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Spatio-temporal analysis of air quality and its relationship with major COVID-19 hotspot places in India

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ABSTRACT

The COVID-19 pandemic spread worldwide, such as wind, with more than 400,000 documented cases as of March 24th, 2020. In this regard, strict lockdown measures were imposed in India on the same date to stop virus spread. Thereafter, various lockdown impacts were observed, and one of the immediate effects was a reduction in air pollution levels across the world and in India as well. In this study, we have observed approximately 40% reduction in air quality index (AQI) during one month of lockdown in India. The detailed investigations were performed for 14 major hotspot places where the COVID-19 cases were >1000 (as of 1st June 2020) and represents more than 70% associated mortality in India. We assessed the impact of lockdown on different air quality indicators, including ground ($PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3, and AQI) and tropospheric nitric oxide (NO_2) pollutants, through ground monitoring stations and Sentinel-5 satellite datasets respectively. The highest reductions were noticed in NO_2 (-48.68%), $PM_{2.5}$ (-34.84%) and PM_{10} (-33.89%) air pollutant (unit in μg/m^3) post-lockdown. Moreover, tropospheric NO_2 (mol/m^2) concentrations were also improved over Delhi, Mumbai, Kolkata, Thane, and Ahmedabad metro cities. We found strong positive correlation of COVID-19 mortality with PM_{10} ($R^2 = 0.145$; r = 0.38) and AQI ($R^2 = 0.17$; r = 0.412) pollutant indicators that significantly improved next time point. The correlation finding suggests that long-term bad air quality may aggravate the clinical symptoms of the disease.

1. Introduction

The COVID-19 outbreak started in Wuhan city, the capital of Hubei Province (Raibhandari et al., 2020), when the first case of coronavirus was reported in December 2019 (Huang et al., 2020). The severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) gradually spread throughout the world and became a global health issue (Chen et al., 2020a; Gilbert et al., 2020), and the World Health Organization (WHO) later declared it a pandemic (Huang et al., 2020; Cucinotta and Vanelli (2020)). In India, the first SARS-CoV-2 case was reported in Kerala state in Jan 2020 (Gautam and Hens, 2020) and gradually spread in Maharashtra, Gujarat, Delhi, and the rest of the states. Later, a countrywide lockdown was declared by the Prime Minister of India on the midnight of March 24th, 2020 that has been extended until April and further extended until June 2020 due to the fear of spreading the virus. By this countrywide lockdown, transportation and industrial activities were almost stopped, and as a beneficial outcome, air pollution levels were drastically reduced in various cities of India (Sharma et al., 2020) as reported by the Central Pollution Control Board (CPCB). Different pollution indexes have been adopted throughout the world, including various air pollutants, and in India, the air quality index (AQI) is often adopted to express the magnitude of air pollution (Shenfeld, 1970; Ott and Thorn, 1976; Murena, 2004). In the initial stage, some significant pollutants were not included, which harms the respiratory system (Radojevic and Hassan, 1999; Qian et al., 2004). In this context, Indian National Air Quality Standards (INAQS) have included various air pollutants (PM2.5, PM10, O3, SO2, NO2, NH3, and CO) to calculate the AQI through more than 200 monitoring stations across India (http://www.cpcb.nic.in).

India is one of the most polluted countries, and 21 Indian cities are on the list of the world's 30 most polluted cities (https://www.iqair.com/us/world-most-polluted-cities), which take almost 12.4 million lives every year (Balakrishnan et al., 2018). The environmental pollutants during the COVID-19 lockdown revealed a reduction in the levels of air pollutants that have been restored within few months because of limited human activities (Sicard et al., 2020). Under such conditions, the

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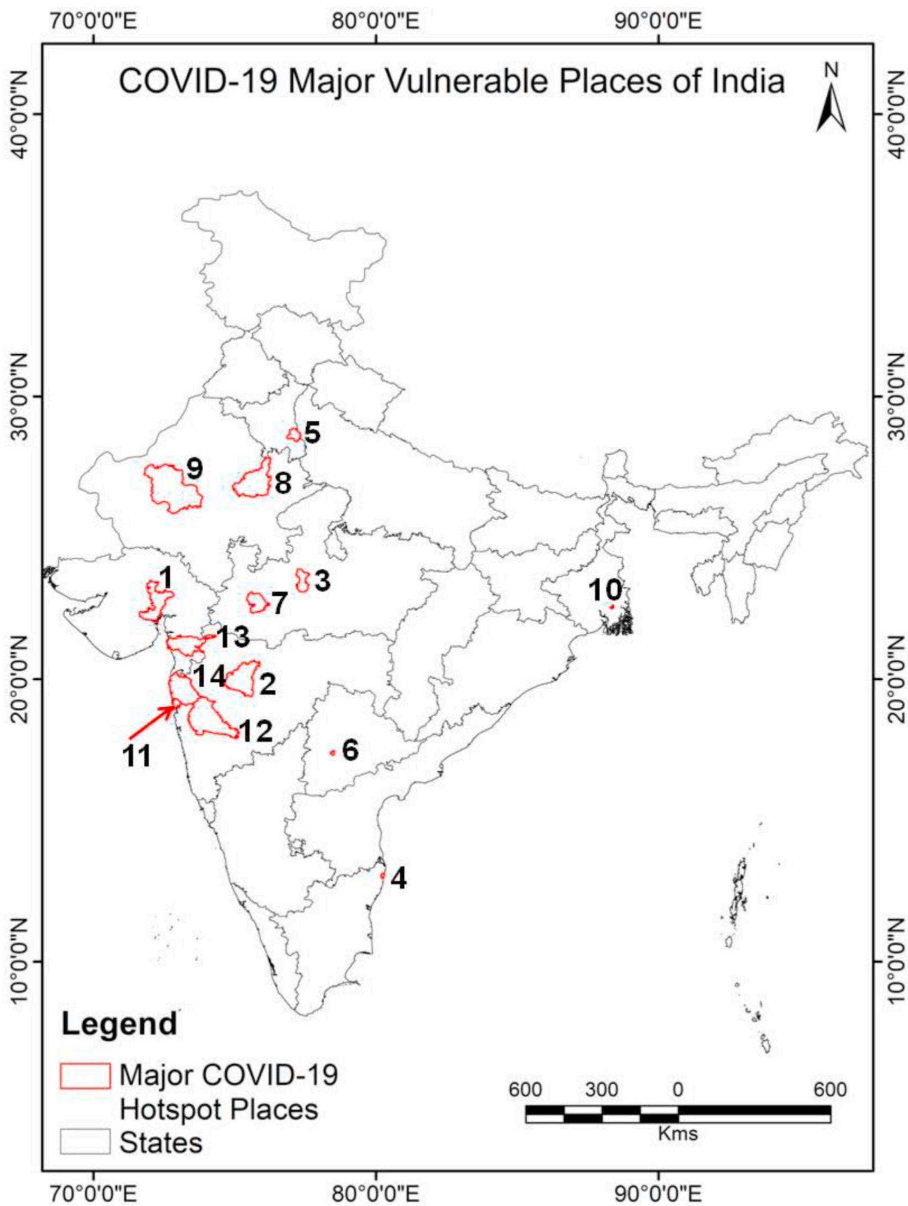

Fig. 1. Study area: The major COVID-19 vulnerable places are marked in red along with their respective codes. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
COVID-19 mortality on two different time periods.

S.No.	Places	As of 1st June 2020		As of 15th June 2020	
		Cases	Deaths	Cases	Deaths
1	Ahmedabad	10590	722	16640	1187
2	Aurangabad	1289	48	2668	135
3	Bhopal	1271	59	2195	72
4	Chennai	11131	87	31896	344
5	Delhi	13677	287	41182	1327
6	Hyderabad	1178	23	3196	23
7	Indore	3064	116	4.63	170
8	Jaipur	1849	79	2532	133
9	Jodhpur	1275	17	2181	27
10	Kolkata	1693	184	3672	293
11	Mumbai	31972	1026	58226	2182
12	Pune	5996	274	12184	480
13	Surat	1351	62	2579	100
14	Thane	6958	93	18080	434

COVID-19 lockdown beneficially improved the air quality throughout the globe, and a decline in different air pollutants has been reported worldwide and in India employing ground monitoring stations and remote sensing datasets (Chauhan and Singh, 2020; Nakada and Urban, 2020). The drastic deduction (more than 50%) in different air pollutants was highlighted in megacity Delhi, India (Mahato et al., 2020). In India, different studies have been investigated the effect of COVID-19 lockdown on tropospheric and ground air pollutant indicators and highlighted that the air quality has improved significantly over the major cities (Singh and Chauhan, 2020).

Interestingly, studies have established a relationship between air pollution and mortalities related to SARS-CoV-2 (Zhu et al., 2020; Conticini et al., 2020). In this regard, ground and tropospheric pollutant (PM and NO_2) levels were correlated (Qin et al., 2020). Therefore, people living in polluted regions generally inhale toxic pollutants from the past couple of years and are more prone to toxic pollutants, which makes the immune system weaker (Viehmann et al., 2015; Schraufnagel et al., 2019). In this study, we targeted only those 14 hotspot regions of

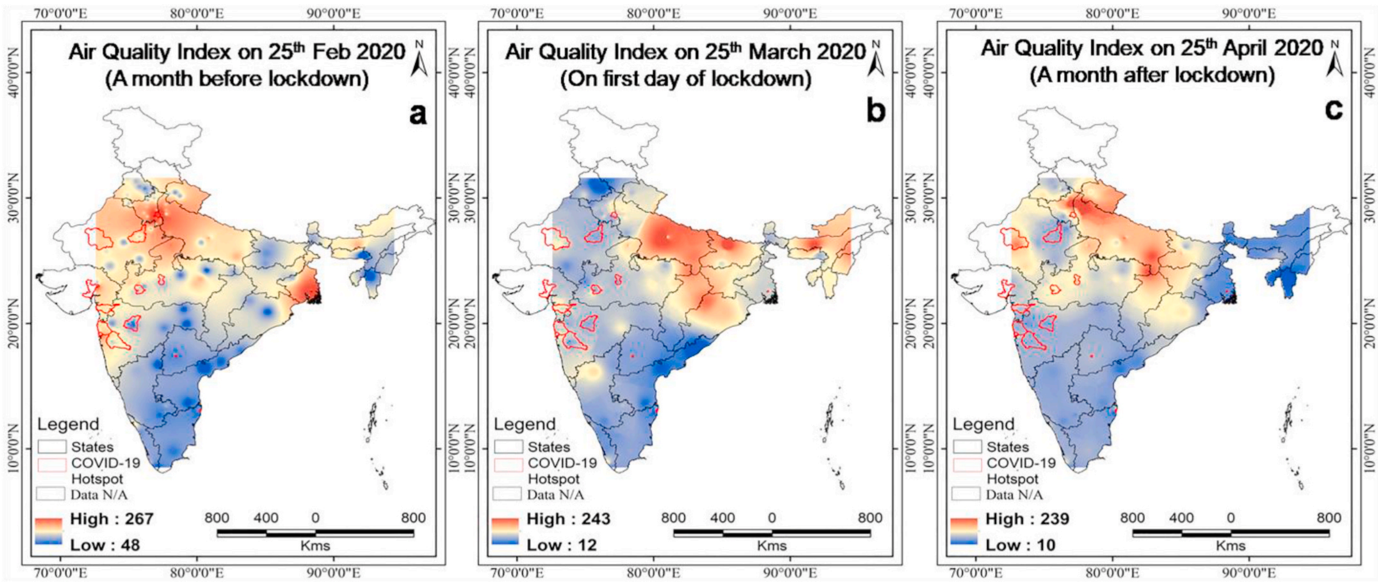

Fig. 2. Air quality index levels in India: (a) a month before, (b) a next day and a month after (c) country lockdown.

India where the COVID-19 cases and mortalities (representing more than 70%) are reported to be high. Accordingly, this research aims to assess the reduction of AQI and different air pollutants ($PM_{2.5}$, PM_{10}, NO_2, O_3, and SO_2) at the ground monitoring station and extract the changes in tropospheric NO_2 concentration by employing remote sensing data. Moreover, the study also tried to establish the relationship between air pollutants and COVID-19 mortalities.

2. Material and methods

To assure the post-lockdown changes in air pollution, we employed in situ air quality monitoring data for more than 200 stations in India. Later, the inverse distance weighted (IDW) interpolation technique was used to obtain the raster values for the maximum area. These AQIs were assessed on 25th Febraury 2020 (a month before lockdown), 25th March 2020 (first day of lockdown) and 25th April 2020 (a month after lockdown) on different dates to monitor the variations. Moreover, detailed investigations were performed using ground and tropospheric pollutant indicators for Ahmedabad, Aurangabad, Bhopal, Chennai, Delhi, Hyderabad, Indore, Jaipur, Jodhpur, Kolkata, Mumbai, Pune, Surat, and Thane cities (Fig. 1). The criterion behind selecting these major places is that we have considered only those places where the number of cases was more than 1000 as of 1st June 2020 (Table 1). The statistical analysis was performed using the Air Quality Index (AQI), and other pollutants, *i.e.*, $PM_{2.5}$, PM_{10}, NO_2, SO_2 and O_3 (units in μg/m^3), monthly average data of the mentioned places were procured for pre-lockdown (February 25th, 2020 and March 24th, 2020) and post-lockdown (March 25th, 2020 and April 24th, 2020) periods from the Central Pollution Control Board (CPCB) portal (https://cpcb.nic.in/). At the same time, remote sensing data were analyzed using Google Earth Engine that was collected from Copernicus Sentinel-5 Precursor Tropospheric Monitoring Instrument (S5p/TROPOMI) to determine the average monthly spatial variations in tropospheric NO_2 (mol/m^2) concentrations and extensively used for air quality applications (Veefkind et al., 2012). Moreover, linear regression and correlation analyses were performed between different air pollutants and COVID-19 mortalities (as of 1 June 2020) obtained from different portals handled by the Ministry of Health & Family Welfare (https://www.mohfw.gov.in & https://www.mygov.in/covid-19). A similar investigation was performed after 2 weeks (as of 15th June 2020) of updated COVID-19 mortalities (Table 1) to assess the variations in the relationship between these variables.

3. Results and discussion

3.1. Air pollution levels and reduction due to COVID-19 lockdown

In India, three weeks of lockdown was declared at midnight on the 24th of March 2020. Thereafter, the country has observed a remarkable reduction of approximately 36.10% in AQI on 25th March 2020 compared to a month before (25th Feb 2020) lockdown as per our statistical calculation using more than 200 air quality monitoring station data. The overall AQI of India has been reduced drastically as per the investigations. The maximum and minimum AQI values are visible and highlight the improvements over the period of time (pre-, during- and post-lockdown dates) in India (Fig. 2a–c). The average AQI before a month of lockdown was 128, which dropped down at 89 (on a very first day of lockdown) and further decreased after a month of lockdown to 72. This continuous reduction in the AQI clearly indicates that the atmospheric pollution of India has greatly improved under the COVID-19 lockdown.

In this research, we analyzed one-month average changes (between 25th Feb to 24th March 2020 and 25th March to 24th April 2020) as per the lockdown dates (pre and post) in different air pollutant indicators, i. e., $PM_{2.5}$, PM_{10}, NO_2, O_3, SO_2 (units in μg/m^3) and AQI. We found that all air pollutant concentrations decreased drastically in April 2020 (post-lockdown period) compared to March 2020 (pre-lockdown) (Fig. 3a–f). The $PM_{2.5}$ was >100 μg/m^3 in Jodhpur, Surat, and Thane cities, whereas Delhi, Jodhpur, Mumbai and Ahmadabad were the leading cities in PM_{10} (most of them had >110 μg/m^3) concentrations before the lockdown period (Fig. 3a and b). These regions have more traffic and industrial burdens, which is the main reason for the high level of PM concentrations. A similar pattern was found in NO_2 levels where these pollutants were recorded higher at Indore, Thane, Jodhpur, and Ahmedabad stations (Fig. 3c), whereas SO_2 concentration was higher at Aurangabad, Pune and Thane cities in a pre-lockdown phase that had been reduced considerably (Fig. 3d). Interestingly, in 6 out of 14 cities, an increase was observed in the O_3 level after lockdown (Fig. 3e). Aurangabad, Chennai, Delhi, and Kolkata are few cities where the O_3 level has increased partially. A significant improvement has been noticed in the AQI levels of all cities, among which Ahmedabad, Delhi, Jodhpur, and Kolkata cities were leading to poor air quality (Fig. 3f).

The changes (positive and negative percentages) in different air pollutants were calculated (Fig. 4 and Table 2), and accordingly, it was found that the average AQI dropped almost -31.59% in the studied

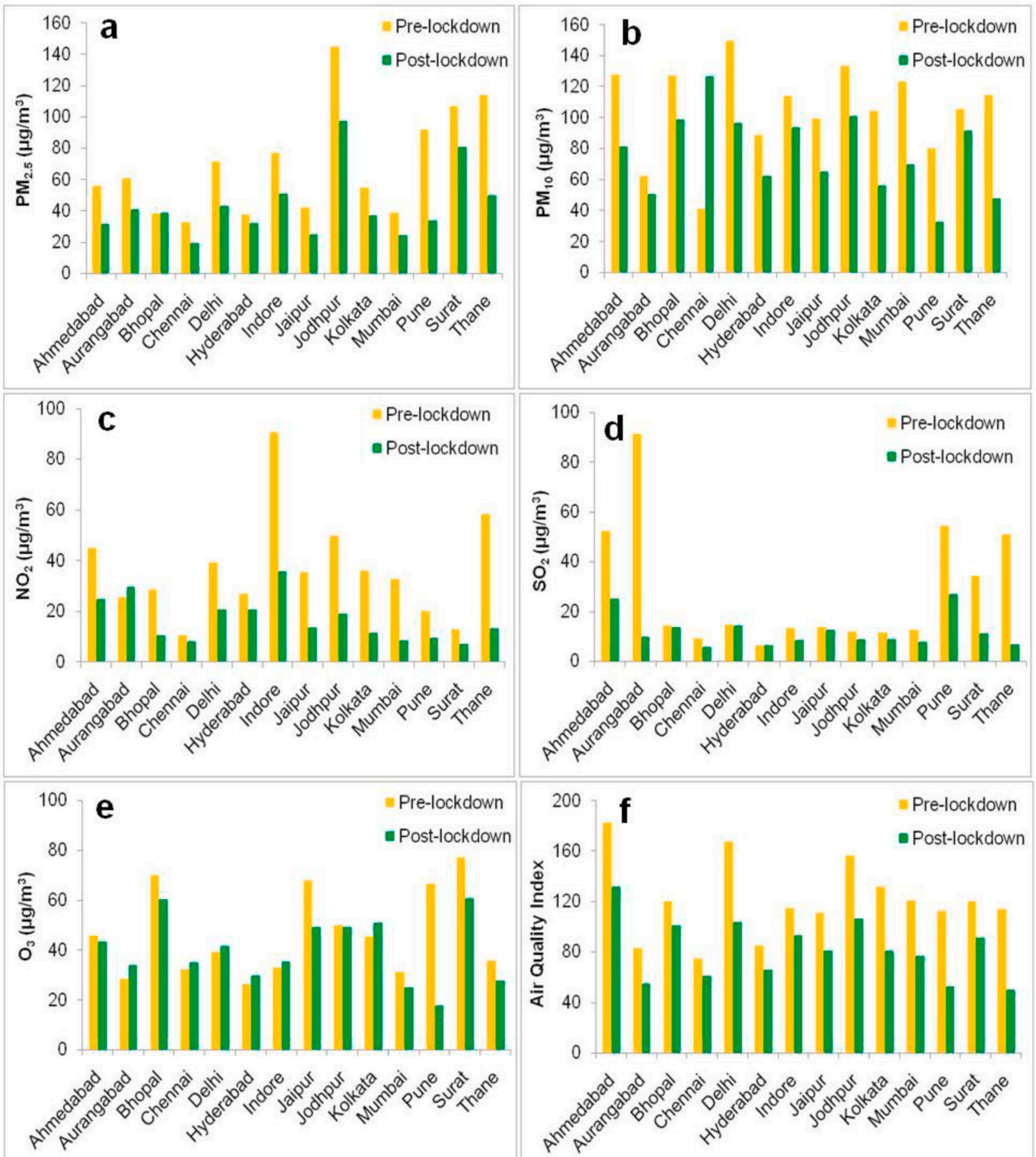

Fig. 3. The pre- and post-lockdown variation in (a) $PM_{2.5}$, (b) PM_{10}, (c) NO_2, (d) SO_2, (e) O_3 and AQI (f) pollutant levels recorded at ground monitoring stations of different cities.

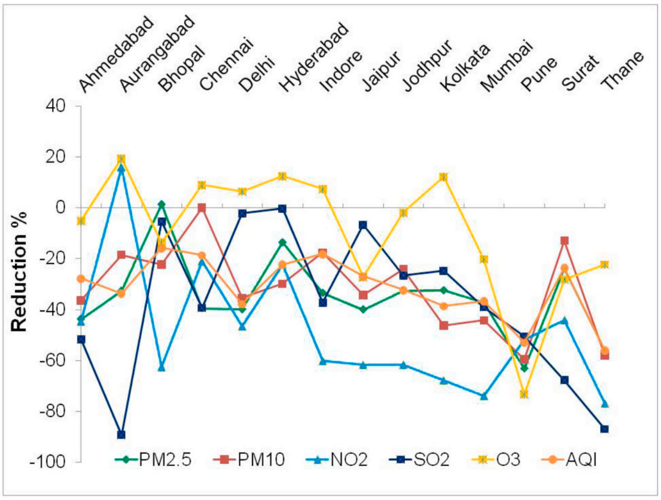

Fig. 4. The change reduction percentage of all air quality indicators.

cities. The highest average reduction was found in NO_2 (-48.68) compared to other pollutants. The similar trends of reductions were also observed in SO_2 (37.76%), $PM_{2.5}$ (34.84%), PM_{10} (33.89%) and O_3 (9.06%) air pollutant indicators. The results reveal that the NO_2 levels have decreased more in Thane, Mumbai, and Kolkata cities after imposed lockdown with 77%, 74%, and 68%, respectively. These cities are known for heavy traffic loads with a lower density of roads that increase the burden of NO_2 levels. A similar trend of reduction is observed in both particulate matters ($PM_{2.5}$ and PM_{10}) with less variation. Remarkable improvements in PM2.5 concentrations were observed at Pune, Thane, and Ahmedabad, which were reduced 63%, 56%, and 43%, respectively; however, they were high before the lockdown period in Jodhpur city. The prominent source of $PM_{2.5}$ is organic aerosols and motor vehicle traffic, which are totally anthropogenic induced activities that stopped due to lockdown. PM_{10} is highly controlled by construction sites, burning activities, industrial sources, and dust factors that make Delhi, Jodhpur and Mumbai cities more prone to PM_{10} air pollutants. However, higher reductions during lockdown were noticed in Pune (59.7%), Thane (58%), and Kolkata (44.3%). The SO_2 pollutants that have shown considerable variation post-lockdown and the reduction have counted high in comparison to the other pollutants. The major reduction is observed in Aurangabad (-89%), and the rest of the cities and the chief reason behind the reduction in SO_2 level is an industrial activity that processes materials that contain sulfur. The concentration of O_3 shows a negligible increase due to the high insolation between April and August in the Indian subcontinent (Gorai et al., 2017). The concentration of O_3 increases in Aurangabad (19.2%), Hyderabad (12.29%), Kolkata (12.03%), Chennai (8.87%), and Delhi (6.3%) cities, as they are known for industrial and transport dominated places.

The findings of this research are more or less similar with other studies where they performed short-term (a week/month) pre- and post-lockdown analysis in different ground air pollutants that were declined significantly over the Kolkata, Delhi, Mumbai and Chennai metro cities (Singh and Chauhan, 2020; Bedi et al., 2020).

Moreover, tropospheric NO_2 (mol/m^2) pollutant concentrations were also mapped to observe the temporal variation through remote sensing data. Accordingly, we found a massive improvement in Delhi, Mumbai, Thane, Ahmedabad, Chennai and Hyderabad cities, as the highest NO_2 concentration (red color) scale showed 0.0001 mol/m^2, which is totally invisible post-lockdown compared to pre-lockdown (Fig. 5). Our spatio-temporal findings about declined tropospheric NO_2 concentrations is well corroborate with other studies where the average short-term reductions were reported $<$12% post-lockdown in India (Biswal et al., 2020; Naqvi et al., 2020).

3.2. *Relationship of air pollutants and COVID-19 mortalities*

The considered 14 places have covered almost $>$70% of COVID-19 mortalities and their growth rate is high in these hotspot regions compared to the rest of Indian places. Mumbai and Delhi are the main COVID-19 hotspots and polluted places in India and across the world. People inhale these toxic pollutants and die in past decades; therefore, determining the relationship between COVID-19 mortality and atmospheric pollution is an important task. In this regard, our linear regression results have shown satisfactory positive relationships with $PM_{2.5}$, PM_{10}, and AQI pollutant indicators (Fig. 6a, b and f). The analysis showed promising associations between COVID-19 deaths and PM_{10} ($R^2 = 0.145$; $r = 0.38$, $p = 0.039$), AQI ($R^2 = 0.17$; $r = 0.412$, $p = 0.21$) and $PM_{2.5}$ ($R^2 = 0.107$; r = 0.-32, $p = 0.081$) air pollutants. The poor/negative correlations between these variables were found with SO_2 and O_3 air pollutants (Fig. 6d and e). The NO_2 pollutant at the ground had an insignificant relationship (Fig. 6c), whereas high concentrations of tropospheric NO_2 (mol/m^2) over the Mumbai, Delhi, Thane and Ahmedabad places (Fig. 5) indicate that it is a contributing factor, as the COVID-19 deaths are greater in these regions compared to the rest of the investigated places. However, we could make this relationship stronger when less vulnerable COVID-19 places would be correlated with good air quality regions.

We have taken the COVID-19 mortalities data again after 2 weeks (as of 15th June 2020) to analyze the depth relationship between these two variables, and our results again corroborate with significant improvements. As per the updated COVID-19 mortalities data, this relationship and correlation with PM_{10} ($R^2 = 0.207$; $r = 0.455$, $p = 0.036$) and AQI ($R^2 = 0.18$; $r = 0.425$, $p = 0.044$) were stronger with significant improvements than before (Fig. 7a and b).

Table 2
Post-lockdown percentage changes in air pollutant levels compared to pre-lockdown.

S. No.	Places	$PM_{2.5}$	PM_{10}	NO_2	SO_2	O_3	AQI
1	Ahmedabad	-43.83	-36.42	-44.85	-51.71	-5.29	-27.87
2	Aurangabad	-32.79	-18.54	15.89	-89.40	19.30	-33.73
3	Bhopal	1.35	-22.42	-62.78	-5.34	-13.83	-15.83
4	Chennai	-39.53	210.67	-21.24	-39.41	8.87	-18.67
5	Delhi	-39.98	-35.55	-46.74	-2.17	6.33	-37.87
6	Hyderabad	-13.61	-29.94	-22.41	-0.32	12.30	-22.35
7	Indore	-33.51	-17.72	-60.35	-37.31	7.27	-18.29
8	Jaipur	-40.03	-34.40	-61.89	-6.81	-27.33	-27.03
9	Jodhpur	-32.73	-24.14	-61.85	-26.67	-2.00	-32.36
10	Kolkata	-32.50	-46.29	-67.98	-24.85	12.03	-38.64
11	Mumbai	-37.15	-44.33	-74.05	-39.15	-20.29	-36.74
12	Pune	-63.26	-59.70	-52.00	-50.55	-73.49	-53.02
13	Surat	-24.02	-12.95	-44.23	-67.84	-28.32	-23.67
14	Thane	-56.14	-58.12	-77.05	-87.06	-22.47	-56.14
	Average change %	**-34.84**	**-33.89**	**-48.68**	**-37.76**	**-9.07**	**-31.59**

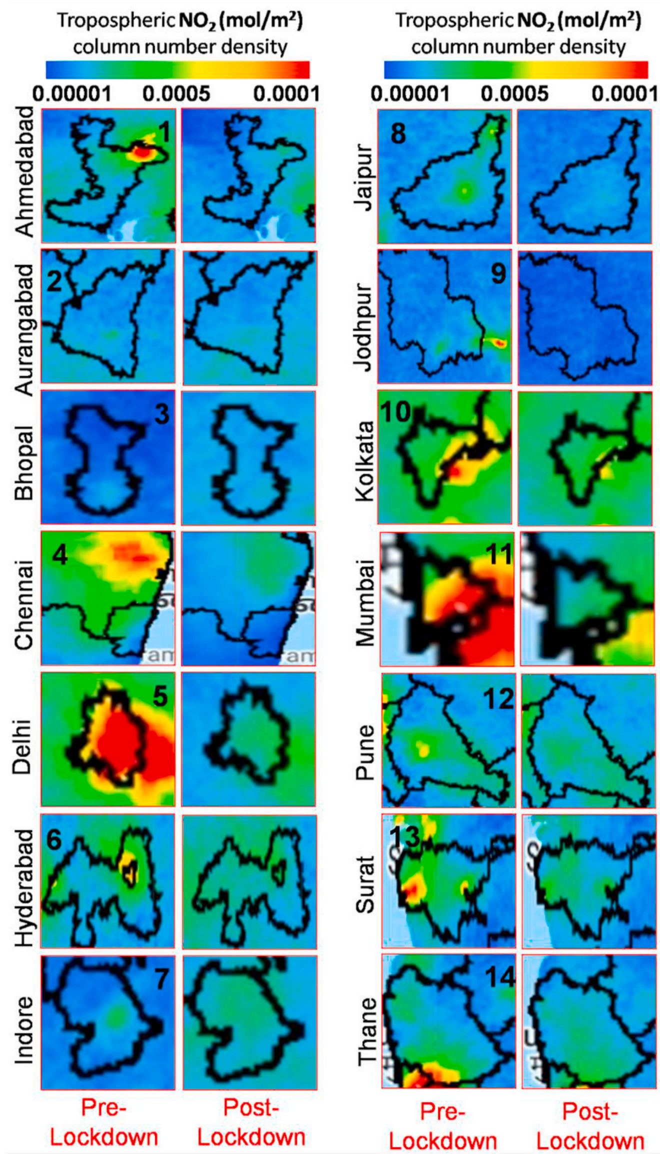

Fig. 5. The average tropospheric NO_2 concentration variations in the study area during a one-month pre- and post-lockdown period.

Interestingly, the associations with remaining air pollutants are still negligible. A similar attempt was also highlighted by Qin et al. (2020), who mentioned that people living in regions with poor air quality are highly vulnerable to COVID-19 due to the long-term inhalation of toxic pollutants. Another study conducted by Cole et al. (2020) examined long-term air pollution exposure in 355 Dutch municipalities and found positive relationship with $PM_{2.5}$, NO_2 and SO_2 pollutants with COVID-19 cases and deaths, where $PM_{2.5}$ was highly correlated compare to rest of the pollutants. The other research found that a small increase in long-term exposure to $PM_{2.5}$ is not good and their model results revealed that a 1 $\mu g/m^3$ increase in $PM_{2.5}$ is responsible for 8% increase in the COVID-19 death rate (Wu et al., 2020). Therefore, poor air quality generally makes a weaker immune system of the human body (Schraufnagel et al., 2019) that may aggravate virus replication and diminish virus clearance by the host.

4. Conclusion

This study investigates the impact of lockdown on air quality that improved significantly, and a detailed study was conducted on 14 major COVID-19-susceptible places in India. Our results reveal that higher reductions were observed in NO_2, PM_{10} and $PM_{2.5}$ ($\mu g/m^3$) pollutants with rates of 48.68%, 34.84% and 33.89%, respectively in 14 major COVID-19 vulnerable places. Moreover, tropospheric NO_2 (mol/m^2) concentrations also decreased, especially over the Delhi, Mumbai, Thane, Pune, Kolkata and Ahmedabad places where the concentration was high before imposing lockdown. We established the relationship between COVID-19 mortalities (on two different time datasets) with different air pollutants and observed satisfactory positive correlations with PM_{10} and AQI indicators. Interestingly, we found improvement in a relationship when correlated again with updated COVID-19 mortalities data. A similar attempt has been made in different regions of the world that strongly supports our results (Wu et al., 2020; Chen et al., 2020; Naqvi et al., 2020). However, SARS-CoV-2 is a communicable disease, but at the same time, people living under poor air quality with weakened immune systems are vulnerable or certain diseases also face higher risks and are experiencing the coronavirus pandemic with particular anxieties.

Ethical statement

All ethical practices have been followed in relation to the

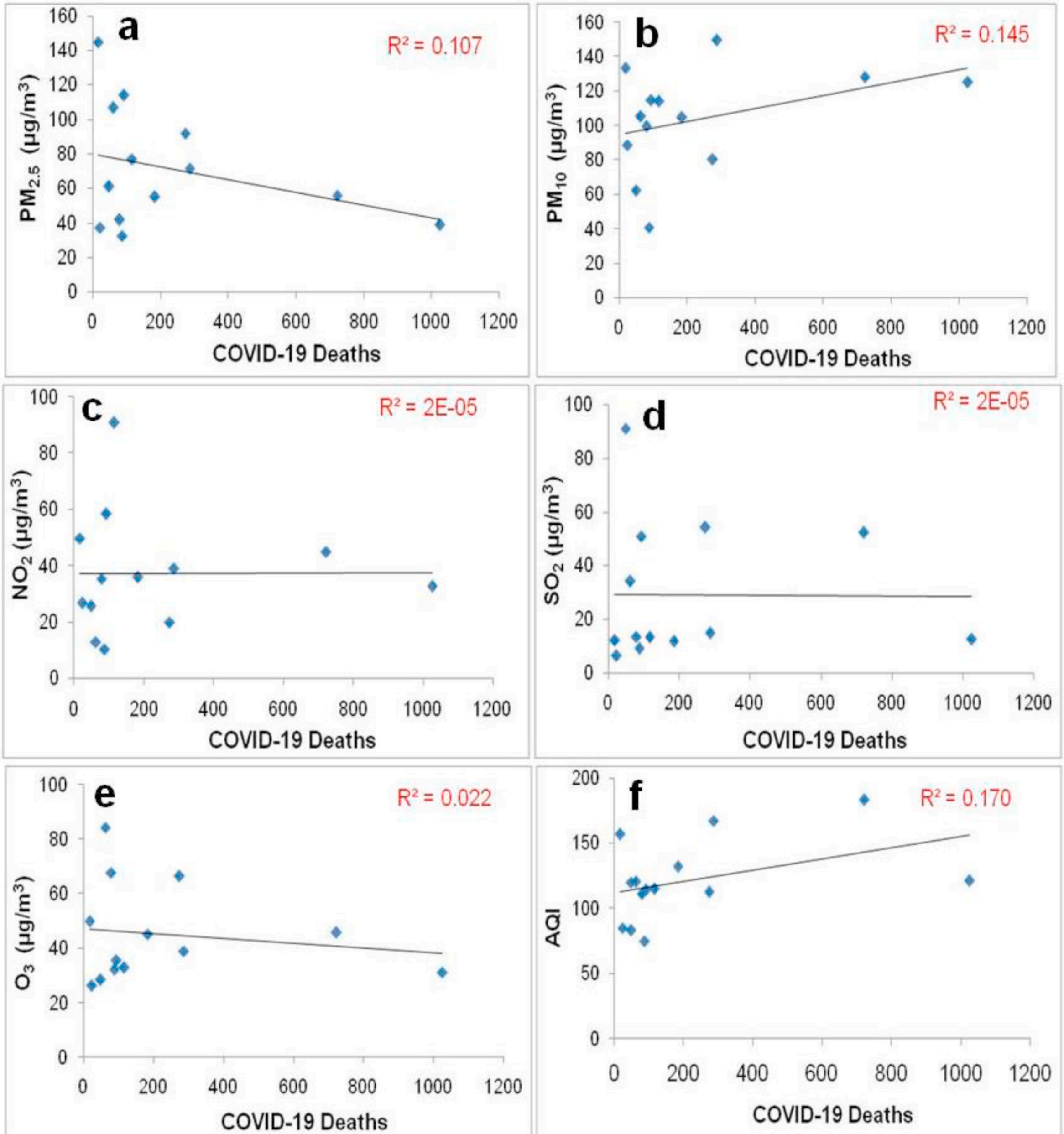

Fig. 6. Linear regression analysis of (a) $PM_{2.5}$, (b) PM_{10}, (c) NO_2, (d) SO_2, (e) O_3 and AQI (f) pollutant indicators with COVID-19 mortality data (as of 1st June 2020).

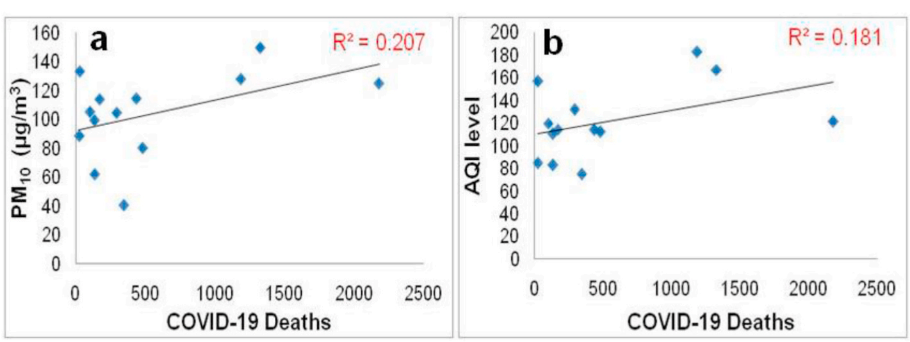

Fig. 7. Relationship of updated COVID-19 mortality data (as of 15th June 2020) with (a) PM_{10} and AQI (b) indicators.

development, data analysis, writing, and publication of this research article.

Author statement

Conceptualization: Naqvi HR, Shakeel A. **Software:** Mutreja G, Naqvi HR. **Analysis:** Mutreja G, Shakeel A. **Writing- draft:** Naqvi HR, Siddiqui MA. **Writing- Review and editing:** Naqvi HR, Siddiqui MA. **Supervision:** Naqvi HR, Siddiqui MA.

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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