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ORIGINAL PAPER

COVID-19 lockdown: a boon in boosting the air quality of major Indian Metropolitan Cities

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Abstract The COVID-19 lockdown has not only helped in combating the community transmission of SARS-CoV-2 but also improved air quality in a very emphatic manner in most of the countries. In India, the first phase of COVID-19 lockdown came into force on March 25, 2020, which was later continued in the next phases. The purpose of this study was to investigate the result of lockdown on air quality of major metropolitan cities—Delhi, Mumbai, Kolkata, Chennai, Bengaluru, Hyderabad, Jaipur, and Lucknow—from March 25 to May 3, 2020. For this study, the concentration of six criteria air pollutants ($PM_{2.5}$, PM_{10}, CO, NO_2, SO_2, and O_3) and air quality index during the COVID-19 lockdown period was compared with the same period of the previous year 2019. The results indicate a substantial improvement in air quality with a drastic decrease in the concentration of $PM_{2.5}$, PM_{10}, CO, and NO_2, while there is a moderate reduction in SO_2 and O_3 concentration. During the lockdown period, the maximum reduction in the concentration of $PM_{2.5}$, PM_{10}, CO, NO_2, SO_2, and O_3 was observed to be − 49% (Lucknow), − 57% (Delhi), − 75% (Mumbai), − 68% (Kolkata), − 48% (Mumbai), and − 29% (Hyderabad), respectively. The value of the air quality index (AQI) also dwindled significantly during the COVID-19 lockdown period. The maximum decline in AQI was observed – 52% in Bengaluru and Lucknow. The order of AQI was satisfactory > moderate > good > poor and the frequency order of prominent pollutants was O_3 > PM_{10} > $PM_{2.5}$ > CO > NO_2 > SO_2 during the lockdown period in all the aforementioned metropolitan cities.

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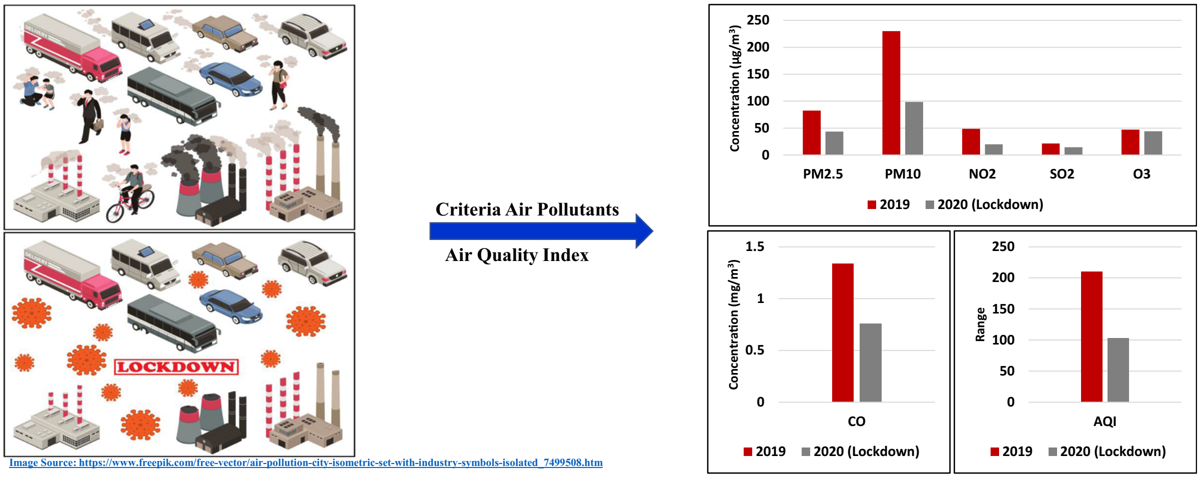
Graphic abstract



Keywords COVID-19 · Lockdown · Criteria pollutants · Air quality index · Metropolitan cities · Prominent pollutant

1 Introduction

The rapid transmission of the COVID-19 pandemic has become a major health threat globally. In late December 2019, an epidemic of pneumonia linked with novel coronavirus disease-2019 (COVID-19) (Huang et al. 2020a, b; Wu et al. 2020) that has its epicenter in Wuhan, China, has spread over 215 countries worldwide (WHO 2020a). The COVID-19 epidemic was declared a public health emergency at a global level by the World Health Organization (WHO) on Jan 30, 2020 (WHO 2020b). The COVID-19 cases burst at an alarming rate with significant mortality (Wang et al. 2020a, b) and have impacted human life and the world economy. The transmission of COVID-19 has mostly occurred between people via respiratory droplets and contact routes (Burke et al. 2020; Chan et al. 2020; Li et al. 2020; Liu et al. 2020a, b; WHO 2020c).

Breaking the chain of transmission of SARS-CoV-2 via social isolation is the only way to control the exponential spread of the COVID-19 pandemic. Social distancing is a prevention strategy to control infection by discouraging/decreasing contact with infected and non-infected people, contaminated surfaces, and also among the general public to slow down the rate of spread of disease. Many countries have imposed dramatic interventions like lockdown of the entire country, curtailing human interaction, restriction on public gatherings, and public transportations to adopt social distancing (He et al. 2020). The first lockdown was intruded in Wuhan, China, and later followed by other countries (Jing 2020). Indian government locked the country for fourteen hours in the name of “Janta Curfew” after Prime Minister’s call on March 22, 2020. After Janta Curfew, India went into complete lockdown on March 25 for 21 days followed by the next lockdown for 19 days from April 15 to May 3, the third phase from May 4 to May 17 and the fourth phase from May 18 to May 31, 2020. The lockdown restricted movement of the public and shut down commercial and industrial establishments that adversely affected the growth and economy of India, but on the flip side, our society and environment gained substantial benefits that would be advantageous to the layperson and moderately counterbalance the cost of this pandemic. Due to the lockdown, dramatic positive changes have happened in the air quality of the world that showed a glimpse of a cleaner world. As per media intelligence, a massive reduction in air pollution due to lockdown has been observed in numerous countries by satellite pictures. A few scientific researchers also reported a significant augmentation in air quality because of COVID-19 lockdown worldwide (Cadotte 2020; Dantas et al. 2020; He et al. 2020; 2020a, b; Isaifan 2020;

Kerimray et al. 2020; Muhammad et al. 2020; Ogen 2020; Shrestha et al. 2020; Sicard et al. 2020; Wang and Su 2020; Wang et al. 2020a, b, Zhu et al. 2020) and in India (Chauhan and Singh 2020; Gautam 2020; Mahato et al. 2020; Saadat et al. 2020; Sharma et al. 2020).

Air quality has emerged as an international community health concern in the last few decades. Air pollution is a severe environmental health threat that causes premature mortality and attributes over seven million deaths per annum worldwide (WHO 2020d). Air pollution means the presence of harmful substances in the air such as airborne particulate matter (PM), fine particulate matter ($PM_{2.5}$), coarse particulate matter (PM_{10}), and gaseous pollutants like ozone (O_3), nitrogen dioxide (NO_2), volatile organic compounds (like benzene), carbon monoxide (CO), sulfur dioxide (SO_2), etc. (Harrison et al. 2002; Newby et al. 2015). According to WHO, particulate pollution, ground-level O_3, CO, sulfur dioxide (SO_2), nitrogen oxides (NO_x), and lead (Pb) are the six major air pollutants that adversely affect human health and the environment (Ghorani-Azam et al. 2016). Particulate matter (PM) pollutant is responsible for most of the pulmonary and cardiac diseases, and mortality (Sadeghi et al. 2015; Sahu et al. 2014). According to a study of Global Burden of Disease (GBD), $PM_{2.5}$ is the 5th most vulnerable pollutant responsible for the death of humans worldwide, which triggered 4.2 million deaths in the year 2015 (Cohen et al. 2017). Ground-level ozone is a probable risk factor for respiratory diseases, predominantly asthma (Gorai et al. 2014), and carbon monoxide toxicity causes hypoxia, apoptosis, and ischemia (Akyol et al. 2014). Exposure of sulfur dioxide is linked with bronchospasm, pulmonary edema, pneumonitis, and acute airway blockage, and nitrogen oxides prominently boost the danger of respiratory problems (Chen et al. 2007). According to WHO, out of the ten most polluted cities worldwide, nine cities are from India. Delhi stands at 6th position in the polluted cities ranking list (Yuda 2019) and holds the 1st rank among all the PM_{10} polluted cities (Donkelaar et al. 2016; WHO 2018). In India, the concentration of air pollutants is beyond ambient air quality standards of the WHO and Central Pollution Control Board (CPCB), India (Garaga et al. 2018; Mukherjee and Agrawal 2018).

Air quality index is an extensively used tool that describes the severity of air pollution (Nagendra et al. 2007). The air quality index is a single value indicator for the air quality assessment to measure the effects on human health (Bortnick et al. 2002; Kyrkilis et al. 2007; Murena 2004; Thom and Ott 1976).

Hence, in this study, the effects of the lockdown on the air quality of the eight metropolitan cities of India were analyzed. The data of six major criteria air pollutants—$PM_{2.5}$, PM_{10}, CO, NO_2, SO_2, and O_3—and air quality index were collected from the official website of the CPCB, India during the lockdown period from March 25 to May 3, 2020, and the same period of the previous year 2019. For assessing the consequences of the lockdown on air quality and daily concentrations of air pollutants, the data of the COVID-19 lockdown period were compared with the data of the same period of the previous year 2019 that helps in better understanding of the enhancement in air quality as a result of COVID-19 lockdown.

2 Materials and methods

2.1 Selection of the metropolitan cities

Eight major metropolitan cities—Delhi, Mumbai, Kolkata, Chennai, Bengaluru, Hyderabad, Jaipur, and Lucknow—were selected to estimate the overall air quality status based on (1) total population, (2) previous year's history of air quality status, (3) urban and industrial development, (4) geographical region, and (5) availability of air quality data (Shrestha et al. 2020). The details of region, population, population density, and number of air quality monitoring stations are shown in Table 1, and locations of the selected metropolitan cities are shown in Fig. 1.

2.2 Selection of air pollutants

Air quality status can be described by calculating the atmospheric concentrations of six criteria pollutants, i.e., $PM_{2.5}$, PM_{10}, carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and ozone (O_3) (EPA 2014). The main source of all criteria pollutants is the combustion of fuel in the automobiles and industries, while O_3 is being formed by the reaction of primary pollutants in the presence of sunlight. Therefore, to assess the outcome of lockdown on air quality of Indian metropolitan cities, the air pollutant parameters, viz. $PM_{2.5}$, PM_{10}, CO, NO_2, SO_2, and O_3, along

Table 1 Details of selected metropolitan cities of India

Metropolitan city name	Region	Coordinates	Population* (million)	Population density* (density/km^2)	No. of air quality monitoring (AQM) stations
Delhi	Northcentral	28.7041° N, 77.1025° E	16.78	11,320	35
Mumbai	Southwestern	19.0760° N, 72.8777° E	12.44	19,652	10
Kolkata	Eastern	22.5726° N, 88.3639° E	4.49	24,306	07
Chennai	Southeastern	13.0827° N, 80.2707° E	4.64	26,553	04
Bengaluru	Southeastern	12.9716° N, 77.5946° E	8.44	4381	10
Hyderabad	Southeastern	17.3850° N, 78.4867° E	6.73	18,172	06
Jaipur	Northwestern	26.9124° N, 75.7873° E	3.07	595	03
Lucknow	Northern	26.8467° N, 80.9462° E	2.81	1816	05

*As per Census 2011

with meteorological parameters such as temperature and relative humidity during the COVID-19 lockdown period from March 25 to May 3, 2020, were studied and compared with the air quality data of the same period of the previous year 2019.

2.3 Data sources

The data of 24 hourly concentrations of $PM_{2.5}$, PM_{10}, NO_2, SO_2 and 8 hourly concentrations of CO and O_3 along with meteorological parameters such as temperature and relative humidity for eight metropolitan cities were downloaded from the online portal of CPCB, India (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing) from 80 air quality monitoring stations spread across the selected eight metropolitan cities. Data were collected for the COVID-19 lockdown period of the year 2020 from March 25 to May 3 and the same period of the previous year 2019. To compress the large data sets, average concentrations were calculated for each pollutant at all stations of each metropolitan city for each day.

2.4 Air quality index (AQI)

Air quality index (AQI) is a tool that represents the weighted values of individual air pollutants into a single value. AQI is computed in the subsequent two steps (CPCB 2015):

(1) Calculation of subindices (for each pollutant): It is calculated by 24 h average concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, NH_3, and 8 hourly concentrations of CO and O_3, and health breakpoint concentration range. For calculation, the minimum three of the above pollutants are obligatory, out of which one has to be either $PM_{2.5}$ or PM_{10}.
The subindex (I_i) for a given pollutant concentration (C_p) is calculated as:

$$I_i = \left[\{(I_{HI} - I_{LO})/(B_{HI} - B_{LO})\} * \left(C_p - B_{LO}\right)\right] + I_{LO}$$

where B_{HI} = breakpoint concentration greater or equal to given concentration; B_{LO} = breakpoint concentration smaller or equal to given concentration; I_{HI} = AQI value corresponding to B_{HI}; I_{LO} = AQI value corresponding to B_{LO}; and C_p = pollutant concentration.

(2) Aggregation of subindices to get an overall AQI: Maximum operator system aggregates AQI, after the calculation of subindices (Ott 1978).

$$\mathrm{AQI} = \mathrm{Max}\ (I_1, I_2, I_3, \ldots, I_n)$$

Indian air quality index (IND-AQI) is categorized into six categories to represent air quality status and its effects on human health (Table 2).

2.5 Prominent pollutants

The "prominent pollutant" is determined every day for all metropolitan cities to measure what pollutant is primarily responsible for the air quality deterioration and identified by the AQI system. The pollutant that

Fig. 1 Locations map of eight metropolitan cities of India. *Source*: https://www.google.com/maps/@24.1580341,82.7349726,5z

has maximum AQI values is identified as a prominent pollutant on that particular day (Cheng et al. 2007).

2.6 Statistical analysis

The Pearson correlation analysis was conducted among the six criteria air pollutants ($PM_{2.5}$, PM_{10}, CO, NO_2, SO_2, and O_3), the meteorological parameter

Table 2 Indian air quality index (IND-AQI) category and range

AQI Range	0-50	51-100	101-200	201-300	301-400	401-500
Category	Good	Satisfactory	Moderate	Poor	Very poor	Severe
Color Code						

(temperature and relative humidity), air quality index, and population density to investigate the interrelationship among them. The Pearson correlation coefficient (R) is ranged from -1 to $+1$, where $R \leq .35$ corresponds to a weak correlation, $R = .36–.67$ exhibits moderate correlation, and $R \geq .68$ represents strong correlation, and it can be positive or negative (Mason et al. 1983; Weber and Lamb 1970).

3 Results and discussion

3.1 Overview of air pollutants

The average concentrations of six criteria air pollutants monitored in eight metropolitan cities are summarized in Table 3. The average concentration of $PM_{2.5}$ ranged from 17.03 ± 8.14 µg/m^3 (Chennai) to 51.66 ± 13.05 µg/m^3 (Lucknow) during the assessment period. The variation in the average concentration of $PM_{2.5}$ was observed in Delhi (− 47%), Mumbai (+ 1%), Kolkata (− 38%), Chennai (− 48%), Bengaluru (− 52%), Hyderabad (− 23%), Jaipur (− 47%), and Lucknow (− 49%) during the COVID-19 lockdown in comparison with the same period of the previous year 2019 (Table 3; Fig. 2). The data of the average concentration of PM_{10} were available for six cities except for Chennai and Lucknow, ranged from 47.88 ± 10.82 µg/m^3 (Bengaluru) to 98.51 ± 34.03 µg/m^3 (Delhi) during the lockdown period. The downturn in the average concentration of PM_{10} was recorded in Delhi (− 57%), Mumbai (− 27%), Kolkata (− 47%), Bengaluru (− 54%), Hyderabad (− 41%), and Jaipur (− 52%) (Table 3; Fig. 2).

The decrease in the concentration of PM_{10} along with $PM_{2.5}$ was observed in a similar pattern in Delhi, Kolkata, Bengaluru, Hyderabad, and Jaipur during the lockdown period; it indicated that a substantial fraction of PM_{10} is determined by $PM_{2.5}$ concentration in most aforementioned cities (> 60%) (Wang et al. 2014; Zhang and Cao 2015) (Fig. 2). The vehicular exhaust, industrial emission, dust fallout, and construction-demolition activities are the major source of PM_{10} and $PM_{2.5}$ pollution. The reduction in the concentration of $PM_{2.5}$ and PM_{10} was due to a ~ 80% drop in vehicular flux (Cyberlab 2020) and shut down of the industrial and constructional activities during the lockdown period. In Wuhan, fossil fuel combustion and vehicles on roads are the main contributors to $PM_{2.5}$ (Wang et al. 2017). In Barcelona, particulate matter emission is added in the atmosphere by road transport (+ 18%) and non-road transport (+ 21%) (Karamchandani et al. 2017). Both these reports support the findings of our current study that transportation activities are major contributors of particulate matter (PM) in the environment, which were suspended during the lockdown period, which consequently declined the concentration of $PM_{2.5}$ and PM_{10} in the environment. The reduction in the concentration of $PM_{2.5}$ and PM_{10} in the present study is also supported by a similar study by Sicard et al. (2020). They also observed 36% and 49% reduction in $PM_{2.5}$ and PM_{10} concentration, respectively, in Wuhan, China, during the lockdown period in 2020. Huang et al. (2020a, b) exhibited 9% to 34% decrease in $PM_{2.5}$ concentration in China during the lockdown period in 2020.

The average concentration of CO ranged from $.41 \pm .09$ mg/m^3 (Kolkata) to $.99 \pm .04$ mg/m^3 (Lucknow) during the lockdown period. A decrease in the average concentration of CO in Delhi (− 43%), Mumbai (− 75%), Kolkata (− 22%), Chennai (− 32%), Bengaluru (− 28%), Hyderabad (− 23%), Jaipur (− 46%), and Lucknow (− 28%) was observed during the lockdown period as compared to the same period of 2019 (Table 3; Fig. 2). The minimum and maximum value of the average concentration of NO_2 was ranged 7.92 ± 2.53 µg/m^3 (Chennai) and 21.42 ± 4.71 µg/m^3 (Hyderabad), respectively. The significant decline in the average concentration of NO_2 was exhibited in Delhi (– 59%), Mumbai (– 59%), Kolkata (– 68%), Chennai (– 32%), Bengaluru (– 64%), Hyderabad (– 37%), Jaipur (– 62%), and Lucknow (– 66%) (Table 3; Fig. 3).

Carbon monoxide and NO_2 both have also exhibited significant decline during the COVID-19 lockdown period (Fig. 2 and 3). The emission of CO and NO_2 is primarily associated with the combustion process of fuel like gasoline and diesel in vehicles and industries. COVID-19 lockdown majorly shut down vehicular movement, industrial activities that diminished the concentration of CO and NO_x in the environment. The transport sector (road transport: 39% and non-road transport: 8%) largely emits NO_x pollutants in Europe (EEA 2019). In China, industrial activities were stopped due to the COVID-19 lockdown dropped 30% and 25% of NO_2 and carbon emission, respectively (Isaifan 2020). During the lockdown period, Sicard et al. (2020) noticed a similar reduction in mean NO_2 concentration in urban stations of all European cities (– 57%) and traffic stations of Wuhan (– 65%); Huang et al. (2020a, b) reported a more than 60% reduction in NO_2 and 13% to 41% reduction in CO concentration in China; Dantas et al. (2020) reported 30.3% to 48.5% diminutions in CO concentration in Rio de Janeiro, Brazil.

The average concentration of sulfur dioxide (SO_2) ranged from 5.54 ± 1.79 μg/m^3 (Chennai) to 14.38 ± 2.55 μg/m^3 (Delhi) during the lockdown period. The variation in the average concentration of SO_2 was observed in Delhi (– 32%), Mumbai (– 48%), Kolkata (+ 25%), Chennai (– 22%), Bengaluru (+ 9%), Hyderabad (– 9%), Jaipur (– 9%), and Lucknow (– 16%) (Table 3; Fig. 3).

The average SO_2 concentration also exhibited mixed trends during the lockdown and showed a significant decline in six metropolitan cities—Delhi, Mumbai, Chennai, Hyderabad, Jaipur, and Lucknow—while there was an increase in two metropolitan cities—Kolkata and Bengaluru (Fig. 3). Burning coal is a prime source of SO_2 emission in the environment, and during the lockdown period, coal power plants might not have been shut down. Therefore, it would be a possible reason for a slight variation in SO_2 concentration during the lockdown as compared to the non-lockdown period of the previous year. Huang et al. (2020a, b) also observed 15–42% diminution in SO_2 concentration in China during the lockdown in 2020, which is similar to our results.

The average concentration of O_3 ranged from 23.69 ± 8.10 μg/m^3 (Mumbai) to 49.55 ± 6.85 μg/m^3 (Jaipur) during the lockdown period. The variation in the average concentration of O_3 was observed in Delhi (– 06%), Mumbai (– 02%), Kolkata (+ 63%), Chennai (+ 51%), Bengaluru (– 25%), Hyderabad (– 29%), Jaipur (– 17%), and Lucknow (– 28%) (Table 3; Fig. 3).

A mixed trend is also observed in O_3 concentration during the lockdown, a slight decline in six metropolitan cities (Delhi, Mumbai, Bengaluru, Hyderabad, Jaipur, and Lucknow), while there is an increase in two metropolitan cities (Kolkata, Chennai) (Fig. 3). A slight variation in O_3 concentration compared to other criteria pollutants like $PM_{2.5}$, PM_{10}, CO, and NO_2 during the lockdown period might be due to three reasons: (1) Owing to the lockdown of vehicular movement and industrial activities, the reduction in NO concentration may decrease the consumption of ozone molecules (titration, $NO + O_3 = NO_2 + O_2$), thus increasing the O_3 concentration. (2) The concentration of PM_{10} and $PM_{2.5}$ decreases drastically during the lockdown period, which may allow extra sunlight through the atmosphere, accelerating more photochemical activities and thereby increasing ozone formation (Dang and Liao 2019; Li et al. 2019). (3) From March to August, Sun migrates in the north that causes augmentation of insolation and temperature in the northern hemisphere and leads to acceleration in ozone production (Gorai et al. 2017). Sicard et al. (2020) also reported similar results. They recorded 24%, 14%, 27%, 2.4%, and 36% rise in O_3 concentration at urban stations of Nice, Rome, Turin, Valencia, and Wuhan, respectively, during the COVID-19 lockdown in 2020.

3.2 Overview of meteorological parameters

The average temperature ranged from 24.27 ± .69 °C (Bengaluru) to 31.31 ± 1.04 °C (Mumbai) during the lockdown period. The variation in average temperature was observed in Delhi (– 7%), Mumbai (+ 2%), Kolkata (+ 1%), Chennai (– 3%), Bengaluru (– 10%), Hyderabad (+ 3%), Jaipur (– 7%), and Lucknow (– 5%) during lockdown as compared to the same period of the previous year 2019 (Table 3; Fig. 4). The average relative humidity ranged from

Table 3 Mean concentrations, standard deviation, maximum, minimum, and % variation in six criteria air pollutants, temperature, relative humidity, and air quality index of selected metropolitan cities of India

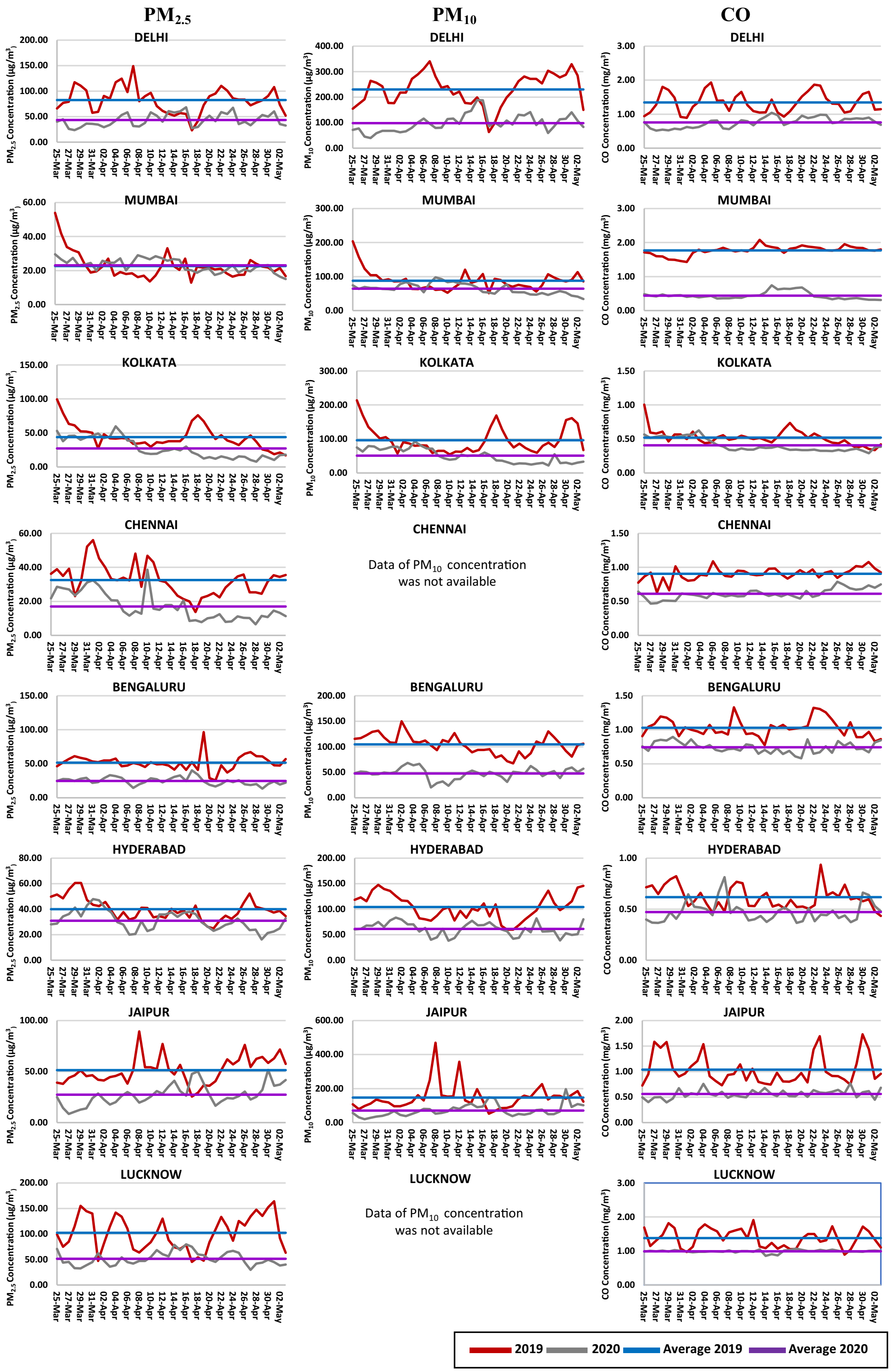
City	Parameters	Unit	2019				2020				Variation
			Mean	SD	Max.	Min.	Mean	SD	Max.	Min.	%
Delhi	$PM_{2.5}$	μg/m^3	82.42	24.80	149.27	23.25	43.60	12.51	68.55	23.62	− 47
	PM_{10}	μg/m^3	230.18	61.87	341.03	63.18	98.51	34.03	188.43	39.28	− 57
	CO	mg/m^3	1.34	.30	1.93	.89	.76	.15	1.04	.52	− 43
	NO_2	μg/m^3	48.52	9.69	63.51	27.30	19.85	3.73	27.38	14.24	− 59
	SO_2	μg/m^3	21.29	4.04	29.09	11.31	14.38	2.55	19.29	10.33	− 32
	O_3	μg/m^3	47.04	6.07	61.21	32.97	44.19	8.87	60.98	24.06	− 6
	Temperature	°C	28.55	3.46	33.91	21.63	26.62	2.71	31.21	20.92	− 7
	Relative humidity	%	35.34	10.03	56.55	15.53	48.09	8.73	69.71	34.31	+ 36
	Air quality index		210.18	49.72	302.00	84.00	103.43	28.74	180.00	45.00	− 51
Mumbai	$PM_{2.5}$	μg/m^3	22.72	7.76	53.91	12.83	23.04	3.76	29.55	14.96	+ 1
	PM_{10}	μg/m^3	87.93	28.49	203.83	51.13	64.29	15.10	97.50	33.81	− 27
	CO	mg/m^3	1.77	.13	2.08	1.43	.44	.11	.75	.32	− 75
	NO_2	μg/m^3	20.28	8.27	35.33	2.48	8.24	1.62	12.00	5.88	− 59
	SO_2	μg/m^3	22.74	5.96	40.86	1.03	11.76	3.46	17.33	5.99	− 48
	O_3	μg/m^3	24.14	8.74	49.64	11.69	23.69	8.10	48.04	13.19	− 2
	Temperature	°C	30.61	.82	32.30	29.18	31.31	1.04	33.87	29.59	+ 2
	Relative humidity	%	69.86	6.03	78.09	45.56	73.88	5.25	80.53	58.69	+ 6
	Air quality index		96.90	14.76	165.00	80.00	68.30	13.93	97.00	40.00	− 30
Kolkata	$PM_{2.5}$	μg/m^3	43.99	17.05	99.54	17.05	27.24	14.64	59.80	7.73	− 38
	PM_{10}	μg/m^3	96.04	38.12	213.39	54.48	50.77	20.38	92.87	21.78	− 47
	CO	mg/m^3	.52	.11	1.01	.34	.41	.09	.63	.29	− 22
	NO_2	μg/m^3	34.62	17.43	113.70	15.55	11.00	2.91	17.91	6.49	− 68
	SO_2	μg/m^3	6.53	4.54	18.96	1.77	8.18	2.08	12.84	5.20	+ 25
	O_3	μg/m^3	29.43	10.21	51.99	13.46	47.88	12.73	71.42	27.89	+ 63
	Temperature	°C	28.30	1.41	30.79	25.63	28.56	1.82	30.91	23.85	+ 1
	Relative humidity	%	68.83	8.61	84.75	47.35	68.62	11.82	88.73	45.42	− 30
	Air quality index		88.63	43.32	204.00	27.00	71.43	29.83	146.00	32.00	− 19
Chennai	$PM_{2.5}$	μg/m^3	32.51	9.14	55.99	13.76	17.03	8.14	38.60	6.57	− 48
	CO	mg/m^3	.90	.09	1.09	.63	.61	.07	.79	.47	− 32
	NO_2	μg/m^3	11.57	3.12	24.87	8.06	7.92	2.53	11.90	3.71	− 32
	SO_2	μg/m^3	7.14	.75	10.79	6.09	5.54	1.79	12.51	4.02	− 22
	O_3	μg/m^3	24.61	6.36	41.57	12.33	37.21	5.00	51.06	26.16	+ 51
	Temperature	°C	30.32	1.04	33.33	28.50	29.53	.99	31.12	27.56	− 3
	Relative humidity	%	59.76	4.58	69.79	48.65	67.85	2.69	76.68	63.36	+ 14
	Air quality index		71.48	19.81	119.00	44.00	48.50	6.53	62.00	39.00	− 32

Table 3 continued

City	Parameters	Unit	2019				2020				Variation
			Mean	SD	Max.	Min.	Mean	SD	Max.	Min.	%
Bengaluru	$PM_{2.5}$	μg/m^3	51.73	11.28	96.69	25.66	24.79	5.56	40.47	13.42	− 52
	PM_{10}	μg/m^3	104.86	18.05	150.17	67.28	47.88	10.82	68.24	20.17	− 54
	CO	mg/m^3	1.03	.13	1.33	.77	.74	.08	.90	.58	− 28
	NO_2	μg/m^3	33.58	5.08	47.23	21.56	11.94	2.02	17.29	8.99	− 64
	SO_2	μg/m^3	5.61	1.26	9.20	3.80	6.13	1.01	10.60	4.16	+ 9
	O_3	μg/m^3	53.35	6.19	65.66	38.08	40.27	5.70	51.20	30.74	− 25
	Temperature	°C	26.99	1.44	29.17	24.29	24.27	.69	25.90	23.03	− 10
	Relative humidity	%	47.40	9.05	69.57	33.58	51.85	11.11	76.69	33.11	+ 9
	Air quality index		116.83	15.81	158.00	88.00	56.48	6.33	69.00	41.00	− 52
Hyderabad	$PM_{2.5}$	μg/m^3	40.01	8.40	60.61	24.86	30.95	7.56	47.85	16.20	− 23
	PM_{10}	μg/m^3	104.26	24.03	147.60	59.82	61.39	12.63	83.34	38.00	− 41
	CO	mg/m^3	.62	.11	.94	.43	.47	.10	.81	.37	− 23
	NO_2	μg/m^3	33.94	5.77	47.32	23.90	21.42	4.71	30.87	11.29	− 37
	SO_2	μg/m^3	6.50	1.78	10.39	2.85	5.93	1.73	10.11	3.77	− 9
	O_3	μg/m^3	41.60	6.46	58.10	29.53	29.56	5.28	42.08	20.69	− 29
	Temperature	°C	29.37	.62	30.91	28.18	30.20	.57	31.17	28.42	+ 3
	Relative humidity	%	44.60	4.98	56.33	34.08	48.64	5.54	62.22	37.29	+ 9
	Air quality index		96.50	17.53	130.00	62.00	63.10	11.35	98.00	41.00	− 35
Jaipur	$PM_{2.5}$	μg/m^3	51.39	13.14	89.44	25.53	27.32	10.18	51.69	8.40	− 47
	PM_{10}	μg/m^3	147.81	74.92	469.54	52.00	71.38	35.63	196.18	20.25	− 52
	CO	mg/m^3	1.04	.29	1.73	.73	.56	.08	.77	.40	− 46
	NO_2	μg/m^3	35.88	8.46	64.10	24.17	13.59	2.80	23.07	10.41	− 62
	SO_2	μg/m^3	14.10	2.13	19.85	10.24	12.84	2.04	18.53	8.45	− 9
	O_3	μg/m^3	59.67	11.70	81.53	36.59	49.55	6.85	65.67	32.00	− 17
	Temperature	°C	31.88	4.05	36.36	17.48	29.55	3.21	34.95	20.88	− 7
	Relative humidity	%	22.21	10.81	60.09	11.24	34.09	14.05	82.32	16.80	+ 53
	Air quality index		135.40	49.83	364.00	59.00	79.10	23.71	168.00	45.00	− 42
Lucknow	$PM_{2.5}$	μg/m^3	102.17	33.45	164.34	45.15	51.66	13.05	79.96	29.60	− 49
	CO	mg/m^3	1.38	.27	1.91	.89	.99	.04	1.07	.86	− 28
	NO_2	μg/m^3	43.06	14.90	85.27	28.24	14.57	4.85	25.66	7.54	− 66
	SO_2	μg/m^3	8.40	1.61	11.84	5.40	7.08	1.24	11.06	4.97	− 16
	O_3	μg/m^3	39.38	6.49	53.82	27.77	28.48	7.12	48.55	18.61	− 28
	Temperature	°C	32.71	2.42	39.46	28.83	31.01	2.19	35.20	27.07	− 5%
	Relative humidity	%	40.52	9.51	62.98	19.75	46.95	12.99	77.11	30.27	+ 16
	Air quality index		209.40	61.35	314.00	90.00	100.40	34.59	220.00	58.00	− 52

*Data of PM_{10} concentration were not available at Chennai and Lucknow

34.09 ± 14.05% (Jaipur) to 73.88 ± 5.25% (Mumbai) during the lockdown period. The variation in average relative humidity was observed in Delhi (+ 36%), Mumbai (+ 6%), Kolkata (− .30%), Chennai (+ 14%), Bengaluru (+ 9%), Hyderabad (+ 9%), Jaipur (+ 53%), and Lucknow (+ 16%) during lockdown as compared to the non-lockdown period of 2019 (Table 3; Fig. 4).


PM2.5
PM10
CO
DELHI
MUMBAI
KOLKATA
CHENNAI
Data of PM10 concentration was not available
BENGALURU
HYDERABAD
JAIPUR
LUCKNOW
Data of PM10 concentration was not available
PM2.5 Concentration (µg/m³)
PM10 Concentration (µg/m³)
CO Concentration (mg/m³)
2019
2020
Average 2019
Average 2020

◀**Fig. 2** Daily variation and average difference in mean $PM_{2.5}$, PM_{10} and CO concentrations during March 25 to May 3, 2020 (COVID-19 lockdown period), and March 25 to May 3, 2019

3.3 Air quality index

In India, the air quality index is categorized among six categories: good (0–50), satisfactory (51–100), moderate (101–200), poor (201–300), very poor (301–400), and severe (401–500) (Table 2). The details of daily air quality index and prominent pollutants of selected eight metropolitan cities are depicted in Table 4. The average air quality index of the eight metropolitan cities is summarized in Table 3. The average air quality index ranged from 48.50 ± 6.53 (Chennai) to 103.43 ± 28.74 (Delhi) during the lockdown period. The reduction in average air quality index was observed in Delhi (− 51%), Mumbai (− 30%), Kolkata (− 19%), Chennai (− 32%), Bengaluru (− 52%), Hyderabad (− 35%), Jaipur (− 42%), and Lucknow (− 52%) during the lockdown as compared to the same period of 2019 (Table 3). In the comparison of daily air quality index of the same period of 2019, out of eight metropolitan cities, three cities like Chennai, Bengaluru and Hyderabad exhibited a consistent reduction throughout the lockdown period, while daily air quality index of Delhi, Mumbai, Kolkata, Jaipur, and Lucknow increased on a few days (Fig. 5).

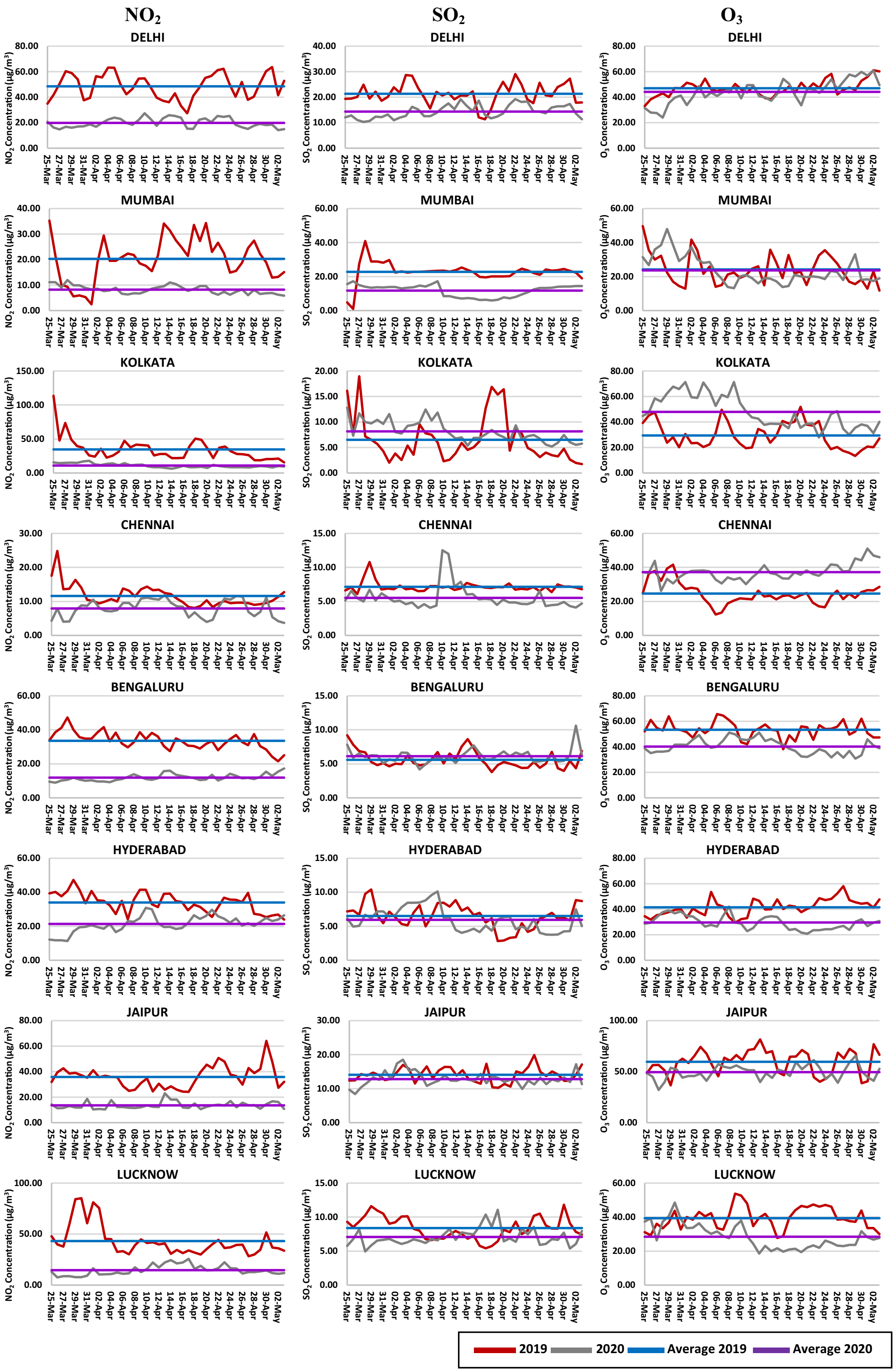
During the lockdown period, the air quality index on most of the days was observed to be good and satisfactory in all the metropolitan cities (Fig. 6) that indicated an improvement in air quality due to a reduction in vehicular and industrial emissions. The air quality index of Delhi was detected to be in a good, satisfactory, and moderate category by 2.5%, 52.50%, and 45% days, respectively, during lockdown days, while it was satisfactory, moderate, poor, and very poor by 2.5%, 40%, 55%, and 2.5% days, respectively, during the same period of 2019. The air quality index of Mumbai was found good and satisfactory by 10% and 90% days, respectively, during the lockdown period, while it was satisfactory and poor by 87.5% and 12.5% days, respectively, in the non-lockdown period of 2019. The air quality index of Kolkata was noticed good (30% days), satisfactory (47.5% days), and moderate (22.5% days) during lockdown period, while it was good (10% days), satisfactory (65% days), moderate (20% days), and poor (5% days) in the same period of 2019. The air quality of Chennai was observed good (35% days) and satisfactory (65% days) in lockdown period, while it was good (10% days), satisfactory (77.5% days), and moderate (12.5% days) in the previous year. The air quality index of Bengaluru was detected good and satisfactory by 17.5% and 82.5% days, respectively, during lockdown days, while it was satisfactory and moderate by 12.5% and 87.5% days, respectively, in the non-lockdown period of 2019. The air quality index of Hyderabad was observed to be good and satisfactory by 12.5% and 87.5% days, respectively, during lockdown days, while it was satisfactory and moderate by 57.5% and 42.5% days, respectively, on the same dates of the previous year. The air quality of Jaipur was good (5% days), satisfactory (82.5% days), and moderate (12.5% days) in lockdown period, while it was satisfactory (17.5% days), moderate (77.5% days), poor (2.5% days), and very poor (2.5% days) during the same period of the year 2019. The air quality index of Lucknow was noticed satisfactory (62.5% days), moderate (35% days), and poor (2.5%) during the lockdown period, while it was satisfactory (5% days) and moderate (42.5% days), poor (45%), and very poor (7.5% days) in the same period of the previous year.

The order of air quality index during lockdown for all metropolitan cities was satisfactory > moderate > good > poor, while it was moderate > satisfactory > poor > good > very poor during the same period of the previous year 2019.

3.4 Prominent pollutants

Table 4 demonstrates the prominent pollutants on all days during the lockdown in all metropolitan cities, and Fig. 7 illustrates the frequency of prominent pollutants in percentage during the study period.

Throughout the lockdown period, it was observed that ozone was the most prominent air pollutant in all metropolitan cities. The frequency of ozone as a prominent pollutant for Delhi, Mumbai, Kolkata, Chennai, Bengaluru, Hyderabad, Jaipur, and Lucknow was 75%, 42.50%, 97.50%, 80%, 80%, 32.50%, 62.50%, and 25%, respectively, while it was 25%, 0%, 7.50%, 10%, 62.50%, 32.50%, 27.50%, and 2.5%, respectively, during the same period of 2019.


NO2
SO2
O3
DELHI
MUMBAI
KOLKATA
CHENNAI
BENGALURU
HYDERABAD
JAIPUR
LUCKNOW
NO2 Concentration (µg/m³)
SO2 Concentration (µg/m³)
O3 Concentration (µg/m³)
25-Mar 27-Mar 29-Mar 31-Mar 02-Apr 04-Apr 06-Apr 08-Apr 10-Apr 12-Apr 14-Apr 16-Apr 18-Apr 20-Apr 22-Apr 24-Apr 26-Apr 28-Apr 30-Apr 02-May
2019
2020
Average 2019
Average 2020

◀**Fig. 3** Daily variation and average difference in mean NO_2, SO_2, and O_3 concentrations during March 25 to May 3, 2020 (COVID-19 lockdown period), and March 25 to May 3, 2019

During the lockdown period, the second and third most frequent prominent pollutants were PM_{10} and $PM_{2.5}$, respectively, while $PM_{2.5}$ and PM_{10} were the second and third most prominent pollutants, respectively, during 2019. The frequency of PM_{10} was observed in Delhi (55%), Mumbai (100%), Kolkata (37.5%), Bengaluru (77.5%), Hyderabad (92.5%), and Jaipur (77.5%) during the lockdown period. The frequency of $PM_{2.5}$ was observed in Delhi (65%), Mumbai (0%), Kolkata (37.5%), Chennai (55%), Bengaluru (72.5%), Hyderabad (57.5%), Jaipur (2.5%), and Lucknow (100%) during the lockdown period.

Carbon monoxide was the fourth prominent pollutant during the lockdown period. The frequency of carbon monoxide for Delhi, Mumbai, Kolkata, Chennai, Bengaluru, Hyderabad, Jaipur, and Lucknow during the lockdown was 10%, 22.5%, 2.5%, 75%, 60%, 5%, 2.5%, and 17.5%, respectively, while it was 0%, 70%, 2.50%, 85%, 10%, 0%, 0%, and 15%, respectively, during non-lockdown period of the previous year. The occurrence of NO_2 and SO_2 as a prominent pollutant during the lockdown as well as the non-lockdown period of 2019 was very less frequent.

The overall frequency order of prominent pollutants during lockdown was $O_3 > PM_{10} > PM_{2.5} > CO > NO_2 > SO_2$, while it was $PM_{2.5} > PM_{10} > CO > O_3 > NO_2 > SO_2$ during the same period of 2019 in all metropolitan cities. A diminution in the concentration of $PM_{2.5}$ and PM_{10} during the lockdown period could also induce the evolution reaction of O_3 by allowing more solar radiation in the troposphere (Heuss et al. 2003; Li et al. 2017; Liu et al. 2013; Murphy et al. 2007; Wolff et al. 2013) that may be a possible reason for O_3 to become a prominent pollutant instead of $PM_{2.5}$ and PM_{10}.

3.5 Correlation among criteria air pollutants, temperature, relative humidity, air quality index, and population density

Pearson correlation coefficient (R) was computed among the six criteria air pollutants ($PM_{2.5}$, PM_{10}, CO, NO_2, SO_2, and O_3), meteorological parameters (temperature and relative humidity) and air quality index for all the eight metropolitan cities during the lockdown and the same period of the previous year 2019 (Tables 5 and 6).

During the lockdown period, $PM_{2.5}$ and PM_{10} were strongly correlated ($R \geq .68$) in Delhi, Mumbai, Kolkata, Hyderabad, and Jaipur, while they were strongly correlated ($R \geq .68$) in Delhi, Mumbai, Hyderabad, and Jaipur during the same period of the year 2019. The strong correlation between $PM_{2.5}$ and PM_{10} during the lockdown period and the same period of 2019 clarified that $PM_{2.5}$ contributes to the formation of PM_{10} (Wang et al. 2014, 2017; Zhang and Cao 2015).

A strong correlation ($R \geq .68$) between $PM_{2.5}$ and NO_2 in Delhi, Kolkata, and Lucknow, and PM_{10} and temperature in Delhi, Kolkata, and Jaipur was observed during COVID-19 lockdown period, while CO and NO_2 in Delhi, Mumbai, Kolkata, and Hyderabad, and CO and SO_2 in Delhi, Kolkata, and Hyderabad were strongly correlated ($R \geq .68$) during the same period of the previous year.

Air quality index and $PM_{2.5}$ were strongly correlated ($R \geq .68$) in Delhi, Mumbai, Kolkata, Chennai, Hyderabad, Jaipur, and Lucknow during the lockdown period. It was also strongly correlated ($R \geq .68$) in Delhi, Mumbai, Kolkata, Chennai, Hyderabad, Jaipur, and Lucknow during the same period of the year 2019. The correlation between air quality index and PM_{10} was found strong ($R \geq .68$) in Delhi, Mumbai, Kolkata, Hyderabad, and Jaipur during the lockdown period and it was also strong ($R \geq .68$) in Delhi, Mumbai, Hyderabad, and Jaipur during the same period of the previous year. The strong positive correlation between air quality index and $PM_{2.5}$, and AQI and PM_{10} during the lockdown period and non-lockdown period of 2019 indicated that $PM_{2.5}$ followed by PM_{10} dominantly influences the air quality. Yan et al. (2016) also observed that $PM_{2.5}$ was chiefly degrading the air quality in Beijing and China.

During the lockdown period, the air quality index was strongly correlated ($R \geq .68$) with CO in Delhi, Mumbai, and Kolkata. A weak correlation ($R \leq .35$) between SO_2 and $PM_{2.5}$ in Mumbai, Bengaluru, Hyderabad, and Jaipur; SO_2 and PM_{10} in Mumbai, Bengaluru, and Jaipur; SO_2 and CO in Bengaluru, Jaipur, and Lucknow; SO_2 and air quality index in Chennai, Bengaluru, and Jaipur; ozone (O_3) and $PM_{2.5}$ in Delhi, Mumbai, and Jaipur; O_3 and PM_{10} in

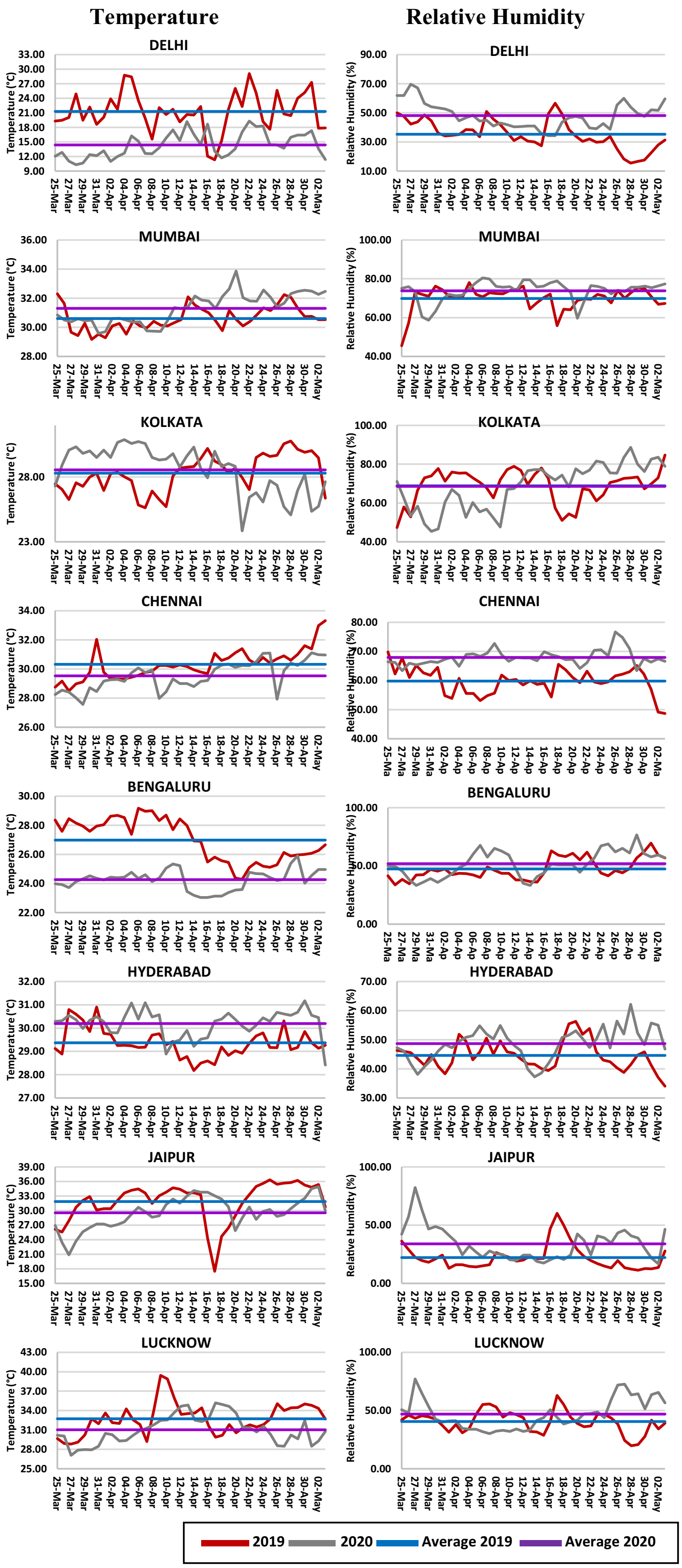


Fig. 4 Daily variation and average difference in mean temperature and relative humidity during March 25 to May 3, 2020 (COVID-19 lockdown period), and March 25 to May 3, 2019

Table 4 Air quality index and prominent pollutant during March 25 to May 3, 2020 (COVID-19 lockdown period) and March 25 to May 3, 2019

Date	Delhi				Mumbai				Kolkata				Chennai				Bengaluru				Hyderabad				Jaipur				Lucknow			
	2019	Prominent Pollutant	2020	Prominent Pollutant	2019	Prominent Pollutant	2020	Prominent Pollutant	2019	Prominent Pollutant	2020	Prominent Pollutant	2019	Prominent Pollutant	2020	Prominent Pollutant	2019	Prominent Pollutant	2020	Prominent Pollutant	2019	Prominent Pollutant	2020	Prominent Pollutant	2019	Prominent Pollutant	2020	Prominent Pollutant	2019	Prominent Pollutant	2020	Prominent Pollutant
25-Mar	139	PM_{10}, $PM_{2.5}$	77	O_3, PM_{10}, $PM_{2.5}$	165	PM_{10}	87	PM_{10}	202	$PM_{2.5}$	97	$PM_{2.5}$, O_3	68	$PM_{2.5}$, CO	46	CO, $PM_{2.5}$	98	$PM_{2.5}$, PM_{10}	57	$PM_{2.5}$, CO, PM_{10}	105	PM_{10}, $PM_{2.5}$	60	PM_{10}, $PM_{2.5}$	110	PM_{10}	63	PM_{10}, O_3	196	$PM_{2.5}$	220	$PM_{2.5}$
26-Mar	159	$PM_{2.5}$, PM_{10}	92	O_3, $PM_{2.5}$	138	PM_{10}	69	PM_{10}, O_3	204	$PM_{2.5}$	86	$PM_{2.5}$, O_3	78	$PM_{2.5}$, CO	56	CO, $PM_{2.5}$	115	$PM_{2.5}$, PM_{10}	58	$PM_{2.5}$, CO, PM_{10}	113	$PM_{2.5}$, PM_{10}	59	PM_{10}	90	O_3, PM_{10}	52	PM_{10}, O_3	194	$PM_{2.5}$	90	$PM_{2.5}$
27-Mar	171	PM_{10}, $PM_{2.5}$	69	O_3, $PM_{2.5}$	122	PM_{10}	66	PM_{10}, O_3	130	$PM_{2.5}$, PM_{10}	116	$PM_{2.5}$, O_3	66	$PM_{2.5}$, CO, O_3	48	$PM_{2.5}$	121	$PM_{2.5}$, PM_{10}, O_3	54	$PM_{2.5}$, CO, PM_{10}	104	PM_{10}, $PM_{2.5}$	67	PM_{10}	91	O_3, PM_{10}	45	O_3	171	$PM_{2.5}$, CO	84	$PM_{2.5}$
28-Mar	234	PM_{10}, $PM_{2.5}$	45	NO_2, O_3, CO	105	PM_{10}	72	PM_{10}, O_3	127	PM_{10}, $PM_{2.5}$	102	$PM_{2.5}$, O_3, PM_{10}	73	$PM_{2.5}$, O_3	57	$PM_{2.5}$	140	$PM_{2.5}$, PM_{10}	53	$PM_{2.5}$, O_3, PM_{10}	120	PM_{10}, $PM_{2.5}$	68	PM_{10}	103	PM_{10}, $PM_{2.5}$	48	O_3, PM_{10}	216	$PM_{2.5}$	68	$PM_{2.5}$, CO
29-Mar	232	PM_{10}, $PM_{2.5}$	62	NO_2, PM_{10}, $PM_{2.5}$	91	PM_{10}	71	PM_{10}, O_3	168	$PM_{2.5}$	102	$PM_{2.5}$, O_3, PM_{10}	84	$PM_{2.5}$, O_3, CO	46	$PM_{2.5}$	158	O_3, $PM_{2.5}$, PM_{10}	57	$PM_{2.5}$, O_3, PM_{10}	128	$PM_{2.5}$, PM_{10}	79	PM_{10}, $PM_{2.5}$	144	$PM_{2.5}$, PM_{10}	65	O_3, PM_{10}	284	$PM_{2.5}$	58	$PM_{2.5}$, CO, O_3
30-Mar	233	PM_{10}, $PM_{2.5}$	71	O_3, $PM_{2.5}$	99	PM_{10}	69	PM_{10}, O_3	94	PM_{10}	112	$PM_{2.5}$, O_3, PM_{10}	76	$PM_{2.5}$, O_3, CO	52	$PM_{2.5}$	134	$PM_{2.5}$, PM_{10}, O_3	63	$PM_{2.5}$, O_3, PM_{10}	130	$PM_{2.5}$, PM_{10}	73	PM_{10}, $PM_{2.5}$	125	$PM_{2.5}$, PM_{10}	67	O_3, PM_{10}	287	$PM_{2.5}$	65	$PM_{2.5}$
31-Mar	182	PM_{10}, $PM_{2.5}$	76	PM_{10}, O_3, $PM_{2.5}$	80	PM_{10}	67	PM_{10}, O_3	106	$PM_{2.5}$, PM_{10}	112	$PM_{2.5}$, O_3, PM_{10}	112	$PM_{2.5}$	54	$PM_{2.5}$, O_3	139	$PM_{2.5}$, PM_{10}, O_3	55	CO, O_3, PM_{10}	123	PM_{10}, $PM_{2.5}$	69	PM_{10}, $PM_{2.5}$	116	$PM_{2.5}$, PM_{10}	63	O_3, PM_{10}	216	$PM_{2.5}$	94	$PM_{2.5}$, O_3
01-Apr	151	PM_{10}, $PM_{2.5}$	73	PM_{10}, CO, $PM_{2.5}$	90	PM_{10}	57	PM_{10}, O_3	66	PM_{10}	137	$PM_{2.5}$, O_3	119	$PM_{2.5}$, CO	61	$PM_{2.5}$, O_3	126	$PM_{2.5}$, PM_{10}, O_3	52	CO, $PM_{2.5}$, PM_{10}	99	PM_{10}, $PM_{2.5}$	84	PM_{10}, $PM_{2.5}$	99	PM_{10}, O_3	70	O_3, PM_{10}	148	$PM_{2.5}$, NO_2	136	$PM_{2.5}$
02-Apr	198	PM_{10}, $PM_{2.5}$, O_3	69	PM_{10}, NO_2, $PM_{2.5}$	86	PM_{10}	72	PM_{10}, O_3	75	PM_{10}	101	$PM_{2.5}$, O_3	106	$PM_{2.5}$, CO	62	$PM_{2.5}$, O_3	151	$PM_{2.5}$, PM_{10}, O_3	59	CO, O_3, PM_{10}	113	PM_{10}, $PM_{2.5}$	98	$PM_{2.5}$	97	PM_{10}, O_3	65	O_3	230	$PM_{2.5}$, NO_2	111	$PM_{2.5}$, O_3
03-Apr	187	PM_{10}, $PM_{2.5}$, O_3	79	PM_{10}, O_3, $PM_{2.5}$	99	CO	85	PM_{10}	64	PM_{10}	109	$PM_{2.5}$, O_3	116	$PM_{2.5}$, CO	56	$PM_{2.5}$, O_3, CO	122	$PM_{2.5}$, PM_{10}, CO	69	CO, $PM_{2.5}$, PM_{10}	104	PM_{10}, $PM_{2.5}$	73	PM_{10}	114	O_3, $PM_{2.5}$	62	O_3, PM_{10}	252	$PM_{2.5}$	73	$PM_{2.5}$, O_3
04-Apr	254	PM_{10}, $PM_{2.5}$	87	PM_{10}, O_3, $PM_{2.5}$	88	CO	81	PM_{10}	82	PM_{10}	146	$PM_{2.5}$, O_3	62	$PM_{2.5}$, CO	55	$PM_{2.5}$, O_3, CO	120	PM_{10}, $PM_{2.5}$	64	O_3, $PM_{2.5}$, PM_{10}	98	PM_{10}, $PM_{2.5}$	67	PM_{10}	111	O_3, PM_{10}	67	O_3, PM_{10}	314	$PM_{2.5}$	67	$PM_{2.5}$, O_3, CO
05-Apr	264	$PM_{2.5}$, PM_{10}	102	O_3, $PM_{2.5}$	91	CO	77	PM_{10}	78	PM_{10}, $PM_{2.5}$	95	$PM_{2.5}$, O_3, PM_{10}	79	$PM_{2.5}$, CO	55	$PM_{2.5}$, O_3, CO	113	$PM_{2.5}$, PM_{10}, O_3	64	CO, $PM_{2.5}$, PM_{10}	85	O_3, PM_{10}	66	PM_{10}	141	PM_{10}, $PM_{2.5}$	74	O_3, PM_{10}	279	$PM_{2.5}$	104	$PM_{2.5}$
06-Apr	266	PM_{10}, $PM_{2.5}$	142	$PM_{2.5}$	91	CO	58	PM_{10}, O_3	88	PM_{10}	82	$PM_{2.5}$, O_3	77	$PM_{2.5}$, CO	46	$PM_{2.5}$, O_3, CO	120	O_3, PM_{10}, $PM_{2.5}$	58	O_3, $PM_{2.5}$, PM_{10}	85	$PM_{2.5}$, O_3, PM_{10}	62	PM_{10}	140	PM_{10}	80	PM_{10}	209	$PM_{2.5}$	89	$PM_{2.5}$
07-Apr	302	PM_{10}	90	PM_{10}, NO_2	93	CO	64	PM_{10}	66	O_3	91	$PM_{2.5}$, O_3, PM_{10}	71	$PM_{2.5}$, CO	40	O_3, CO	120	O_3, PM_{10}, $PM_{2.5}$	48	O_3, $PM_{2.5}$, CO	73	$PM_{2.5}$, PM_{10}	47	PM_{10}	130	PM_{10}	73	PM_{10}	175	$PM_{2.5}$	76	$PM_{2.5}$, CO
08-Apr	264	PM_{10}, $PM_{2.5}$	83	PM_{10}, O_3	93	CO	97	PM_{10}	68	PM_{10}, $PM_{2.5}$	75	O_3	76	$PM_{2.5}$, CO	44	O_3, $PM_{2.5}$, CO	109	O_3, PM_{10}, $PM_{2.5}$	52	O_3, CO	77	PM_{10}, $PM_{2.5}$	41	PM_{10}, NO_2	364	PM_{10}	68	PM_{10}, O_3	136	$PM_{2.5}$, CO, NO_2	78	$PM_{2.5}$, O_3, CO
09-Apr	204	PM_{10}, O_3, $PM_{2.5}$	86	O_3, $PM_{2.5}$, PM_{10}	90	CO	94	PM_{10}	67	PM_{10}, $PM_{2.5}$	91	O_3	96	$PM_{2.5}$, CO	42	O_3, $PM_{2.5}$, CO	122	$PM_{2.5}$, O_3	54	O_3, $PM_{2.5}$	88	PM_{10}, $PM_{2.5}$	63	PM_{10}, NO_2	144	PM_{10}	71	O_3, PM_{10}	136	$PM_{2.5}$	99	$PM_{2.5}$, O_3
10-Apr	238	PM_{10}	118	$PM_{2.5}$, O_3	93	CO	83	PM_{10}	60	PM_{10}, NO_2	68	O_3	79	$PM_{2.5}$, CO	62	$PM_{2.5}$	119	$PM_{2.5}$, PM_{10}	55	$PM_{2.5}$, O_3, CO	98	PM_{10}, $PM_{2.5}$	52	NO_2, O_3, PM_{10}	134	PM_{10}	73	O_3, PM_{10}	184	$PM_{2.5}$, CO	88	$PM_{2.5}$, O_3
11-Apr	183	PM_{10}, $PM_{2.5}$	124	O_3, $PM_{2.5}$	89	CO	77	PM_{10}	58	PM_{10}, $PM_{2.5}$	61	O_3	118	$PM_{2.5}$	43	O_3, SO_2, $PM_{2.5}$	103	$PM_{2.5}$, PM_{10}	49	CO, $PM_{2.5}$, O_3	77	PM_{10}, $PM_{2.5}$	65	NO_2, O_3, $PM_{2.5}$	138	$PM_{2.5}$, PM_{10}	84	PM_{10}	191	$PM_{2.5}$	128	$PM_{2.5}$
12-Apr	212	PM_{10}, O_3, $PM_{2.5}$	94	O_3, $PM_{2.5}$, PM_{10}	93	CO	87	PM_{10}	62	PM_{10}, $PM_{2.5}$	57	PM_{10}, O_3	77	$PM_{2.5}$	44	O_3, CO	118	PM_{10}, $PM_{2.5}$, O_3	58	O_3, CO, $PM_{2.5}$	83	PM_{10}, $PM_{2.5}$	58	PM_{10}, NO_2, $PM_{2.5}$	264	PM_{10}	84	PM_{10}	268	$PM_{2.5}$	134	$PM_{2.5}$
13-Apr	170	PM_{10}, $PM_{2.5}$	126	$PM_{2.5}$, PM_{10}	100	CO	76	PM_{10}	74	PM_{10}, $PM_{2.5}$	56	O_3, PM_{10}	74	$PM_{2.5}$, CO	44	O_3, $PM_{2.5}$, CO	112	PM_{10}, $PM_{2.5}$, O_3	49	$PM_{2.5}$, O_3, PM_{10}	93	O_3, PM_{10}	66	$PM_{2.5}$, PM_{10}	130	$PM_{2.5}$, PM_{10}	81	PM_{10}	228	$PM_{2.5}$	96	$PM_{2.5}$
14-Apr	137	PM_{10}, $PM_{2.5}$	130	O_3, $PM_{2.5}$, PM_{10}	95	CO	81	PM_{10}, CO	64	PM_{10}, $PM_{2.5}$	53	PM_{10}, O_3	57	$PM_{2.5}$	46	O_3, $PM_{2.5}$, CO	104	PM_{10}, $PM_{2.5}$, O_3	58	O_3, PM_{10}, NO_2	95	PM_{10}, $PM_{2.5}$	74	O_3, $PM_{2.5}$, PM_{10}	117	PM_{10}	118	PM_{10}	146	$PM_{2.5}$, CO	166	$PM_{2.5}$
15-Apr	168	PM_{10}, $PM_{2.5}$	155	PM_{10}, CO	92	CO	81	CO, PM_{10}	68	PM_{10}, $PM_{2.5}$	53	O_3, PM_{10}	59	$PM_{2.5}$, CO	42	O_3, CO, $PM_{2.5}$	111	$PM_{2.5}$, PM_{10}, O_3	64	$PM_{2.5}$, O_3, CO	89	PM_{10}, $PM_{2.5}$	72	$PM_{2.5}$, PM_{10}	130	$PM_{2.5}$, PM_{10}	93	PM_{10}	153	$PM_{2.5}$	121	$PM_{2.5}$
16-Apr	180	PM_{10}, $PM_{2.5}$	180	$PM_{2.5}$, PM_{10}	95	CO	65	CO, PM_{10}	84	$PM_{2.5}$, O_3	67	PM_{10}	52	CO, $PM_{2.5}$	50	$PM_{2.5}$, CO, O_3	105	O_3, PM_{10}, $PM_{2.5}$	52	CO, O_3, $PM_{2.5}$	102	PM_{10}, O_3, $PM_{2.5}$	71	$PM_{2.5}$, PM_{10}	165	PM_{10}	87	PM_{10}, O_3	156	$PM_{2.5}$	142	$PM_{2.5}$, O_3
17-Apr	84	PM_{10}, O_3	105	O_3, PM_{10}	85	CO	65	CO, PM_{10}	116	$PM_{2.5}$	53	O_3, PM_{10}	50	CO	43	O_3, CO	104	PM_{10}, $PM_{2.5}$	66	$PM_{2.5}$, PM_{10}, CO	82	PM_{10}, O_3, $PM_{2.5}$	74	$PM_{2.5}$, PM_{10}	59	O_3, PM_{10}	127	PM_{10}	100	$PM_{2.5}$	167	$PM_{2.5}$
18-Apr	114	O_3	98	$PM_{2.5}$, CO, O_3	94	CO	68	CO, PM_{10}	178	$PM_{2.5}$, PM_{10}	40	$PM_{2.5}$, PM_{10}, O_3	45	CO	40	O_3, CO	101	O_3, $PM_{2.5}$	68	$PM_{2.5}$, CO, PM_{10}	106	PM_{10}, O_3, $PM_{2.5}$	68	$PM_{2.5}$, PM_{10}	81	O_3, PM_{10}	126	PM_{10}	117	$PM_{2.5}$, CO	118	$PM_{2.5}$
19-Apr	157	$PM_{2.5}$, PM_{10}, O_3	85	O_3, $PM_{2.5}$, PM_{10}	94	CO	67	CO, PM_{10}	170	$PM_{2.5}$	62	O_3	50	$PM_{2.5}$, CO	44	O_3, CO	93	O_3, CO	52	$PM_{2.5}$, PM_{10}, O_3	79	PM_{10}, O_3, $PM_{2.5}$	65	PM_{10}, $PM_{2.5}$	98	O_3, PM_{10}	90	PM_{10}	90	$PM_{2.5}$, NO_2, O_3	113	$PM_{2.5}$
20-Apr	198	O_3, PM_{10}, $PM_{2.5}$	119	$PM_{2.5}$	97	CO	82	CO, PM_{10}	116	$PM_{2.5}$, PM_{10}	40	O_3	63	$PM_{2.5}$, CO	39	O_3, CO	127	O_3, PM_{10}	41	$PM_{2.5}$, O_3, PM_{10}	62	PM_{10}, O_3, $PM_{2.5}$	57	PM_{10}, $PM_{2.5}$, O_3	104	O_3	66	PM_{10}, O_3	145	$PM_{2.5}$, CO	90	$PM_{2.5}$
21-Apr	203	PM_{10}, $PM_{2.5}$	87	O_3, PM_{10}, NO_2	95	CO	65	PM_{10}, CO	82	$PM_{2.5}$, PM_{10}	49	O_3, PM_{10}	72	$PM_{2.5}$, CO	44	O_3, CO	104	O_3, CO, PM_{10}	59	CO, $PM_{2.5}$, O_3	62	PM_{10}, O_3, $PM_{2.5}$	50	$PM_{2.5}$, PM_{10}, NO_2	104	O_3, $PM_{2.5}$	73	O_3	216	$PM_{2.5}$	78	$PM_{2.5}$, CO
22-Apr	236	PM_{10}, $PM_{2.5}$	131	$PM_{2.5}$, O_3	97	CO	51	PM_{10}, O_3	86	PM_{10}, $PM_{2.5}$	50	O_3	44	CO	44	$PM_{2.5}$, O_3, CO	88	PM_{10}, $PM_{2.5}$, O_3	55	PM_{10}, $PM_{2.5}$, O_3	63	PM_{10}, O_3, $PM_{2.5}$	48	$PM_{2.5}$, PM_{10}, O_3	126	PM_{10}, $PM_{2.5}$	80	O_3	259	$PM_{2.5}$	89	$PM_{2.5}$
23-Apr	247	PM_{10}	122	$PM_{2.5}$, PM_{10}	98	CO	63	PM_{10}, CO	64	O_3	32	O_3, CO	54	$PM_{2.5}$, CO	40	O_3, CO	106	CO, PM_{10}, $PM_{2.5}$	59	$PM_{2.5}$, PM_{10}, O_3	98	PM_{10}, O_3, $PM_{2.5}$	50	$PM_{2.5}$, O_3, PM_{10}	152	$PM_{2.5}$, PM_{10}	62	O_3	291	$PM_{2.5}$	130	$PM_{2.5}$
24-Apr	221	PM_{10}, $PM_{2.5}$, O_3	139	$PM_{2.5}$, O_3	90	CO	50	PM_{10}	73	PM_{10}, NO_2	34	O_3	56	$PM_{2.5}$, CO	44	O_3, CO	97	PM_{10}, O_3, $PM_{2.5}$	65	$PM_{2.5}$, PM_{10}, O_3	80	O_3, PM_{10}	60	$PM_{2.5}$, PM_{10}	145	PM_{10}, $PM_{2.5}$	63	O_3	197	$PM_{2.5}$	131	$PM_{2.5}$
25-Apr	251	PM_{10}, $PM_{2.5}$	98	O_3, PM_{10}	88	CO	48	SO_2, PM_{10}	59	PM_{10}, $PM_{2.5}$	51	O_3	60	$PM_{2.5}$, CO	45	O_3, CO	119	PM_{10}, $PM_{2.5}$, O_3	58	$PM_{2.5}$, O_3, PM_{10}	103	PM_{10}, O_3, $PM_{2.5}$	59	$PM_{2.5}$, PM_{10}, O_3	150	PM_{10}	61	PM_{10}, O_3	215	$PM_{2.5}$	126	$PM_{2.5}$
26-Apr	215	PM_{10}, $PM_{2.5}$	120	PM_{10}, O_3	92	CO	57	PM_{10}, SO_2, O_3	68	PM_{10}, $PM_{2.5}$	56	O_3	58	$PM_{2.5}$, CO	44	CO, NO_2	135	$PM_{2.5}$, PM_{10}	58	$PM_{2.5}$, PM_{10}, O_3	101	PM_{10}, $PM_{2.5}$	69	PM_{10}, $PM_{2.5}$	181	PM_{10}	87	PM_{10}	304	$PM_{2.5}$	90	$PM_{2.5}$
27-Apr	256	PM_{10}	89	O_3	96	PM_{10}	52	SO_2, O_3, PM_{10}	87	PM_{10}	36	O_3, PM_{10}	57	$PM_{2.5}$, CO	48	O_3, CO	133	$PM_{2.5}$, PM_{10}	43	PM_{10}, CO, O_3	119	PM_{10}	54	O_3, NO_2, PM_{10}	128	PM_{10}	61	O_3	179	$PM_{2.5}$	60	$PM_{2.5}$, O_3, CO
28-Apr	264	PM_{10}, $PM_{2.5}$	100	O_3	99	PM_{10}	53	SO_2, PM_{10}, O_3	80	PM_{10}	39	O_3	59	$PM_{2.5}$, CO	49	O_3, CO	132	$PM_{2.5}$, PM_{10}	60	PM_{10}, O_3, $PM_{2.5}$	108	PM_{10}, $PM_{2.5}$	53	PM_{10}, $PM_{2.5}$	139	$PM_{2.5}$, PM_{10}	69	O_3, CO	254	$PM_{2.5}$	67	$PM_{2.5}$
29-Apr	248	PM_{10}, $PM_{2.5}$	125	O_3	93	CO	81	O_3, SO_2, PM_{10}	74	PM_{10}	49	O_3	63	$PM_{2.5}$, CO	54	O_3, CO	132	PM_{10}, O_3, $PM_{2.5}$	48	PM_{10}, CO, O_3	98	PM_{10}, $PM_{2.5}$	46	O_3, NO_2, PM_{10}	145	$PM_{2.5}$, PM_{10}	81	O_3, $PM_{2.5}$	268	$PM_{2.5}$	70	$PM_{2.5}$
30-Apr	250	PM_{10}, $PM_{2.5}$	138	O_3	93	CO	60	SO_2, PM_{10}	45	$PM_{2.5}$, PM_{10}	48	O_3	65	$PM_{2.5}$, CO	49	O_3, NO_2	113	$PM_{2.5}$, PM_{10}	50	O_3, PM_{10}, CO	90	PM_{10}, $PM_{2.5}$	55	PM_{10}, O_3, NO_2	150	$PM_{2.5}$, PM_{10}	168	PM_{10}	287	$PM_{2.5}$	80	$PM_{2.5}$
01-May	295	PM_{10}	146	O_3, $PM_{2.5}$	88	CO	51	SO_2, PM_{10}, O_3	32	PM_{10}	49	O_3	72	$PM_{2.5}$, CO	60	O_3, CO	95	$PM_{2.5}$, O_3, PM_{10}	61	PM_{10}, O_3, CO	94	PM_{10}, $PM_{2.5}$	58	PM_{10}, O_3, CO	147	NO_2, PM_{10}	94	PM_{10}	309	$PM_{2.5}$	88	$PM_{2.5}$
02-May	257	$PM_{2.5}$, PM_{10}	112	O_3	109	PM_{10}	43	SO_2, PM_{10}, O_3	27	NO_2	44	O_3	60	$PM_{2.5}$	51	O_3, CO	102	PM_{10}, $PM_{2.5}$	58	CO, O_3, PM_{10}	115	PM_{10}, $PM_{2.5}$	51	CO, NO_2, O_3	167	$PM_{2.5}$, PM_{10}	97	PM_{10}	234	$PM_{2.5}$	66	$PM_{2.5}$
03-May	183	O_3, NO_2, $PM_{2.5}$	93	O_3, PM_{10}	90	CO	40	SO_2, PM_{10}, O_3	33	CO	56	O_3	56	$PM_{2.5}$, CO	51	O_3, CO	112	$PM_{2.5}$, PM_{10}	56	PM_{10}, O_3, CO	118	PM_{10}, $PM_{2.5}$	73	PM_{10}, O_3	143	PM_{10}, $PM_{2.5}$	106	PM_{10}	142	$PM_{2.5}$	66	$PM_{2.5}$

AQI Range	0-50	51-100	101-200	201-300	301-400	401-500
Category	Good	Satisfactory	Moderate	Poor	Very poor	Severe
Color Code						

Air Quality Index
DELHI
Air Quality Index
MUMBAI
KOLKATA
CHENNAI
BENGALURU
HYDERABAD
JAIPUR
LUCKNOW
Air Quality Index
2019
2020
Average 2019
Average 2020

◀**Fig. 5** Daily variation in percentage and average difference in air quality index during March 25 to May 3, 2020 (COVID-19 lockdown period) and March 25 to May 3, 2019

Mumbai, Kolkata, and Hyderabad; O_3 and air quality index in Mumbai, Chennai, Bengaluru, Hyderabad, and Jaipur; CO and NO_2 in Mumbai, Chennai, Hyderabad, and Jaipur; CO and temperature in Mumbai, Bengaluru, Hyderabad, Jaipur, and Lucknow were observed during the lockdown period.

A negative strong correlation ($R \geq -.68$) was observed between temperature and relative humidity in Delhi, Kolkata, and Jaipur and a negative moderate correlation ($R = -.36$ to $-.67$) between temperature and $PM_{2.5}$ in Mumbai, Chennai, and Bengaluru; relative humidity and $PM_{2.5}$ in Delhi, Bengaluru, Hyderabad, and Jaipur; relative humidity and PM_{10} in Delhi, Hyderabad, and Jaipur, and O_3 and NO_2 in Mumbai, Hyderabad, Jaipur, and Lucknow were observed during the lockdown period.

During the lockdown period, negative weak correlation ($R \leq -.35$) was exhibited between CO and $PM_{2.5}$ in Bengaluru, Hyderabad, and Lucknow; CO and O_3 in Mumbai, Bengaluru, and Jaipur; relative humidity and CO in Mumbai, Bengaluru, and Jaipur; relative humidity and SO_2 in Mumbai, Chennai, Bengaluru, and Lucknow; relative humidity and O_3 in Chennai, Bengaluru, Jaipur, and Lucknow; air quality index and NO_2 in Mumbai, Chennai, Bengaluru and Hyderabad; air quality index and temperature in Chennai, Bengaluru and Hyderabad; and air quality index and relative humidity in Mumbai, Chennai, Bengaluru, and Lucknow.

Pearson correlation coefficient (R) was also computed between air quality index and population density. During the lockdown, a negative moderate correlation ($R = -.36$ to $-.67$) was observed between air quality index and population density, while a negative strong correlation was observed ($R \geq -.68$) between air quality index and population density during the same period of the year 2019.

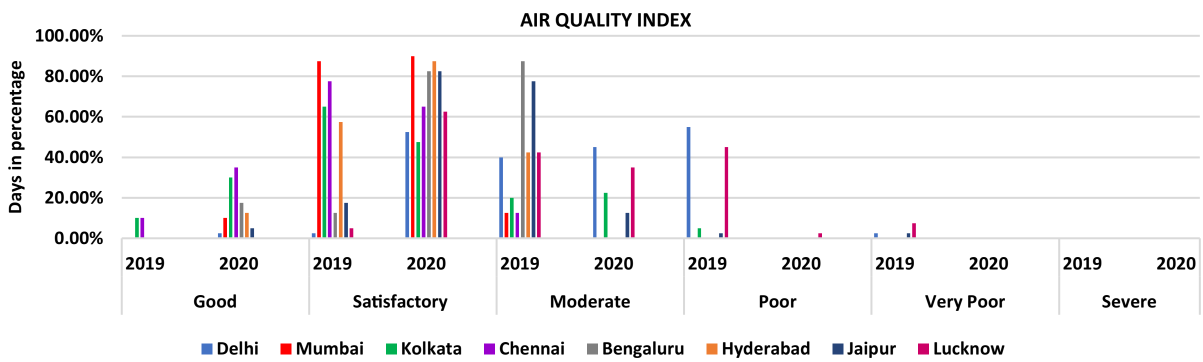


Fig. 6 Categorywise variation in air quality index during March 25 to May 3, 2020 (COVID-19 lockdown period), and March 25 to May 3, 2019

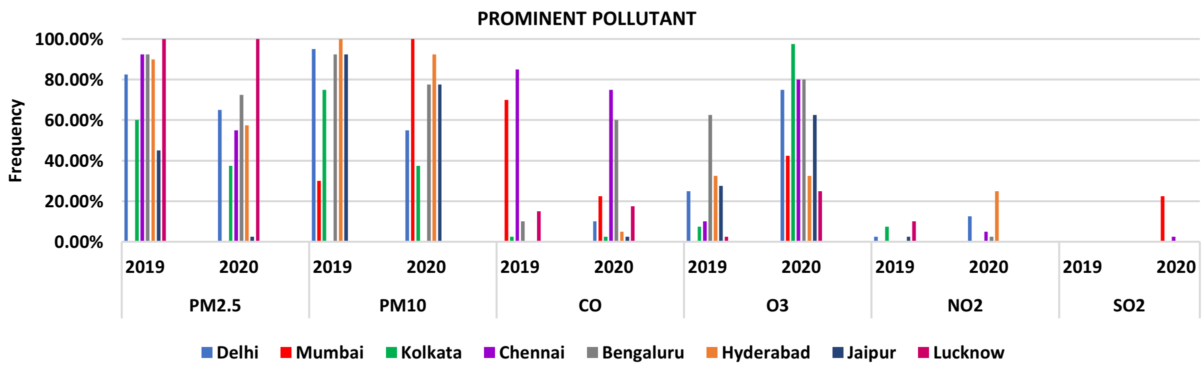


Fig. 7 Frequency of prominent pollutant during March 25 to May 3, 2020 (COVID-19 lockdown period) and March 25 to May 3, 2019

Table 5 Correlation analysis of six criteria air pollutants, temperature, relative humidity, and air quality index of selected metropolitan cities of India during March 25 to May 3, 2020 (COVID-19 lockdown period)

Delhi 2020 Parameters	$PM_{2.5}$	PM_{10}	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	.86	.81	.79	.85	.10	.64	−.49	.86
PM_{10}		1	.81	.64	.76	.25	.83	−.66	.94
CO			1	.63	.77	.33	.73	−.48	.82
NO_2				1	.63	−.17	.47	−.59	.55
SO_2					1	.37	.70	−.56	.78
O_3						1	.55	−.38	.37
T							1	−.79	.81
RH								1	−.59
AQI									1

Mumbai 2020 Parameters	$PM_{2.5}$	PM_{10}	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	.83	.06	−.32	.17	.22	−.51	−.01	.80
PM_{10}		1	.13	−.41	.02	.10	−.52	−.07	.88
CO			1	.04	−.69	−.12	.26	−.18	.32
NO_2				1	−.20	−.42	.59	.27	−.23
SO_2					1	.42	−.48	−.08	−.07
O_3						1	−.36	−.62	.09
T							1	−.01	−.36
RH								1	−.09
AQI									1

Kolkata 2020 Parameters	$PM_{2.5}$	PM_{10}	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	.94	.90	.77	.66	.74	.68	−.72	.92
PM_{10}		1	.83	.72	.63	.72	.70	−.72	.88
CO			1	.80	.51	.64	.52	−.60	.86
NO_2				1	.67	.69	.36	−.79	.81
SO_2					1	.75	.55	−.78	.72
O_3						1	.70	−.91	.90
T							1	−.72	.66
RH								1	−.83
AQI									1

Chennai 2020 Parameters	$PM_{2.5}$	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	−.51	.08	.42	−.21	−.65	−.35	.71
CO		1	.09	−.17	.60	.46	.45	−.04
NO_2			1	.40	−.22	−.16	.38	−.11
SO_2				1	−.28	−.41	−.05	.10
O_3					1	.45	−.11	.23
T						1	.00	−.16
RH							1	−.27
AQI								1

Table 5 continued

Bengaluru 2020 Parameters	$PM_{2.5}$	PM_{10}	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	.38	−.10	−.18	.09	.36	−.41	−.47	.64
PM_{10}		1	.27	.00	.15	−.16	−.05	−.26	.59
CO			1	−.07	.02	−.07	.32	−.24	.18
NO_2				1	.23	.10	−.12	.15	−.09
SO_2					1	.05	−.10	−.15	.15
O_3						1	−.05	−.28	.20
T							1	.50	−.07
RH								1	−.20
AQI									1

Hyderabad 2020 Parameters	$PM_{2.5}$	PM_{10}	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	.87	−.03	−.38	.06	.37	−.28	−.52	.88
PM_{10}		1	−.04	−.41	−.04	.32	−.23	−.48	.78
CO			1	.21	.36	.17	.25	.24	−.01
NO_2				1	.00	−.48	−.23	.40	−.34
SO_2					1	.28	.21	.16	−.01
O_3						1	−.02	−.54	.33
T							1	.42	−.29
RH								1	−.44
AQI									1

Jaipur 2020 Parameters	$PM_{2.5}$	PM_{10}	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	.93	.29	.23	.09	.09	.76	−.57	.90
PM_{10}		1	.20	.24	.09	.00	.74	−.56	.95
CO			1	.35	.11	−.01	.26	−.15	.23
NO_2				1	.11	−.44	.37	−.22	.19
SO_2					1	−.10	.21	−.40	.12
O_3						1	.24	−.32	.12
T							1	−.85	.70
RH								1	−.53
AQI									1

Lucknow 2020 Parameters	$PM_{2.5}$	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	−.29	.83	.59	−.41	.63	−.29	.89
CO		1	−.18	.14	.02	.03	.02	−.23
NO_2			1	.64	−.66	.75	−.29	.61
SO_2				1	−.46	.62	−.15	.39
O_3					1	−.53	−.15	−.21
T						1	−.57	.46
RH							1	−.23
AQI								1

*Data of PM_{10} concentration were not available at Chennai and Lucknow

Table 6 Correlation analysis of six criteria air pollutants, temperature, relative humidity, and air quality index of selected metropolitan cities of India during March 25 to May 3, 2019

Delhi 2019

Parameters	$PM_{2.5}$	PM_{10}	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	.78	.79	.73	.66	.13	−.01	.25	.77
PM_{10}		1	.54	.51	.53	.29	−.45	.67	.97
CO			1	.89	.72	.18	−.12	.32	.55
NO_2				1	.78	.28	−.22	.28	.52
SO_2					1	.12	−.46	.39	.47
O_3						1	−.33	.45	.38
T							1	−.82	−.39
RH								1	.64
AQI									1

Mumbai 2019

Parameters	$PM_{2.5}$	PM_{10}	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	.94	−.08	.24	−.37	.55	−.56	.36	.88
PM_{10}		1	−.09	.18	−.43	.48	−.59	.40	.86
CO			1	.81	−.26	.02	−.08	.62	−.05
NO_2				1	−.50	.31	−.43	.57	.27
SO_2					1	−.34	.67	−.50	−.56
O_3						1	−.43	.28	.54
T							1	−.44	−.65
RH								1	.35
AQI									1

Kolkata 2019

Parameters	$PM_{2.5}$	PM_{10}	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	.61	.86	.78	.75	.53	−.14	−.71	.93
PM_{10}		1	.47	.55	.52	.23	.13	−.63	.60
CO			1	.84	.71	.58	−.31	−.66	.74
NO_2				1	.74	.55	−.42	−.71	.71
SO_2					1	.74	−.20	−.87	.71
O_3						1	−.45	−.73	.50
T							1	.04	−.19
RH								1	−.69
AQI									1

Chennai 2019

Parameters	$PM_{2.5}$	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	−.10	.27	−.18	.17	−.12	−.12	.73
CO		1	−.24	−.33	−.43	.45	−.19	−.13
NO_2			1	.21	.40	−.41	.15	.23
SO_2				1	.45	−.16	.12	.12
O_3					1	−.12	.31	.23
T						1	−.39	−.25
RH							1	−.09
AQI								1

Table 6 continued

Bengaluru 2019 Parameters	$PM_{2.5}$	PM_{10}	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	.41	−.08	.09	−.07	−.15	.13	−.07	.25
PM_{10}		1	−.03	.60	.21	.04	.63	−.54	.66
CO			1	.44	−.18	−.04	−.19	−.04	.04
NO_2				1	.21	.12	.41	−.64	.53
SO_2					1	.02	.33	−.52	−.09
O_3						1	.21	−.37	.32
T							1	−.58	.35
RH								1	−.36
AQI									1

Hyderabad 2019 Parameters	$PM_{2.5}$	PM_{10}	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	.82	.61	.65	.52	−.19	.52	−.30	.85
PM_{10}		1	.30	.35	.60	−.03	.46	−.63	.92
CO			1	.73	.21	−.17	.44	.01	.45
NO_2				1	.40	−.36	.33	−.10	.43
SO_2					1	−.16	.16	−.58	.54
O_3						1	−.12	−.34	.05
T							1	−.09	.44
RH								1	−.57
AQI									1

Jaipur 2019 Parameters	$PM_{2.5}$	PM_{10}	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	.84	.12	−.03	.23	.13	.67	−.51	.84
PM_{10}		1	−.07	−.27	.12	.12	.42	−.27	.94
CO			1	.66	.09	−.50	.17	−.31	.01
NO_2				1	−.22	−.42	.21	−.36	−.20
SO_2					1	−.01	.28	−.25	.04
O_3						1	.13	−.05	.05
T							1	−.90	.39
RH								1	−.22
AQI									1

Lucknow 2019 Parameters	$PM_{2.5}$	CO	NO_2	SO_2	O_3	T	RH	AQI
$PM_{2.5}$	1	.50	.22	.71	.07	.15	−.38	.86
CO		1	.23	.41	.28	.16	.21	.51
NO_2			1	.62	.06	−.06	−.06	.29
SO_2				1	.03	−.06	−.36	.69
O_3					1	.51	−.08	.05
T						1	−.34	.14
RH							1	−.32
AQI								1

*Data of PM_{10} concentration were not available at Chennai and Lucknow

4 Conclusion

The COVID-19 lockdown saved tens of thousands lives and controlled the transmission of SARS-CoV-2 primarily in many of the countries. Subsequently, it also restored the air quality of the world in a very impressive way. Major Indian metropolitan cities also re-established the degraded air quality during the COVID-19 lockdown period. It is concluded that out of six criteria pollutants, the concentration of four criteria pollutants like $PM_{2.5}$, PM_{10}, CO, and NO_2 drastically decreased, while the concentration of SO_2 and O_3 declined slightly in most of the metropolitan cities during the COVID-19 lockdown period. The order of air quality index during lockdown for all metropolitan cities was satisfactory > moderate > good > poor, while it was moderate > satisfactory > poor > good > very poor during the previous year. It is concluded that the frequency order of prominent pollutants during lockdown was $O_3 > PM_{10} > PM_{2.5} > CO > NO_2 > SO_2$, while it was $PM_{2.5} > PM_{10} > CO > O_3 > NO_2 > SO_2$ during the same period of 2019 in all metropolitan cities. Overall air quality was improved during the lockdown period in Indian metropolitan cities. Further, based on the results of this study it is suggested that India should implement the lockdown once in a month to repair the damage of the air quality caused by heavy vehicular and industrial emissions.

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Compliance with ethical standards

Conflict of 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.

References

Akyol, S., Erdogan, S., Idiz, N., Celik, S., Kaya, M., Ucar, F., et al. (2014). The role of reactive oxygen species and oxidative stress in carbon monoxide toxicity: An in-depth analysis. *Redox Report, 19,* 180–189. https://doi.org/10.1179/1351000214Y.0000000094.

Bortnick, S. M., Coutant, B. W., & Eberly, S. I. (2002). Using continuous $PM_{2.5}$ monitoring data to report an air quality index. *Journal of the Air & Waste Management Association, 52,* 104–112. https://doi.org/10.1080/10473289.2002.10470763.

Burke, R. M., Midgley, C. M., Dratch, A., Fenstersheib, M., Haupt, T., Holshue, M., et al. (2020). Active monitoring of persons exposed to patients with confirmed COVID-19 United States. *Morbidity and Mortality Weekly Report, 1,* 1. https://doi.org/10.15585/mmwr.mm6909e1externalicon.

Cadotte, M. (2020). Early Evidence that COVID-19 Government Policies Reduce Urban Air Pollution. https://doi.org/10.31223/osf.io/nhgj3.

Chan, J., Yuan, S., Kok, K., Kai Wang-To, K., Chu, H., Yang, J., et al. (2020). A familial cluster of pneumonia associated with the 2019 novel coronavirus indicating person-to-person transmission: A study of as family cluster. *Lancet*. https://doi.org/10.1016/S0140-6736(20)30154-9.

Chauhan, A., & Singh, R. P. (2020). Decline in PM_{25} concentrations over major cities around the world associated with COVID-19. *Environmental Research, 187,* 109634. https://doi.org/10.1016/j.envres.2020.109634.

Chen, T. M., Gokhale, J., Shofer, S., & Kuschner, W. G. (2007). Outdoor air pollution: Nitrogen dioxide, sulfur dioxide, and carbon monoxide health effects. *American Journal of the Medical Sciences, 333,* 249–256. https://doi.org/10.1097/MAJ.0b013e31803b900f.

Cheng, W. L., Chen, Y. S., Zhang, J., Lyons, T. J., Pai, J. L., & Chang, S. H. (2007). Comparison of the revised air quality index with the PSI and AQI indices. *Science of the Total Environment, 382,* 191–198. https://doi.org/10.1016/j.scitotenv.2007.04.036.

Cohen, A. J., Brauer, M., Burnett, R., Anderson, H. R., Frostad, J., Estep, K., et al. (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: An analysis of data from the global burden of diseases study 2015. *Lancet, 389,* 1907–1918. https://doi.org/10.1016/S0140-6736(17)30505-6.

CPCB. (2015). *National Air Quality Index* (pp. 1–55). New Delhi: Central Pollution Control Board.

Cyberlab. (2020). *Dados de contagem veicular*. https://twitter.com/cyberlabsai?ref_src=twsrc%5Egoogle%7Ctwcamp%5Eserp%7Ctwgr%5Eauthorc. Accessed April 10, 2020.

Dang, R., & Liao, H. (2019). Radiative forcing and health impact of aerosols and ozone in China as the consequence of clean air actions over 2012–2017. *Geophysical Research Letters, 46,* 12511–12519. https://doi.org/10.1029/2019GL084605.

Dantas, G., Siciliano, B., Franca, B. B., da Silva, C. M., & Arbilla, G. (2020). The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro, Brazil. *Science of the Total Environment, 729,* 139085. https://doi.org/10.1016/j.scitotenv.2020.13.

Donkelaar, A., Martin, R. V., Brauer, M., Hsu, N. C., Kahn, R. A., Levy, R. C., et al. (2016). Global estimates of fine particulate matter using a combined geophysical-statistical method with information from satellites, models, and monitors. *Environmental Science Technology, 50,* 3762–3772. https://doi.org/10.1021/acs.est.5b05833.

EEA. (2019). *European Environment Agency, European Union Emission Inventory Report*.

Environmental Protection Agency (EPA). (2014). *Air Quality Index: A Guide to Air Quality and Your health*. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, https://www3.epa.gov/airnow/aqi_brochure_02_14.pdf.

Garaga, R., Sahu, S. K., & Kota, S. H. (2018). A review of air quality modeling studies in India: Local and Regional Scale. *Current Pollution Reports, 4,* 59–73. https://doi.org/10.1007/s40726-018-0081-0.

Gautam, S. (2020). The influence of COVID-19 on air quality in India: a boon or inutile. *Bulletin of Environmental Contamination and Toxicology*. https://doi.org/10.1007/s00128-020-02877-y.

Ghorani-Azam, A., Riahi-Zanjani, B., & Balali-Mood, M. (2016). Effects of air pollution on human health and practical measures for prevention in Iran. *Journal of Research in Medical Sciences, 21,* 65. https://doi.org/10.4103/1735-1995.189646.

Gorai, A. K., Tchounwou, P. B., & Mitra, G. (2017). Spatial variation of ground level ozone concentrations and its health impacts in an urban area in India. *Aerosol and Air Quality Research, 17*(4), 951. https://doi.org/10.4209/aaqr.2016.08.0374.

Gorai, A. K., Tuluri, F., & Tchounwou, P. B. A. (2014). GIS based approach for assessing the association between air pollution and asthma in New York State, USA. *International Journal of Environmental Research and Public Health, 11,* 4845–4869. https://doi.org/10.3390/ijerph110504845.

Harrison, R. M., Thornton, C. A., Lawrence, R. G., Mark, D., Kinnersley, R., & Ayres, J. G. (2002). Personal exposure monitoring of particulate matter, nitrogen dioxide, and carbon monoxide, including susceptible groups. *Occupational and Environmental Medicine, 59*(10), 671–679. https://doi.org/10.1136/oem.59.10.671.

He, G., Pan, Y., & Tanaka, T. (2020). COVID-19, city lockdown, and air pollution: evidence from China. https://doi.org/10.1101/2020.03.29.20046649.

Heuss, J. M., Kahlbaum, D. F., & Wolff, G. T. (2003). Weekday/weekend ozone differences: What can we learn from them? *Journal of the Air & Waste Management Association, 53,* 772–788. https://doi.org/10.1080/10473289.2003.10466227.

Huang, X., Ding, A., Gao, J., Zheng, B., Zhou, D., Qi, X., Tang, R., Ren, C., Nie, W., Chi, X., Wang, J. (2020a). Enhanced secondary pollution offset reduction of primary emissions during COVID-19 lockdown in China. https://doi.org/10.31223/osf.io/hvuzy.

Huang, C., Wang, Y., Li, X., Ren, L., Zhao, J., Hu, Y., et al. (2020b). Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China. *Lancet, 395,* 497–506. https://doi.org/10.1016/s0140-6736(20)30183-5.

Isaifan, R. J. (2020). The dramatic impact of coronavirus outbreak on air quality: Has it saved as much as it has killed so far? *Global Journal of Environmental Science and Management, 6*(3), 275–288. https://doi.org/10.22034/GJESM.2020.03.01.

Jing, G. (2020). *Diary of a Life in Locked-Down Wuhan*. https://www.bbc.com/news/world-asia-china-51276656.

Karamchandani, P., Long, Y., Pirovano, G., Balzarini, A., & Yarwood, G. (2017). Source-sector contributions to european ozone and fine PM in 2010 using AQMEII modeling data. *Atmospheric Chemistry and Physics, 17,* 5643–5664. https://doi.org/10.5194/acp-17-5643-2017.

Kerimray, A., Baimatova, N., Ibragimova, O. P., Bukenov, B., Kenessov, B., Plotitsyn, P., et al. (2020). Assessing air quality changes in large cities during COVID-19 lockdowns: The impacts of traffic-free urban conditions in Almaty, Kazakhstan. *Science of the Total Environment, 730,* 139179. https://doi.org/10.1016/j.scitotenv.2020.139179.

Kyrkilis, G., Chaloulakou, A., & Kassomenos, P. A. (2007). Development of an aggregate air quality index for an urban mediterranean agglomeration: relation to potential health effects. *Environment International, 33,* 670–676. https://doi.org/10.1016/j.envint.2007.01.010.

Li, Q., Guan, X., Wu, P., Wang, X., Zhou, L., Tong, Y., et al. (2020). Early transmission dynamics in Wuhan, China, of novel coronavirus-infected Pneumonia. *New England Journal of Medicine, 382,* 1199–1207. https://doi.org/10.1056/NEJMoa2001316.

Li, K., Jacob, D. J., Liao, H., Shen, L., Zhang, Q., & Bates, K. H. (2019). Anthropogenic drivers of 2013–2017 trends in summer surface Ozone in China. *Proceedings of the National Academy of Sciences, 116,* 422–427. https://doi.org/10.1073/pnas.1812168116.

Li, M., Wang, T., Xie, M., Li, S., Zhaung, B., & Chen, P. (2017). Impacts of aerosol- radiation feedback on local air quality during a severe haze episode in Nanjing Megacity, Eastern China. *Tellus B, 69,* 1339548. https://doi.org/10.1080/16000889.2017.133.9548.

Liu, J., Liao, X., Qian, S., Yuan, J., Wang, F., Liu, Y., et al. (2020a). Community transmission of severe acute respiratory syndrome coronavirus 2, Shenzhen, China. *Emerging Infectious Diseases, 1,* 1. https://doi.org/10.3201/eid2606.200239.

Liu, F., Page, A., Strode, S.A., Yoshida, Y., Choi, S., Zheng, B., Lamsal, L.N., Li, C., Krotkov, N.A., Eskes, H., Vander, A.R. (2020b). Abrupt declines in tropospheric nitrogen dioxide over China after the outbreak of COVID-19. arXiv preprint arXiv:2004.06542.

Liu, H., Wang, X. M., Pang, J. M., & He, K. B. (2013). Feasibility and difficulties of China's new air quality standard compliance: PRD case of $PM_{2.5}$ and ozone from 2010 to 2025. *Atmospheric Chemistry and Physics, 13,* 12013–12027. https://doi.org/10.5194/acp-13-12013-2013.

Mahato, S., Pal, S., & Ghosh, K. G. (2020). Effect of lockdown amid COVID-19 pandemic on air quality of the megacity

Delhi, India. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2020.139086.
Mason, R. O., Lind, D. A., & Marchal, W. G. (1983). *Statistics an introduction* (pp. 368–383). New York: New York Harcourt Brace Jovanovich Inc.
Muhammad, S., Long, X., & Salman, M. (2020). COVID-19 pandemic and environmental pollution: a blessing in disguise? *Science of the Total Environment, 728,* 138820. https://doi.org/10.1016/j.scitotenv.2020.138820.
Mukherjee, A., & Agrawal, M. (2018). Air pollutant levels are 12 times higher than guidelines in Varanasi, India. Sources and transfer. *Environmental Chemistry Letters, 16,* 1009–1016. https://doi.org/10.1007/s10311-018-0706-y.
Murena, F. (2004). Measuring air quality over large urban areas: Development and application of an air pollution index at the urban area of Naples. *Atmospheric Environment, 38,* 6195–6202. https://doi.org/10.1016/j.atmosenv.2004.07.023.
Murphy, J. G., Day, D. A., Cleary, P. A., Wooldridge, P. J., Millet, D. B., Goldstein, A. H., et al. (2007). The weekend effect within and downwind of sacramento-part 1: observations of ozone, nitrogen oxides, and VOC reactivity. *Atmospheric Chemistry and Physics, 7,* 5327–5339. https://doi.org/10.5194/acp-7-5327-2007.
Nagendra, S. M. S., Venugopal, K., & Jones, S. L. (2007). Assessment of air quality near traffic intersections in Bangalore city using air quality indices. *Transportation Research Part D: Transport and Environment*. https://doi.org/10.1016/j.trd.2007.01.005.
Newby, D. E., Mannucci, P. M., Tell, G. S., Bacarelli, A. A., Brook, R. D., Donaldson, K., et al. (2015). Expert position paper on air pollution and cardiovascular disease. *European Heart Journal, 36*(2), 83–93. https://doi.org/10.1093/eurheartj/ehu458.
Ogen, Y. (2020). Assessing nitrogen dioxide (NO_2) levels as a contributing factor to the coronavirus (COVID-19) fatality rate. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2020.138605.
Ott, W. R. (1978). *Environmental indices theory and practice* (p. 48106). Ann Arbor: Ann Arbor Science Publishers Inc.
Saadat, S., Rawtani, D., & Hussain, C. M. (2020). Environmental perspective of COVID-19. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2020.138870.
Sadeghi, M., Ahmadi, A., Baradaran, A., Masoudipoor, N., & Frouzandeh, S. (2015). Modeling of the relationship between the environmental air pollution, clinical risk factors, and hospital mortality due to Myocardial infarction in Isfahan. *Iran J Res Med Sci, 2*(20), 757–762. https://doi.org/10.4103/1735-1995.168382.
Sahu, D., Kannan, G. M., & Vijayaraghavan, R. (2014). Carbon black particle exhibits size dependent toxicity in human monocytes. *Int J Inflam, 1,* 827019. https://doi.org/10.1155/2014/827019.
Sharma, S., Zhang, M., Jingsi, G. A., Zhang, H., & Kota, S. H. (2020). Effect of restricted emissions during COVID-19 on air quality in India. *Science of the Total Environment, 728,* 138878. https://doi.org/10.1016/j.scitotenv.2020.138878.
Shrestha, A.M., Shrestha, U.B., Sharma, R., Bhattarai, S., Tran, H.N.T., & Rupakheti, M. (2020). Lockdown caused by COVID-19 pandemic reduces air pollution in cities worldwide. https://doi.org/10.31223/osf.io/edt4j.
Sicard, P., Marco, A. D., Agathokleous, E., Feng, Z., Xu, X., Paoletti, E., et al. (2020). Amplified ozone pollution in cities during the COVID-19 lockdown. *Science of the Total Environment, 735,* 139542. https://doi.org/10.1016/j.scitotenv.2020.139542.
Thom, G. C., & Ott, W. R. (1976). A proposed uniform air pollution index. *Atmospheric Environment, 10,* 261–264.
Wang, P., Chen, K., Zhu, S., Wang, P., & Zhang, H. (2020a). Severe air pollution events not avoided by reduced anthropogenic activities during COVID-19 outbreak. *Resources, Conservation and Recycling, 158,* 104814. https://doi.org/10.1016/j.resconrec.2020.104814.
Wang, C., Horby, P. W., Hayden, F. G., & Gao, G. F. (2020b). A novel coronavirus outbreak of global health concern. *The Lancet, 395*(10223), 470–473. https://doi.org/10.1016/s0140-6736(20)30185-9.
Wang, Q., & Su, M. (2020). A preliminary assessment of the impact of COVID-19 on environment—A case study of China. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2020.138915.
Wang, Y., Ying, Q., Hu, J., & Zhang, H. (2014). Spatial and temporal variations of six criteria air pollutants in 31 provincial capital cities in China during 2013-2014. *Environment International, 73,* 413–422. https://doi.org/10.1016/j.envint.2014.08.016.
Wang, S., Yu, S., Yan, R., Zhang, Q., Li, P., Wang, L., et al. (2017). Characteristics and origins of air pollutants in Wuhan, China, based on observations and hybrid receptor models. *Journal of Air Waste Management Association, 67,* 739–753. https://doi.org/10.1080/10962247.2016.1240724.
Weber, J. C., & Lamb, D. R. (1970). Statistics and research in physical education. *St. Louis: CV Mosby Co, 222,* 59–64.
WHO. (2018). *WHO global ambient air quality database (update 2018)*. World Health Organisation.
WHO. (2020a). *Coronavirus disease 2019 (COVID-19) situation report – 137*. World Health Organisation.
WHO. (2020b). *Database: outdoor air pollution in cities; 2003-2010*. Available from: WHO, 2020. Statement on the second meeting of the international health regulations (2005) emergency committee regarding the outbreak of novel coronavirus (2019-Ncov). Jan 30, 2020 (Accessed Feb 1, 2020). World Health Organisation.
WHO. (2020c). *Report of the WHO-China joint mission on coronavirus disease 2019 (COVID-19)*. World Health Organisation.
WHO. (2020d). *Air pollution*. (Date accessed: April 8, 2020). World Health Organisation.
Wolff, G. T., Kahlbaum, D. F., & Heuse, J. M. (2013). The vanishing ozone weekday/weekend effect. *J. Air Waste Manage Assoc., 63,* 292–299. https://doi.org/10.1080/10962247.2012.749312.
Wu, F., Zhao, S., Yu, B., Chen, Y. M., Wang, W., Song, Z. G., et al. (2020). A new coronavirus associated with human respiratory disease in China. *Nature, 579*(7798), 265–269. https://doi.org/10.1038/s41586-020-2008-3.
Yan, S., Cao, H., Chen, Y., Wu, C., Hong, T., & Fan, H. (2016). Spatial and temporal characteristics of air quality and air pollutants in 2013 in Beijing. *Environmental Science and*

Pollution Research, 23, 13996–14007. https://doi.org/10.1007/s11356-016-6518-3.

Yuda, M. (2019). *Asian countries rush to fight toxic air pollution*. Accessed Jan 24, 2019.

Zhang, Y. L., & Cao, F. (2015). Fine particulate matter (PM_{25}) in China at a city level. *Scientific Reports, 5,* 14884. https://doi.org/10.1038/srep14884.

Zhu, Y., Xie, J., Huang, F., & Cao, L. (2020). Association between short-term exposure to air pollution and COVID-19 infection: Evidence from China. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2020.138704138704.