



Social and Travel Lockdown Impact Considering Coronavirus Disease (COVID-19) on Air Quality in Megacities of India: Present Benefits, Future Challenges and Way Forward

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ABSTRACT

The coronavirus disease (COVID-19) created enormous pressure across the globe due to an increasing number of COVID-19 infected cases. All the governments' primary focus is to save humanity from this pandemic problem, and they have lockdown almost the entire nation to stop the spread of infection. This lockdown resulted in a considerable impact on the global as well as a local economy that will take a long time to perform with business as usual scenario. However, improvement in the air quality of the cities across the globe has emerged as a key benefit of this lockdown. Therefore, this study aims to assess the overall impact of social and travel lockdown in five megacities of India; Delhi, Mumbai, Chennai, Kolkata, and Bangalore. The study evaluated the spatiotemporal variations in five criteria pollutants over two time periods, i.e., March–April 2019 and March–April 2020 and 10th–20th March 2020 (before lockdown) and 25th March to 6th April 2020 (during lockdown). The results highlighted a statistically significant decline in all the pollutants in all the megacities except for ozone. It was observed that the concentration of PM_{2.5}, PM₁₀, NO₂ and CO declined by ~41% (66–39 $\mu\text{g m}^{-3}$), ~52% (153–73 $\mu\text{g m}^{-3}$), ~51% (39–19 $\mu\text{g m}^{-3}$) and ~28% (0.9–0.65 mg m^{-3}) during the lockdown phase in comparison to the before lockdown in Delhi, respectively. Similar decline in pollutant concentration was observed in other megacities as well. Further, the study conducted an expert survey to identify the possible challenges India might face after lockdown is over. All the experts said that reviving the economy will be a big challenge for the government, and it may result in some tradeoff while managing the air quality in the near future due to scarcity of funds, etc.

Keywords: Interpolation technique; Arc GIS; Air quality; Vulnerability; Environmental health.

INTRODUCTION

The entire world is facing a severe risk due to COVID-19 (Coronavirus disease) which is affecting almost all the countries (Buono *et al.*, 2020). The World Health Organization (WHO, 2020) declared COVID-19 as a pandemic due to widespread global infection. As of May 13, 2020, ~4,369,933 coronavirus cases have been reported globally. Out of which 2,456,508 are currently infected (98% with mild and 2% with serious or critical conditions) and around 1,913,425 are the closed cases out of which 85% recovered and 15% died. India is also facing a similar challenge due to the COVID-19 pandemic, which created an emergency in the entire country. India is at a critical stage in its fight against COVID-19 with

positive cases crossing 75,048 and death toll at 2440 until May 13, 2020 (MoHFW, 2020). The entire country was under complete lockdown from March 25 to April 14, 2020, for 21 days, which was further extended by the Government of India until May 3, 2020 followed by the third phase of lockdown till May 17, 2020 to tackle the spread of COVID-19. Social and travel restriction resulted in the shutdown of all the businesses which includes industries, transport (air, water, and surface), markets, shops, tourism, construction and demolition, hotels and restaurants, mining and quarrying, etc. except the limited essential services like groceries, milk, fruits and vegetable, medicines, etc. This situation already created a significant impact on the global as well as a local economy that will take adequate time to perform with business as usual scenarios. For e.g., India's fuel growth rate witnessed its worst hit over the last two decades, mainly due to lockdown in March 2020, which resulted in a decline in fuel consumption by nearly 60–70%. However, according to Indian oil companies, consumption of liquefied petroleum gas (LPG) use has been increased by 15% due to more cooking at home. Nevertheless, globally one change that has

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been observed is the improvement in the air quality due to lockdown and travel restrictions (Bao and Zhang, 2020; Saadat *et al.*, 2020). The decline in the levels of air pollution have been recently reported in many countries across the world like China, Brazil, Barcelona etc. A study conducted by Xu *et al.* (2020) reported the impact of COVID-19 on air pollution levels in three cities of central China. The results clearly indicated a decline in the levels of pollutants like $PM_{2.5}$, PM_{10} , SO_2 , CO and NO_2 during the lockdown period. Further, Nakada and Urban (2020) also reported the reduction in NO, NO_2 and CO concentrations by ~77.3% ~54.3% and ~64.8%, respectively, in the city of São Paulo, Brazil during the partial lockdown in February to April 2020 in comparison to the five-year average of the same months from 2015 to 2019. Similar declines in air pollution have been reported by other researchers like Tobías *et al.* (2020) in Barcelona; Dantas *et al.* (2020) in Rio de Janeiro and Mahato *et al.* (2020) in Delhi. Still, there is a cost to that, i.e., the slowdown in the economy of the countries and effect on the mental wellbeing of the communities (European Environment Agency, 2020; Zambrano-Monserrate *et al.*, 2020).

A similar effect has been observed in the Indian context. Before the lockdown, air quality was inferior in most Indian cities, and it affects the most vulnerable people in the community like children, the aging population, women, and the public having respiratory and cardiovascular problems (Aggarwal and Jain, 2015; Kumar *et al.*, 2013; WHO, 2018). The Global Burden of Disease reported that around 3.4 million premature deaths were attributed to exposure to ambient air pollution (Stanaway *et al.*, 2018). However, under the current India wise lockdown situation because of COVID-19, it is

observed that air quality has drastically improved in most of the cities. Ogen (2020) and Wu *et al.* (2020) have reported that improvement in air quality lowers the severity of COVID-19 outcomes. But this situation will not continue for a long time. As soon as the businesses are permitted to resume their operations as indicated by the Government of India after May 17, 2020, the air quality is likely to start deteriorating in most of the cities, and by the time winters will approach, it may create the same conditions as it was in the year 2019. Pollution is inevitable due to a growing economy and results as one of the outcomes of the developing economies for moving towards industrialization. Hence, there is a tradeoff between nature and human activities, which is essential to analyze to make informed decisions. Therefore, considering the current situation, we have analyzed the current state of air quality in most of the megacities in India and identified the potential future challenges. Also, a few policy measures have been suggested to control the air quality in most of the Indian cities in the coming future.

METHODOLOGY

The present study evaluated the impact of social and travel lockdown amid the COVID-19 breakout on the air quality in megacities of India, given its implications in the near future. Fig. 1 presents the overall methodological approach adopted to conduct the study.

Site Description and Data Collection

The study analyses the impact of social and travel lockdown on air quality of five megacities of India, i.e., Delhi,

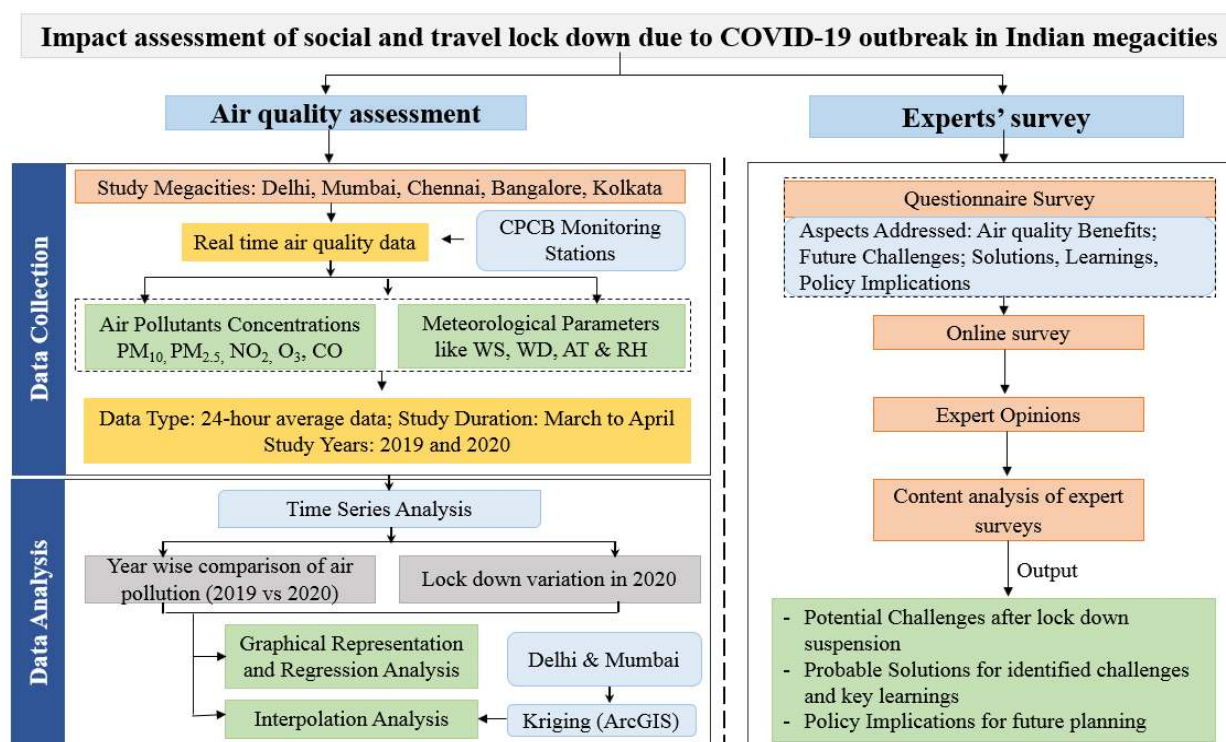


Fig. 1. Overall methodological framework used in the current study to assess the impact of lockdown in view of COVID-19 in megacities of India on air quality.

Mumbai, Chennai, Bangalore, and Kolkata. The megacities being the economic centers of the country are susceptible to relatively higher levels of both national as well as international travel movements. Delhi and Mumbai have been regarded as epicenters for coronavirus in India are analysed separately using spatiotemporal analysis in view of correlation between air pollution exposure and COVID-19 infection. They hence are under scrutiny, and severe restrictions are presenting unusual cases for evaluation of the impact of the lockdown on air pollution. Continuous ambient air quality data monitored by various State Pollution Control Boards (SPCBs) at different monitoring stations in each city under consideration was procured through the Central Pollution Control Board, New Delhi for five criteria pollutants, i.e., particulate matter $\leq 2.5 \mu\text{m}$ ($\text{PM}_{2.5}$), particulate matter $\leq 10 \mu\text{m}$ (PM_{10}), nitrogen dioxide (NO_2), ozone (O_3) and carbon monoxide (CO) along with three meteorological parameters, i.e., ambient temperature (AT), wind speed (WS) and relative humidity (RH). Air pollutants and meteorological data were procured from all the monitoring stations operational in each city, i.e., 38 in Delhi, 10 in Mumbai, 4 in Chennai, 10 in Bangalore, and 7 in Kolkata. Table 1 presents the list of all air quality monitoring stations considered in each city for data collection. Continuous 24-hour average data for the above parameters were collected for 22 days spanning over two months in 2019, i.e., from 20th March to 10th April 2019, while for 32 days in the year 2020, i.e., from 10th March to 10th April 2020.

Data Analysis

Trend Analysis

The impact of social and travel lockdown on air pollution levels of the selected megacities was inspected for two different periods, as indicated below:

1. Yearly comparison: Air quality data for the period representing lockdown months, i.e., March–April 2020 was compared with air quality data of the last year March–April 2019. The air quality of the cities was compared for a period of 22 days spanning over two months, i.e., from 20th March to 10th April for the years 2019 and 2020, respectively. The air quality data has not been analysed for Mumbai city for the same period due to the presence of enormous data gaps in the 2019 data for the pollutants considered in most of the monitoring stations of Mumbai.
2. Lockdown duration comparison was made for the time period of 10th to 20th March 2020 (Before lockdown period) versus 25th March to 6th April 2020 (During lockdown period).

A trend analysis of 24-hour daily average data for the five pollutants was considered for the above stated periods in all the cities to understand the variations in the levels of pollutant accumulation amid the lockdown period. Meteorology plays a significant role in determining air pollution levels. Therefore, time-series data were analyzed to see the effect of meteorology on air quality. A simultaneous trend analysis of meteorological parameters and air pollutants was conducted to validate the impact of lockdown on air pollution levels in the cities. Furthermore, paired t-test was used to test the significant changes in the criteria air pollutant concentrations during the lockdown period.

Spatiotemporal Analysis of Air Pollution over COVID-19 Epicenters of India: Delhi and Mumbai

One of the objectives of the present study was to map the spatiotemporal variations in the air pollution levels achieved through lockdown periods in two of the most significantly COVID-19 affected cities of India, i.e., Delhi and Mumbai. Kriging, a spatial interpolation GIS technique, was employed

Table 1. Monitoring stations considered in the selected megacities cities for data collection.

S. No.	City	Number of Monitoring Stations Considered	List of Monitoring Stations
1	Delhi	38	Alipur-DPCC; Anand Vihar-DPCC; Ashok Vihar-DPCC; Aya Nagar-IMD; Bawana-DPC; Burari Crossing-IMD; CRRM Mathura Road-IMD; Dr. Karni Singh Shooting Range-DPCC; DTU-CPCB; Dwarka-Sector 8-DPCC; East Arjun Nagar-CPCB; IGI Airport (T3)-IMD; IHBAS, Dilshad Garden-CPCB; ITO-CPCB; Jahangirpuri-DPCC; Jawaharlal Nehru Stadium-DPCC; Lodhi Road-IMD; Major Dhyani Chand National Stadium-DPCC; Mandir Marg-DPCC; Mundka-DPCC; Najafgarh-DPCC; Narela-DPCC; Nehru Nagar-DPCC; North Campus, DU-IMD; NSIT Dwarka-CPCB; Okhla Phase-2-DPCC; Patparganj-DPCC; Punjabi Bagh-DPCC; Pusa-DPCC; R K Puram-DPCC; Rohini-DPCC; Shadipur-CPCB; Sirifort-CPCB; Sonia Vihar-DPCC; Sri Aurobindo Marg-DPCC; Vivek Vihar-DPCC; Wazirpur-DPCC
2	Mumbai	10	Bandra; Borivali East; Chhatrapati Shivaji Int. Airport; Colaba; Kurla; Powai; Sion; Vasai, West; Vile Parle west; Worli
3	Chennai	4	Alandur Bus Depot; Manali; Manali Village; Achery Residential Area
4	Bangalore	10	BTM Layout; BWSSB; Bapuji Nagar; City Railway station; Hebbal; Hombegowda Nagar; Jayanagar 5 th Block; Peenya; Sanegurava Hills; Silk Board
5	Kolkata	7	Ballygunge; Bidhannagar; Fort William; Jadavpur; Rabindra Bharti University; Rabindra Sarobar; Victoria

to assess the spatial spread of air pollutants over the cities for the selected periods. Kriging is a powerful statistical technique which assumes that distance or direction between sample points reflect a spatial correlation and hence represent variation in surface (Kumar *et al.*, 2016; van Zoest *et al.*, 2019). It uses a weighted average technique by considering spatial correlation to predict the values for an area from the available data samples as per the following equation:

$$Z(S_o) = \sum_{i=1}^N \lambda_i Z(S_i)$$

where, $Z(S_i)$ = measured value at the i th location;
 λ_i = Unknown weight for measured value at i th location;
 S_o = Prediction location;
 N = number of measured values.

The tool was employed on the air pollutant data procured through the CPCB monitoring stations to interpolate the pollutant concentrations for the entire city. It was done to identify and demonstrate the most affected, i.e., hot spots and least affected (benefited) areas within the cities.

Experts' Opinion through an Online Survey

The study conducted an expert survey to take their opinions to identify the possible challenges India might face soon after the lockdown period is over. A total of 25 responses were received from national experts, including researchers, academicians, industry experts, etc. working in the field of air quality management through an online questionnaire with an online response rate of 64%. The questionnaire was comprised of both 'open-ended' as well as 'closed-ended' questions to gather the perspective of the experts regarding the current scenario as well as future implications of COVID-19 pandemic on India. The questionnaire has been presented in supplementary information (S1). The experts were provided questions to identify the possible challenges and their solutions after the lockdown period is over. The expert opinion survey was also used to identify the major learnings that can be achieved through the lockdown and how these can be used strategically for future planning and air quality management.

RESULTS AND DISCUSSION

The results of the air quality analysis have been presented in terms of yearly and daily variations observed in the pollutant concentrations due to the implementation of lockdown in the selected five megacities (Fig. 2). Spatiotemporal variations in air pollutant concentrations have also been analysed for Delhi and Mumbai. Finally, time series analysis for daily variations in the levels of air pollutants and meteorological parameters was carried out, which highlighted the impact of WS, AT, and RH on the air quality of the cities.

Effects of Lockdown on-Air Quality in Megacities

Fig. 2 shows the concentrations of all the air pollutants in Delhi, Chennai, Kolkata, Bangalore, and Mumbai before and during the lockdown as well as in 2019 and 2020. The

temporal analysis of the variations in the levels of criteria air pollutants revealed that there was a significant decline in the concentration of all the pollutants except for surface ozone (O_3) in the megacities under examination. It is important to highlight that the concentrations of O_3 witnessed an increase in the lockdown period in 2020, while an overall decline was observed when compared for the same duration in 2019. However, the magnitude of the decline in air pollutant concentrations is different in all the megacities. Fig. 2 clearly showed that there is no violation of the National Ambient Air Quality Standards (NAAQS for $PM_{2.5} = 60 \mu g m^{-3}$, $PM_{10} = 100 \mu g m^{-3}$, $NO_2 = 80 \mu g m^{-3}$ (42.54 ppb) based on a 24-hours average; $O_3 = 100 \mu g m^{-3}$ (50.96 ppb) and $CO = 2 mg m^{-3}$ (1.75 ppm) based on 8-hours average) during the lockdown period in all the megacities (the ppb and ppm values are at 25°C and 1013 mb for comparison purpose). However, when compared with the WHO standards (for $PM_{2.5} = 25 \mu g m^{-3}$, $PM_{10} = 50 \mu g m^{-3}$ based on a 24-hours average; $O_3 = 100 \mu g m^{-3}$ based on 8-hours average), Mumbai, Bangalore, and Chennai are within the permissible limits for $PM_{2.5}$; whereas all the megacities violate WHO standards (WHO, 2018) when compared in terms of PM_{10} levels. Moreover, all the megacities are within the permissible limits without any violations for O_3 . Further, all the criteria pollutant concentrations were within the NAAQS limit before the lockdown except for $PM_{2.5}$ in Delhi ($66 \mu g m^{-3}$) and PM_{10} in Delhi, Mumbai and Kolkata, with average concentrations being $153 \mu g m^{-3}$, $126 \mu g m^{-3}$ and $113 \mu g m^{-3}$, respectively, as presented in Figs. 2(a), 2(e) and 2(i). A similar trend was observed for lockdown period March–April 2020 when compared with air quality data of the last year March–April 2019 except for $PM_{2.5}$ ($89 \mu g m^{-3}$) in Delhi and PM_{10} levels in Delhi, Kolkata and Bangalore, $222 \mu g m^{-3}$, $102 \mu g m^{-3}$, $118 \mu g m^{-3}$, respectively, as presented in Figs. 2(b), 2(d) and 2(f). The WHO (2018) reported that bringing down $PM_{2.5}$ levels by $25 \mu g m^{-3}$ would result in a reduction of 15% premature deaths (mortality). Even though impact due to exposure to air pollution will not result in instantaneous mortality, and it is more of a chronic phenomenon. Therefore, immediate benefits would be more in terms of avoided morbidity and increased in healthy days.

Fig. 3 represents the percentage change in all the criteria pollutants considered in each megacity for the two periods of assessment, i.e., before vs. during lockdown in 2020 and March–April 2019 vs March–April 2020. The results of the analysis showed that the maximum dip was observed in NO_2 concentrations in all the cities, with the maximum decline of ~75% being observed in Mumbai for the 'before' and 'during' lockdown duration in 2020. Dutheil *et al.* (2020) also reported a significant reduction in NO_2 levels in China due to COVID-19 pandemic. Further, Delhi witnessed a dramatic decline in all the pollutants, which can be assumed to be historic as compared to the city' air quality since the last two decades. In Delhi, there is a significant (p values vary from 0.02474-0.03E-06) decline of 41%, 52%, 50%, 29% in the average concentration of $PM_{2.5}$ from 66 to $39 \mu g m^{-3}$, PM_{10} from 153 to $73 \mu g m^{-3}$, NO_2 from 39 to $19 \mu g m^{-3}$, and CO from 0.9 to $0.65 mg m^{-3}$, respectively during the lockdown phase in comparison to the before

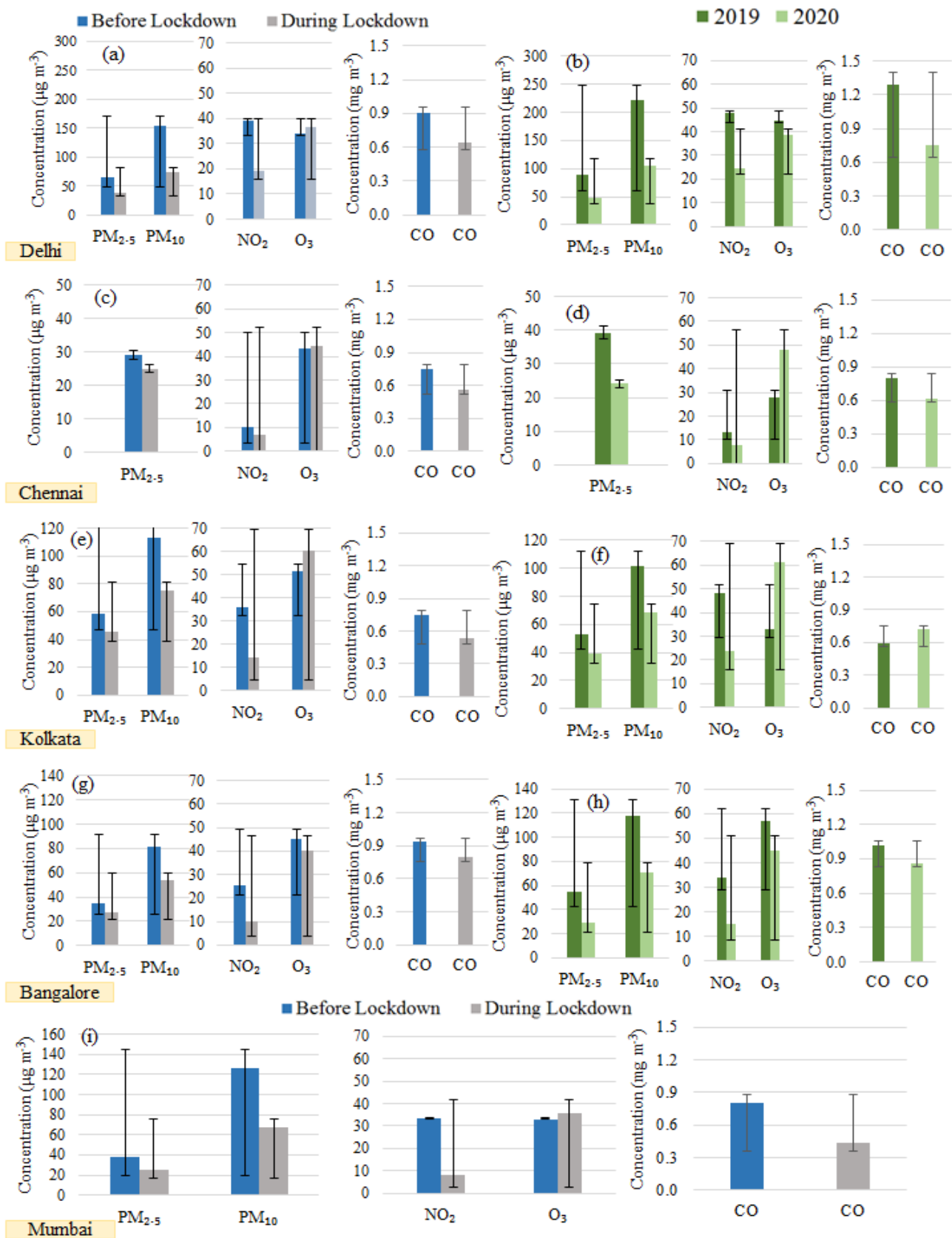


Fig. 2. Effects of lockdown on-air quality during two scenarios, i.e., effect of lockdown on air quality in compared with before lockdown and effect on air quality due to lockdown in March–April 2020 vs. last year March–April 2019. (a–b) is for Delhi; (c–d) is for Chennai; (e–f) is for Kolkata; (g–h) is for Bangalore and (i) is for Mumbai (PM, NO₂ and O₃ are in µg m⁻³ and CO in mg m⁻³).

CITY	BEFORE vs. DURING LOCKDOWN' 2020					MARCH-APRIL 2019 vs. MARCH APRIL 2020				
	PM _{2.5}	PM ₁₀	NO ₂	CO	O ₃	PM _{2.5}	PM ₁₀	NO ₂	CO	O ₃
Delhi	-41%	-52%	-50%	-29%	7%	-45%	-52%	-48%	-41%	-14%
Mumbai	-33%	-47%	-75%	-46%	8%	DNA*	DNA*	DNA*	DNA*	DNA*
Chennai	-14%	DNA*	-32%	-25%	3%	-39%	DNA	-43%	-23%	73%
Bangalore	-22%	-34%	-60%	-16%	-11%	-47%	-40%	-56%	-15%	-21%
Kolkata	-23%	-34%	-60%	-29%	17%	-27%	-32%	-66%	-16%	87%

* DNA: Data Not Available.

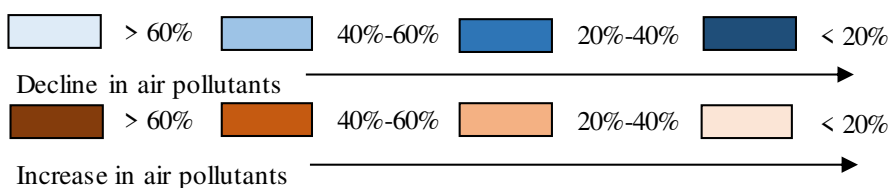
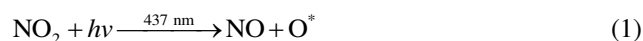


Fig. 3. Percentage decline or increase in criteria air pollutants concentrations in five megacities of India during lockdown and before lockdown period.

lockdown phase. In contrast to this, a ~7% increase in O₃ concentration has been observed (not significant $p = 0.4892$) in the city as shown in Fig. 2(a) due to lockdown as compared to before the lockdown period. Xu *et al.* (2020) also reported the similar reduction in air pollutant concentrations in three cities in Hubei Province, Wuhan, Jingmen, and Enshi in central China except an increase in O₃ concentrations like Indian megacities during the lockdown period. This study compared average air pollutant concentrations for three months, i.e., January to March 2017–2019 vs. January to March 2020. In case of Wuhan city, a decline from 33% to 45% (88.6 to 59.6 $\mu\text{g m}^{-3}$ in January; 67.9 to 38 $\mu\text{g m}^{-3}$ in February, and 53.1 to 34.5 $\mu\text{g m}^{-3}$ in March) was observed in in PM_{2.5} concentration. A decline in PM₁₀, NO₂ and CO concentrations were observed in the range 30% to 48%, 30% to 61% and 7% to 23%, respectively. Likewise Delhi, Wuhan also experienced an increase in O₃ concentration ranging from 9% to 27% (20.4 ppb in January 2017–2019 to 22.3 ppb in January 2020; 27.7 ppb in February 2017–2019 to 35.2 ppb in February 2020 and 36.2 ppb in March 2017–2019 to 42.1 ppb in March 2020), indicating the similar trends as observed in Indian megacities due to COVID-19.

The other megacities of India also witnessed a similar decline in air pollutants as reported in Delhi, as shown in Figs. 2 and 3. Chennai for instance witnessed a decline of ~14% (from 30 to 26 $\mu\text{g m}^{-3}$) in PM_{2.5}, ~30% (10–7 $\mu\text{g m}^{-3}$) in NO₂, ~25% (0.75–0.56 mg m^{-3}) in CO and a rise of ~3% (43–44 $\mu\text{g m}^{-3}$) in O₃ 'during' lockdown phase in comparison to the 'before' lockdown phase in the year 2020 as shown in Fig. 2(c). Similarly, in the 'during' lockdown phase the levels of PM_{2.5} declined from 58 to 45 $\mu\text{g m}^{-3}$ in Kolkata, 35 to 27 $\mu\text{g m}^{-3}$ in Bangalore and 37 to 25 $\mu\text{g m}^{-3}$ in Mumbai, respectively. A similar decline in other pollutants like PM₁₀, NO₂ and CO amounting to 34%, 60% and 29% in Kolkata; 42%, 70% and 38% in Bangalore and 47%, 75% and 46% in Mumbai, respectively was observed in the 'during' lockdown

phase in comparison to the 'before' lockdown phase as shown in Figs. 2(e), 2(g) and 2(i). In contrast to the trend followed by the above pollutants, the concentration of O₃ witnessed an incline in all the cities except for a decline in Bangalore. The concentration of pollutant increased from 51 to 60 $\mu\text{g m}^{-3}$ in Kolkata, 33 to 36 $\mu\text{g m}^{-3}$ in Mumbai and 43 to 44 $\mu\text{g m}^{-3}$ in Chennai as highlighted in Fig. 3. The contrasting trend of O₃ may be due to more favorable conditions for photochemical reactions attributed to increased solar insolation and a decrease in NO₂ leading to changes in the photochemical reactions determining ozone formation and destruction (Sharma *et al.*, 2016; Dang and Liao, 2019; Xu *et al.*, 2020). The underlying chemistry between anthropogenic emissions like NO_x in a VOC-limited environment and O₃ along with the meteorological parameters govern the accumulation of surface ozone in the atmosphere (Gorai *et al.*, 2015; Saini *et al.*, 2017). Similar increasing trends have been observed in the levels of O₃ concentrations during the lockdown period in China by Xu *et al.* (2020). A better understanding about the increasing trend of O₃ concentration in Indian cities can be gathered through the underlying chemistry between NO_x and O₃ as represented in Eqs. (1) to (3):



As evident from the above equations, NO₂ and NO produce contrasting impact on O₃ accumulation. The NO₂ promotes its formation in presence of sunlight while NO depletes it by formulating NO₂ after the reaction. Further, the air pollution studies conducted in Indian cities showed that more than 30–50% of NO_x emissions are released by

vehicles especially diesel vehicles compared to petrol driven vehicles (Aggarwal and Jain, 2015; Jain *et al.*, 2016). Thus, in view of the current lockdown scenario wherein 70–80% of passenger vehicles and 60–70% of goods vehicles are off the road and other reduced combustion activities results in reduced NO_x emissions in a VOC-limited environment, which could have led to an increase in O_3 concentration (Kim *et al.*, 2018; Tobias *et al.*, 2020). It is relevant to point out that the cities considered in the present study lie in VOC limited regions of India (Sharma *et al.*, 2016), thus an increase in the levels of O_3 can be understood by the decline in NO_x emissions.

A similar trend has been observed in $\text{PM}_{2.5}$, PM_{10} , NO_2 , CO, and O_3 concentrations in Mumbai, Chennai, Bangalore, and Kolkata between March–April 2019 versus March–April 2020, as shown in Figs. 2(b)–2(e) and Fig. 3. A significant (p values vary from 0.001–6.22E-10) decrease in concentrations of $\text{PM}_{2.5}$ from 89 to 48 $\mu\text{g m}^{-3}$, PM_{10} from 222 to 97 $\mu\text{g m}^{-3}$, NO_2 from 48 to 25 $\mu\text{g m}^{-3}$, CO from 1.30 to 0.75 mg m^{-3} , and O_3 from 45 to 38 $\mu\text{g m}^{-3}$ amounting to 32%, 34%, 27%, 27%, and 11% reductions, respectively, was observed between March–April 2019 and March–April 2020 in Delhi as shown in Fig. 2 (refer to Table S1 in supplementary information for ‘ p ’ values). The concentrations of air pollutants in Bangalore declined from 55 to 29 $\mu\text{g m}^{-3}$, 118 to 71 $\mu\text{g m}^{-3}$, 34 to 15 $\mu\text{g m}^{-3}$, 1.01 to 0.86 mg m^{-3} and 57 to 45 $\mu\text{g m}^{-3}$ for $\text{PM}_{2.5}$, PM_{10} , NO_2 , CO and O_3 , respectively in March–April 2020 as compared with March–April 2019. A similar trend in reduction of air pollutant concentrations from 55 to 39 $\mu\text{g m}^{-3}$, 102 to 68 $\mu\text{g m}^{-3}$, 48 to 16 $\mu\text{g m}^{-3}$, 0.6 to 0.5 mg m^{-3} in $\text{PM}_{2.5}$, PM_{10} , NO_2 and CO, respectively, was observed in Kolkata in March–April 2020 in comparison to March–April 2019.

It is important to highlight that reduction in $\text{PM}_{2.5}$ levels during the lockdown period may also be attributed to reduce NO_2 levels, which played an influential role in the formation of secondary PM (ARAI and TERI, 2018). In addition to transportation, the other factors that resulted in a reduction in air pollution levels are shutdown of industries, construction and demolition activities, road dust, refused burning and reduction in electricity demand from thermal power plants. The power sector reported that electricity demand has reduced by ~20–30% (regional variation) when compared with a week before the lockdown due to the shutdown of all schools, colleges, theaters, malls, shopping centers, corporate and utility offices and even railway systems, etc. For e.g., all the coal power plants were shutdowns in northern states of India, i.e., Haryana, Punjab and Utter Pradesh) in a radius of around 300 km of Delhi, except two units at Dadri Power Plant in the state of Utter Pradesh (CREA, 2020). However, stubble burning has been observed at various places in India like Central India and Southern plains (which includes cities like Bangalore, Chennai) because farmers cannot sell their agricultural residue due to the non-availability of transport. This may be another reason for the lesser amount of reduction in air pollutant concentrations in cities in Southern India compared to Northern India.

In addition to trend analysis, a spatiotemporal analysis using kriging a spatial interpolation GIS technique was

carried out for Delhi and Mumbai. The spatiotemporal analysis was restricted to these cities since Delhi and Mumbai are among the most significantly affected cities in India due to COVID-19 pandemic having 5,532 and 10,527 COVID-19 cases in, respectively. Further, Frontera *et al.* (2020) and Zhu *et al.* (2020) reported a strong linkage of COVID-19 infection with higher air pollution concentrations. Therefore, Delhi and Mumbai have been analysed separately. Figs. 4(a) and 4(b) present the spatiotemporal variations in all the pollutants before and during the lockdown period in Delhi and Mumbai, respectively. The spatiotemporal analysis would help in identifying the pollution hotspots in the cities. It has been observed that the Central and Northern part of Delhi has more pollution hotspots compared to Mumbai where pollution levels are high in the Southern region. This is attributed to the fact that most of the activities are happening in the same regions, and these are the most populous compared to the rest of the areas in both the cities. In the case of Delhi, Bawana, Jahangirpuri, Anand Vihar, Mundaka are few examples where pollution levels were high. While in Mumbai, many industries such as petroleum refineries, power plants, fertilizer factories, and industries located near peripheral areas in the Southern region of Mumbai are contributing to hotspots for high NO_2 and PM levels. The yearly comparison between March–April 2019 and March–April 2020 highlighted that Central, Northern, Western and Eastern parts of Delhi are more polluted areas in comparison to the Southwest part of the city, as shown in Fig. 4(c). The results of the analysis revealed that the concentration levels of $\text{PM}_{2.5}$, PM_{10} , and NO_2 witnessed the maximum decline during March–April 2020 when compared to March–April 2019. There is clear evidence that due to lockdown conditions because of COVID-19, there is a significant reduction in air pollution levels in Delhi.

Meteorology and Air Quality in Megacities

In general, very high wind speed and temperature and low relative humidity favor more dispersion of air pollutants compared to calm wind speeds or stagnant days (Sharma *et al.*, 2020). Fig. 5 shows the time series analysis of all the criteria air pollutants $\text{PM}_{2.5}$, PM_{10} , NO_2 , O_3 , and CO, along with meteorological parameters like atmospheric temperature (AT), wind speed (WS – measured around 10 m from the ground), and relative humidity (RH) for Delhi. The time series analysis clearly showed that about 1–2 weeks before the lockdown, i.e., AT was in the range of 22–27°C, WS less than 0.5 m s^{-1} , RH in the range of 58–78% which are not favorable conditions for air pollutants dispersion and hence concentrations of all the criteria pollutants was high. However, immediately after the lockdown, the temperature was 27–32°C, WS in the range of 0.7–1.2 m s^{-1} , RH in the range of 50–64%, which are more favorable conditions compared to before lockdown for more dispersion of air pollutants in the atmosphere. Putaud *et al.* (2004) have reported that at 50% RH led to PM_{10} and $\text{PM}_{2.5}$, respectively, 1.09 and 1.07 times as high as gravimetric measurements at 20% relative humidity; this may be attributed to particle-bound water. Further, Jayamurugan *et al.* (2013) also reported the statistically significant negative correlations between

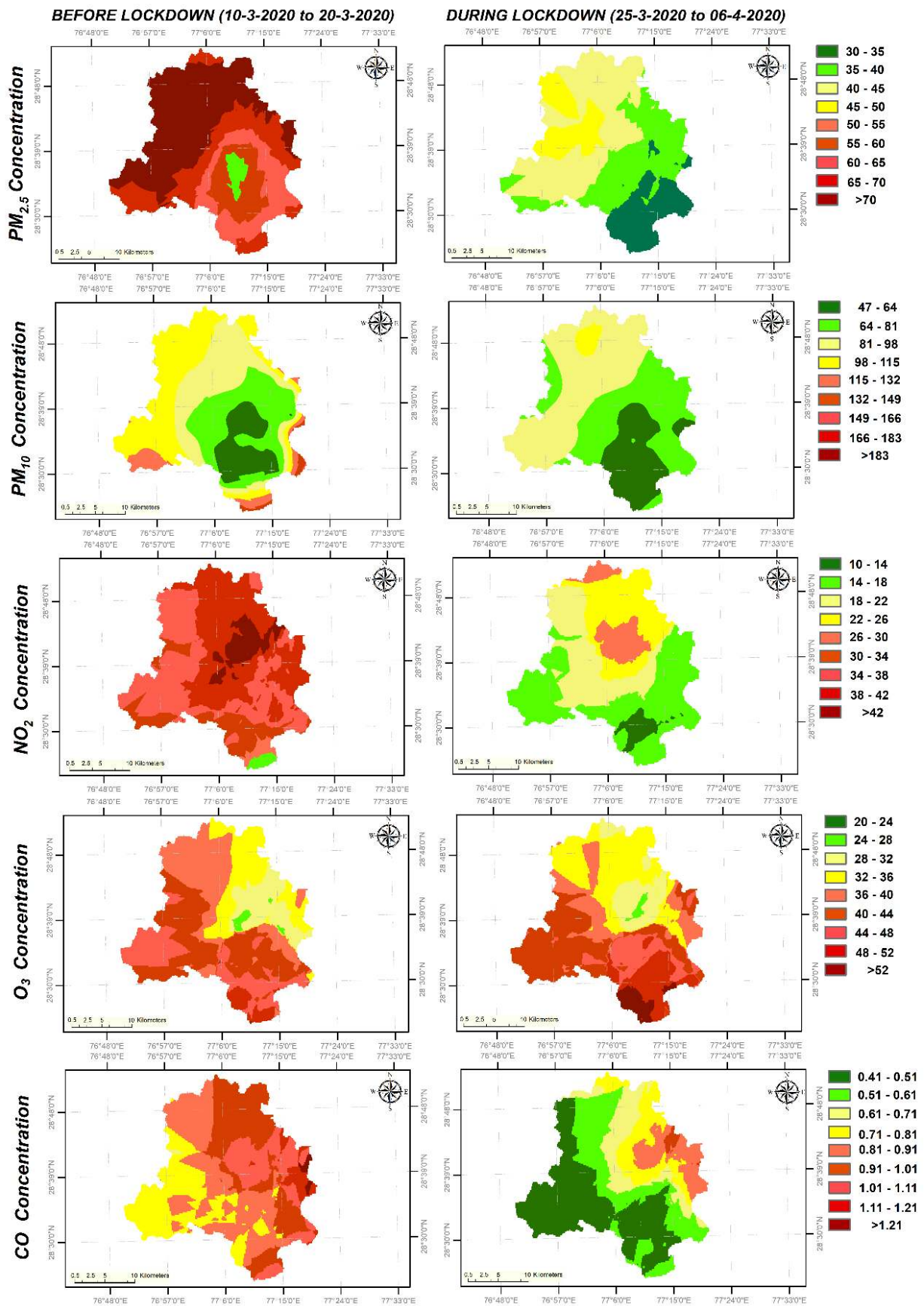


Fig. 4(a). Spatiotemporal variations in air quality due to the lockdown period compared with before lockdown period in Delhi (PM, NO₂ and O₃ are in $\mu\text{g m}^{-3}$ and CO in mg m^{-3}).

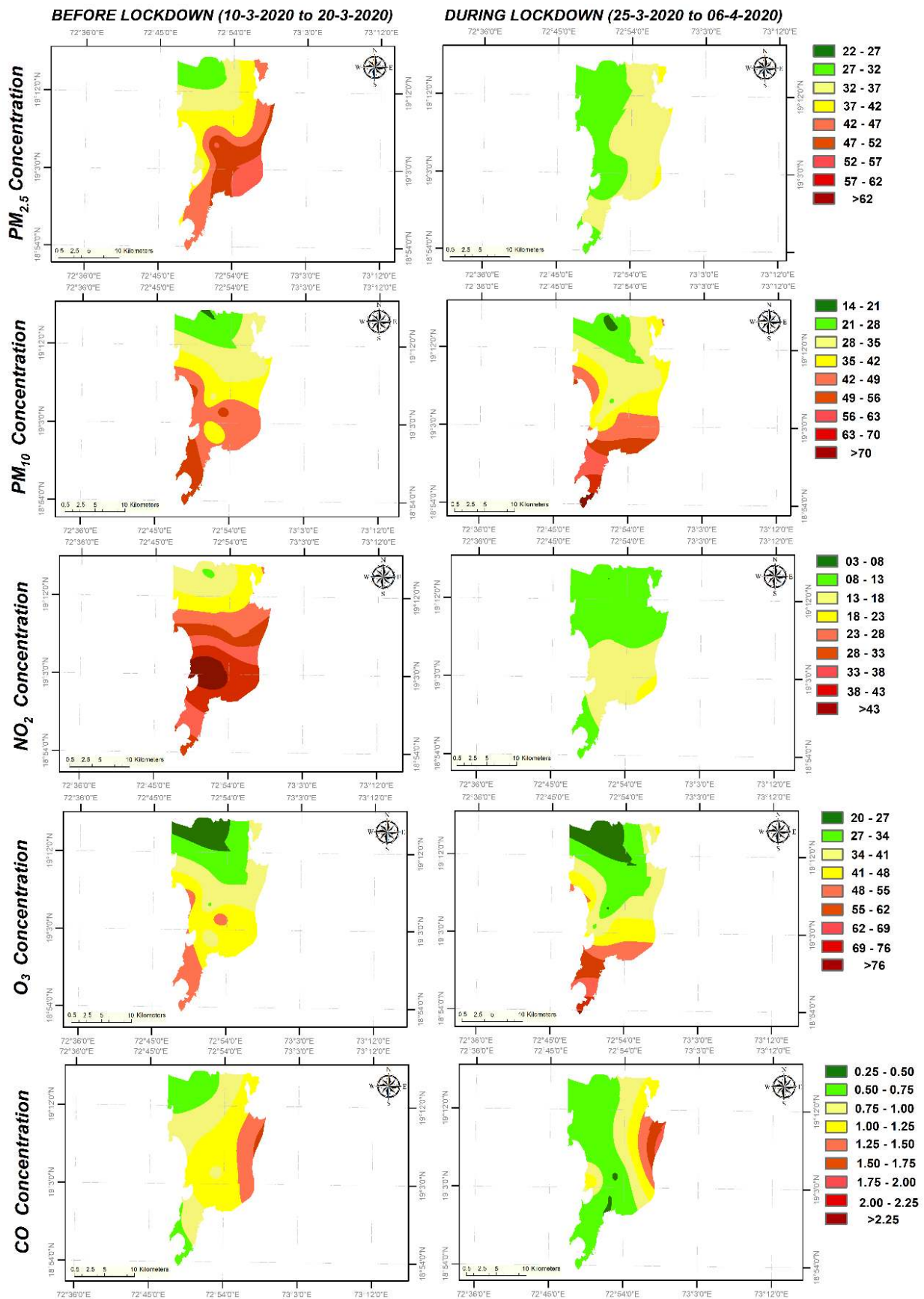


Fig. 4(b). Spatiotemporal variations in air quality due to the lockdown period compared with before lockdown period in Mumbai (PM , NO_2 and O_3 are in $\mu g m^{-3}$ and CO in $mg m^{-3}$).

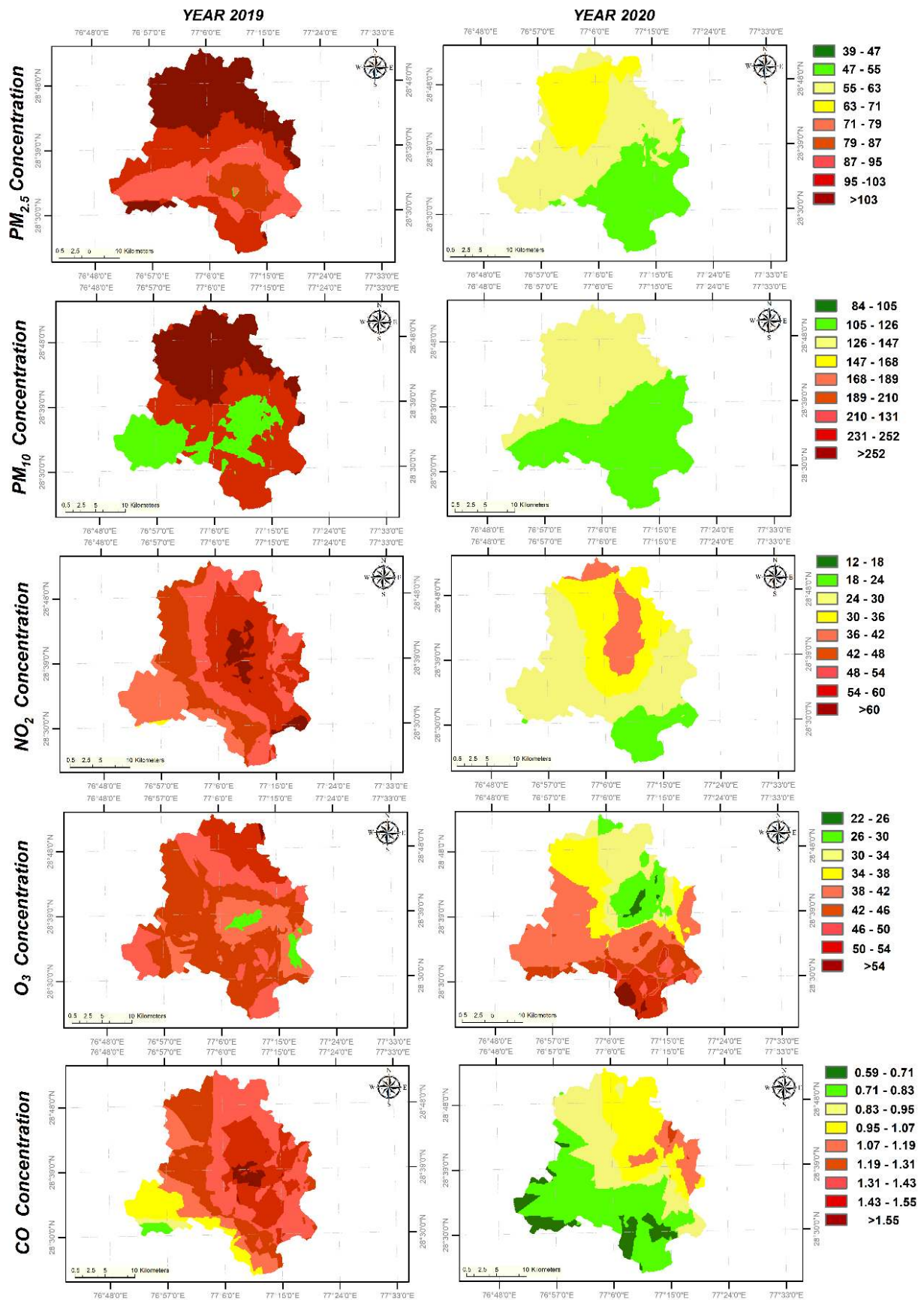


Fig. 4(c). Spatiotemporal variations in air quality in Delhi due to the lockdown in March–April 2020 vs. last year March–April 2019 (PM , NO_2 and O_3 are in $\mu g m^{-3}$ and CO in $mg m^{-3}$).

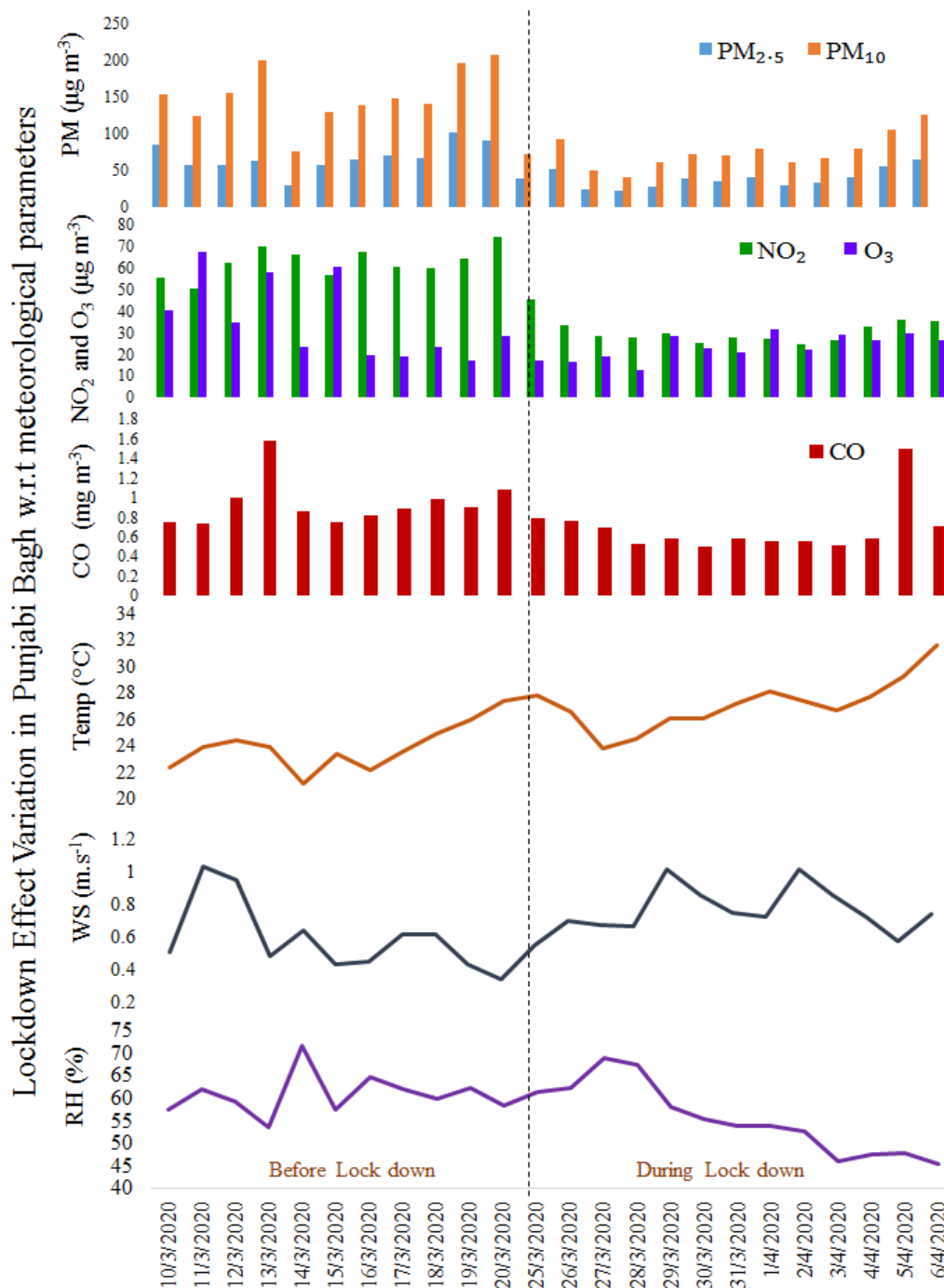


Fig. 5. Trend analysis showing the effect of lockdown period and meteorological parameters on air quality in Delhi - Punjabi Bagh monitoring station.

humidity and particulates (RSPM and SPM) and advocated the influence of humidity for subsiding particulates near the surface. Therefore, along with the lockdown, meteorological parameters also played a significant role in the reduction in air pollution levels in most of the places. Sharma *et al.* (2020) reported that in north India, predominant wind directions were south and southwest with average WS of around 1.5 m s^{-1} , which further results in more dilution to air pollution levels in northern India. In contrast to the WS in northern India during the March and April months of 2020, it was lower in

the southern India, i.e., $\sim 1.0 \text{ m s}^{-1}$ and eastern India, i.e., 0.7 m s^{-1} as reported by Sharma *et al.* (2020). Considering the variations in the meteorological parameters in the selected megacities as per their geographical locations, the decline in air pollutant concentrations was more pronounced in Delhi and Mumbai, thus, indicating the impact of meteorology on air pollution levels amidst the lockdown period as well. Further, similar time series analysis for other megacities have also been presented in Figs. S1–S4 in S3 for more clarity.

Challenges, Learnings and Solutions: Findings from Expert Opinion Survey

The impact of COVID-19 lockdown on the air quality of the country was unanimously accepted by 24 out of the 25 experts who responded to the questionnaire (the response rate of the online survey was 64%). Experts mention that lockdown gave several opportunities to rethink and learn beyond our boundaries to reform the infrastructure and policy measures to reduce the overall impacts on the economy and environment together (Schwartz, 2020). Majority of the experts emphasized that a lot of learnings w.r.t environmental management, especially air pollution can be learnt from this countrywide lockdown. It was highlighted that the lockdown has helped us in understanding the best-case scenario to measure the air quality gains along with the major contributors. Nearly 70% of the experts indicated that reforms in transportation sector like avoiding unnecessary travel and adopting the concept of tele-working can yield significant benefits in terms of air pollution reduction in the business-as-usual days. Expert also highlighted that non-essential activities can be identified and controlled to gain measurable air quality benefits. It is important to highlight that transportation, industries, construction and demolition, road dust, and biomass and refused burning were considered as the most important sources which led to the reduction in air pollution levels in the country.

All the experts stated that it is crucial to adopt an integrated strategy to manage the economy and environment together to plan the future development activities in India post COVID-19. They also highlighted that there would be a decline in the funds allocated to environmental activities in order to recover the economy. In view of the above concerns, all the experts were asked to report the possible challenges that the country might face after the lockdown is over. They were also asked to suggest the possible solutions to overcome the challenges which can be used to devise the future strategies of the country. The findings of the expert responses revealed that these challenges and their possible solutions could be grouped in three areas of development, i.e., social, environmental and economic. An effort was made to consolidate and identify the most frequently highlighted challenges and their solutions. Table 2 summarizes the findings of the expert opinion gathered from the survey along with a comprehensive understanding about their perspectives. In light of the findings of the expert opinion survey, it can be concluded that the present air quality scenarios taught a lesson to all the stakeholders belongs to scientific, academic, policy-decision, and politics how to handle the future air quality scenarios and which sectors need to be controlled, how much, and when (Wang *et al.*, 2020).

CONCLUSIONS

- The study evaluated spatiotemporal variations in five criteria pollutants in Delhi, Mumbai, Chennai, Bangalore, and Kolkata over two time periods. *First*, between March–April 2019 and March–April 2020 and *second* between 10th to 20th March 2020 (before the lockdown) and 25th to 6th April 2020 (during the lockdown). The

results highlighted a statistically significant decline in all the pollutants across all the megacities except for O₃.

- In Delhi, there is a significant decrease of 41%, 52%, 50%, and 29% in PM_{2.5}, PM₁₀, NO₂ and CO concentrations, respectively, whereas ~7% increase in O₃ concentrations during the lockdown phase in comparison to before lockdown phase. A significant decrease in concentrations of PM_{2.5} from 89 to 48 $\mu\text{g m}^{-3}$, PM₁₀ from 222 to 97 $\mu\text{g m}^{-3}$, NO₂ from 48 to 25 $\mu\text{g m}^{-3}$, CO from 1.30 to 0.75 mg m^{-3} , and O₃ from 45 to 38 $\mu\text{g m}^{-3}$ amounting to 32%, 34%, 27%, 27%, and 11% reductions, respectively, was observed between March–April 2019 and March–April 2020 in Delhi.
- Chennai also witnessed a decline of ~14% (from 30 to 26 $\mu\text{g m}^{-3}$) in PM_{2.5}, ~30% (10 to 7 $\mu\text{g m}^{-3}$) in NO₂, ~25% (0.75 to 0.56 mg m^{-3}) in CO and a rise of ~3% (43 to 44 $\mu\text{g m}^{-3}$) in O₃ concentrations in the ‘during’ lockdown phase in comparison to ‘before’ lockdown phase in the year 2020. A similar decline in other pollutants like PM₁₀, NO₂ and CO was observed during the lockdown phase in comparison to the before lockdown phase in other megacities as highlighted in previous sections of the manuscript.
- The concentrations of PM_{2.5}, PM₁₀, NO₂, CO, and O₃ in Mumbai, Chennai, Bangalore, and Kolkata in March–April 2020 was estimated to be lower in comparison to the concentration levels in March–April 2019. The concentrations of air pollutants in Bangalore declined from 55 to 29 $\mu\text{g m}^{-3}$ (~47%), 118 to 71 $\mu\text{g m}^{-3}$ (~40%), 34 to 15 $\mu\text{g m}^{-3}$ (~56%), 1.01 to 0.86 mg m^{-3} (~15%) and 57 to 45 $\mu\text{g m}^{-3}$ (~21%) for PM_{2.5}, PM₁₀, NO₂, CO and O₃, respectively in March–April 2020 as compared with March–April 2019.
- A similar trend in reduction of air pollutant concentrations from 55 to 39 $\mu\text{g m}^{-3}$, 102 to 68 $\mu\text{g m}^{-3}$, 48 to 16 $\mu\text{g m}^{-3}$, 0.6 to 0.5 mg m^{-3} in PM_{2.5}, PM₁₀, NO₂, and CO, respectively, was observed in Kolkata in March–April 2020 in comparison to March–April 2019. This decline in the concentration levels could be attributed to the complete travel lockdown and suspension of all the non-essential travel activities in all the cities. The Timeseries analysis showed meteorology also played an essential role in the dispersion of air pollutants in all the megacities.
- In addition, the expert’s opinion survey highlighted that the most critical challenge for India and even other countries would be uplifting the economy by bringing back all the businesses after the lockdown period is over. Furthermore, reviving the economy is going to be the topmost priority of the government, which might forego the environmental benefits gained amidst the lockdown period.
- Experts highlighted that the COVID-19 situation gave a lot of opportunities to reform our existing infrastructure and policies to make the system more resilient and to adapt to such incidents in the future (Musselwhite *et al.*, 2020). For examples, the government can encourage e-governance initiatives, encourage work from home policy for corporates and various other businesses, improved health infrastructure to tackle such issues, invest in

Table 2. Summary of responses received from experts in terms of potential challenges and possible solutions to manage economy and environment after lockdown in India.

Aspects	Potential Challenges	Feasible Solutions
SOCIAL	<ul style="list-style-type: none"> ▪ Acceptance of the ‘new normal’ among mass population. The COVID-19 impact is going to be in the country for a long time. Thus, acceptance of the fact that social distancing, maintaining hygiene and being conscious about the situation should be inculcated as a habit among the residents of the country is a prominent challenge. 	<ul style="list-style-type: none"> ▪ Self-determination and understanding at individual level about their responsibility for the welfare of the society and country. ▪ Adoption of work from home strategies wherever and whenever possible. ▪ Strategic planning required to increase investment in public health sector.
ENVIRONMENTAL	<ul style="list-style-type: none"> ▪ Increased burden on public health infrastructure. ▪ Degradation in air quality, probably to higher levels than the business-as-usual scenario attributable to increased usage of private modes of transportation in comparison to public transport due to the perception about the public transport in terms of lack of safety due to COVID-19 infection and less management by the agencies in terms of proper sanitisation, etc. ▪ Implementation of air pollution control strategies and plans ▪ Rise in air pollution related co-morbidity in COVID-19 infected patients. ▪ Medical waste in view of COVID-19 may be a major threat if not handle properly. 	<ul style="list-style-type: none"> ▪ Implementation of 'odd-even' strategy for work offices and private vehicles. ▪ A quick transition from fossil fuels-based energy system to renewable and cleaner energy alternatives. ▪ Plantation of trees with high surface area to volume ratio in the pollution hotspot areas. ▪ Regulating construction and demolition activities in urban areas. ▪ The National Clean Air programme (NCAP) needs to scale up significantly to ensure that rapid economic growth and meeting National Ambient Air Quality Standards (NAAQs) are aligned to ensure ground level implementation. ▪ Special collection and treatment mechanisms for medical waste to be used as suggested by the CPCB: Guidelines for Handling, Treatment, and Disposal of Waste Generated during Treatment/Diagnosis/ Quarantine of COVID-19 Patients (March 2020).
ECONOMIC	<ul style="list-style-type: none"> ▪ Recovery of the economic losses and GDP incurred due to the lockdown considering COVID-19. ▪ Prioritization of economic gains in comparison to environmentally sustainable solutions by the local, state as well as national government. ▪ Employment crises and lack of job security as evident from other parts of the world. 	<ul style="list-style-type: none"> ▪ Increase in industrial production. ▪ Support to small scale industry and their modernization. ▪ Recovery and speeding of infrastructure related projects. ▪ Strategic Low Carbon Development Plans to ensure sustainable economic development. ▪ Financial support to make the country self-reliant by having investment in various sectors for stimulating the present economy and making the infrastructure more resilient.

online education infrastructure to have a better adaptation to such incidence in future, investment in sustainable infrastructure, better policy to reduce the vulnerability of migrant workers under such situations, financial support micro, small and medium enterprises, etc.

- Integrated planning that caters to the environment and economy together came out as an essential suggestion from the experts, and they also highlighted to align all the policy decisions in line with the Sustainable Development Goals (SDGs).
- Most important solutions suggested by the experts to have a quick transition from fossil fuels based energy system to renewable and cleaner energy alternatives, sustainable public transport; stringent emissions control measures and proper collection and scientific treatment

and disposal of municipal and medical wastes in the cities to have a clean and breathable environment in the future.

DECLARATION OF COMPETING FOR INTEREST

The authors declare that there are no financial and personal interests to influence the results and work presented in the manuscript.

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AUTHOR STATEMENT

Suresh Jain: Concept, Methodology, Data presentation, Analyses and writing the original manuscript.

Tanya Sharma: Methodology, Data collection, Data analysis, Writing the original manuscript.

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <http://www.aaqr.org>.

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