inconsistencies were observed in the correlation coefficients.

3.4. Determinants of COVID-19 confirmed cases and deaths

To explain the variability in the COVID-19 confirmed cases and deaths separately, the General Linear Model (GLM) was implemented for lockdown (Table 9) and unlock periods (Table 10). In GLM analysis, confirmed cases and deaths were considered as dependent variables. Pollutant concentrations, AQI, and weather variables were treated as covariates. For COVID-19 confirmed cases during the lockdown, O$_3$ concentrations significantly explained the highest variability (34%), followed by temperature (30%), WS (10%), PM$_{2.5}$ (9%), RH (4%) and AQI (2%) (Table 9). For COVID-19 deaths during the lockdown, O$_3$ concentrations explained the highest variability (17%) (Table 9). The complete models explained 74% and 35% variability for confirmed cases and deaths during the lockdown, respectively. Similarly, temperature (22%) significantly explained the highest variability followed by O$_3$ (12%), WS (11%), RH (6%) and PM$_{2.5}$ (4%) for confirmed cases during

Table 9
Explained variability in COVID-19 confirmed cases and deaths in May 2020.

Parameter	Confirmed cases (May 2020)			Deaths (May 2020)		
	β	p value	R^2	β	p value	R^2
	R$^2_{adj}$ = 0.74 (complete model)			R$^2_{adj}$ = 0.35 (complete model)		
T	23.49	0.01**	0.30	0.69	0.08	0.03
WS	5.09	0.21	0.10	−0.35	0.14	0.02
RH	4.40	0.03**	0.04	0.08	0.79	0.00
AQI	3.15	0.12	0.02	0.07	0.23	0.01
PM$_{2.5}$	5.55	0.00**	0.09	0.28	0.03**	0.04
PM$_{10}$	3.84	0.03**	0.00	0.27	0.30	0.01
CO	−75.68	0.47	0.00	−8.47	0.28	0.00
O$_3$	−6.10	0.00**	0.34	−0.28	0.00**	0.17

Table 10
Explained variability in COVID-19 confirmed cases and deaths in June 2020.

Parameter	Confirmed cases (June 2020)			Deaths (June 2020)		
	β	p value	R^2	β	p value	R^2
	R$^2_{adj}$ = 0.66 (complete model)			R$^2_{adj}$ = 0.19 (complete model)		
T	29.82	0.02**	0.22	10.82	0.01**	0.04
WS	−2.56	0.00**	0.11	−9.85	0.16	0.02
RH	−29.08	0.01**	0.06	2.44	0.90	0.00
AQI	0.89	0.42	0.00	0.37	0.24	0.01
PM$_{2.5}$	22.65	0.04**	0.04	1.52	0.37	0.00
PM$_{10}$	29.98	0.32	0.01	−0.52	0.25	0.01
CO	19.84	0.97	0.00	32.80	0.70	0.00
O$_3$	−14.43	0.00**	0.12	−1.47	0.01**	0.06

the unlock period (Table 10). However, for deaths during unlock period, O$_3$ concentrations and temperature explained only 6% and 4% variability, respectively (Table 10). The total models explained about 66% and 19% variability in COVID-19 confirmed cases and deaths during the unlock period. Therefore, our study showed that among the meteorological parameters, temperature was the predominant factor in explaining the variability of confirmed cases and death cases. During

both lockdown and unlock period, the meteorological and pollutant parameters explained higher variability for confirmed cases than for the deaths because, the confirmed cases are the direct outcomes of transmission and for deaths, several other factors such as availability and quality of the medical facilities, age of the affected population, etc. plays a significant role, which were not assessed in the present study.

It was observed in this study that ambient air pollutants and meteorological variables can significantly influence the effect of the COVID-19 pandemic on public health, which is similar to previous studies conducted on several other viruses. It was observed in Japan and USA, that air pollutants and meteorological variables can impact the influenza viability and activity (Iha et al., 2016; Landguth et al., 2020). This has also been observed in a recent study conducted on SARS-COV-2 in Wuhan and XiaoGan (Li et al., 2020). In this study, it is observed that higher temperatures can influence the spread of SARS-COV-2. Similar to a recent study in China, this study also showed that an increase in pollutants concentrations can increase the transmission of SARS-COV-2 (Li et al., 2020). In several studies, it was observed that particulate matter, typically $PM_{2.5}$ and PM_{10} could potentiate viral transmissions. A study by Feng et al. (2016) observed that influenza illness risk increased due to an increase in ambient $PM_{2.5}$ concentrations during the flu season in Beijing, China. In another study, it was found that a 1 μg m^{-3} increase in $PM_{2.5}$ concentrations was associated with a 15% increase in COVID-19 related death rate (Wu et al., 2020). Yao et al. (2020) used multiple linear regression and reported that higher $PM_{2.5}$ and PM_{10} concentrations are correlated with higher death rates (Yao et al., 2020). From the analysis of data obtained for Northern Italy, which was one of the first epicenters of COVID-19 outbreak, Fattorini and Regoli (2020) reported a significant association of $PM_{2.5}$ and PM_{10} with COVID-19 cases. Similar observations were reported from studies in the USA (Xiao et al., 2020), England (Travaglio et al., 2020), China (Wang et al., 2020) and Italy (Ogen et al., 2020). It was reported that influenza and syncytial virus attached to the particulates can remain suspended in the air for longer durations, which allows the transmission of the viruses through airborne PM (Lindsley et al., 2010). Additionally, due to the negative effect on the human respiratory system caused by PM, the viral replication in the respiratory system can be enhanced (Xian et al., 2020). PM has the ability to form the condensation nuclei for viral attachments (Lee et al., 2014). Due to its extremely small size, $PM_{2.5}$ can reach the deeper parts of the lungs such as alveoli. When the SARS-COV-2 virus is attached to $PM_{2.5}$, it creates a direct passage into the deeper parts of the respiratory system, which is ultimately responsible for the person to be diseased and may even cause death.

Other than PM, it is also observed in our study that CO significantly influenced the daily confirmed cases and deaths during the lockdown period. A study in Jinan, China reported a similar finding that the CO can have the ability to increase the risk of influenza-like virus. Another study in Wuhan, China also reported that CO and SARS-COV-2 are positively associated (Li et al., 2020). The negative β values in Tables 9 and 10 suggests that with an increase in ozone concentrations, there was a slight decrease in the number of confirmed cases and deaths. This may be due to the virucidal activity of the ozone on the host defense. Many previous studies observed that ambient ozone is associated with the reduction of COVID-19 transmission (Ran et al., 2020). Against many respiratory infections like influenza and SARS-CoV-1 viruses, the ozone gas is highly effective in disinfection and sterilization (Elvis and Ekta, 2011). Ozone gas has the capability of inactivating and destroying SARS-CoV-2 viruses. Since this virus is an enveloped virus, due to the strong oxidizing power of ozone gas, the virus is particularly vulnerable to oxidation attack (Tizaoui, 2020). For the reduction in the COVID-19 infectivity, ozone primed immunity against viral infections might play a crucial role. Particularly, exposure to ambient ozone can trigger slight allergic reactions in human respiratory system, which can enhance the pulmonary innate immunity (Ran et al., 2020). Ozone has the capability of damaging the structure of the virus integrity making them incapable of reproducing further (Tizaoui, 2020). It was reported in previous

studies that climate and weather conditions among other factors play a major role in corona virus transmission (Pica and Bouvier, 2012). Meteorological parameters such as temperature, RH and wind speed are believed to be the major drivers of the transmission of viruses (Dalziel et al., 2018; Kutter et al., 2018). Several laboratory and epidemiological studies reported that temperature is the crucial factor for transmission of MERS-CoV and SARS-COV-1 (Casanova et al., 2010; van Doremalen et al., 2013). Similar to these studies, our study also showed that the temperature explained a major percentage of the total variability in the daily confirmed cases and deaths. However, the meteorological parameters like RH and wind speed explained lower variabilities.

4. Conclusions

The study revealed that the lockdown to counter the COVID-19 pandemic resulted in significant cleaning of the air environment. A 65–73% reduction of ambient PM_{10}, $PM_{2.5}$ and CO levels in five megacities was observed during the lockdown period in comparison to the normal time. However, the ozone concentrations increased in Delhi and Kolkata during the lockdown period. Although the improvement in air quality is temporary, yet this experience can be used as a future strategy in air quality management, especially when aggressive air quality management through limited lockdown may be enforced in a city or an industrial belt that encounters severe deterioration in air quality, which often happens during winter season. The positive correlation between PM and CO concentrations with COVID-19 incidences needs further research for better understanding of the mechanism behind it. Nevertheless, the findings suggest that an effective and sustained air quality management program not only ensures the regular health benefits of the population, but also greatly reduces the morbidity and mortality from highly contagious diseases like SARS-COV-2 (2019), MERS-COV (2012) and SARS-COV (2003) which are now becoming more frequent. The future studies should assess the association of more pollutants such as NO_x, VOC with COVID-19 incidences. We found a combination of meteorological parameters (T, RH and WS) and pollutants (PM_{10}, $PM_{2.5}$ and CO) could better correlate with the number of confirmed cases than the deaths, which is expected because number of deaths depend on the medical infrastructure, its quality and affordability by the public. As opposed, our study showed that increase in the ozone concentrations caused a reduction in the infection of the viruses. A more comprehensive study that combines all three factors (ambient pollution levels in terms of at least the criteria pollutants included in the national ambient air quality standard, meteorological parameters, and state of medical facilities and access to it) has the potential to give a better understanding of the transmission and infection of COVID-19 and similar infectious diseases. Our study suggests that air quality should be included as a part of the combined approach towards human health protection and sustainable development. In addition, it is to be noted here that our study did not consider socio economic factors, lifestyle factors and preexisting medical conditions of the individuals effected by the SARS-CoV-2. Considering these limitations, our findings of the study should be taken as hypotheses based rather than confirmatory. More studies in these directions need to be conducted to solve the complex question whether the air pollutant concentrations combined with meteorology could effect the transmission ability of the viruses.

Credit author contribution statement

Soma Sekhara Rao Kolluru: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision. Aditya Kumar Patra: Validation, Resources, Writing – review & editing. Nazneen Allaudeen: Writing – original draft. S M Shiva Nagendra: Writing – review & editing.

Declaration of competing interest

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

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