Short-term impacts of air pollutants in three megacities of India during COVID-19 lockdown

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Abstract

Lockdown was imposed by the Indian government in the month of March 2020 as an early precaution to the COVID-19 pandemic which obstructed the socio-economic growth globally. The main aim of this study was to analyse the impact of lockdown (imposed in March and continued in April 2020) on the existing air quality in three megacities of India (Delhi, Mumbai and Kolkata) by assessing the trends of PM₁₀ and NO₂ concentrations. A comparison of the percentage reduction in concentrations of lockdown period with respect to same period in year 2019 and pre-lockdown period (February 14–March 24) was made. It was observed from the study that an overall decrease of pollutant concentrations was in the ranges of 30–60% and 52–80% of PM₁₀ and NO₂, respectively, in the three cities during lockdown in comparison with previous year and pre-lockdown period. The overall decrease in concentrations of pollutants at urban sites was greater than the background sites. Highest decline in concentrations of PM₁₀ were observed in Kolkata city, followed by Mumbai and Delhi, while decline in NO₂ was highest in Mumbai. Results also highlighted that capital city Delhi had the worst air quality amongst three cities, with particulate matter (PM₁₀) being the dominant pollutant. Although COVID-19 has significantly affected the human life considering the mortality and morbidity, lockdowns imposed to control the pandemic had significantly improved the air quality in the selected study locations, although for the short amount of period.

Keywords PM₁₀ · NO₂ · Megacities · Trend analysis · India

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1 Introduction

Urbanization and industrialization are viewed to be the impelling forces behind the economic growth of a country. However, the demographic expansion of cities due to urbanization has led to uncontrolled and chaotic industrial advancements and vehicular sources. These have become the primary elements of environmental concern on a global scale, especially in developing countries (Sharma and Sharma, 2016).

The sources of air contaminants are primarily due to different anthropogenic activities such as industrial and automobile emissions, agriculture and biomass burning, construction activities, pyrotechnic display and other such associated activities (Guttikunda et al., 2014; Hama et al., 2019). Moreover, natural events like dust and desert storms, forest fires, volcanic eruptions, sea spray aerosols and pollen grains also severely affect the air quality (Almeida et al., 2005). These sources release gaseous pollutants include the carbon monoxide (CO), sulphur dioxide (SO₂) and oxides of nitrogen (NO, NO₂, NO_x), ozone (O₃), particulate matter in different size range (PM₁₀, PM_{2.5}) and heavy metals (Guttikunda et al., 2014; Sharma et al., 2020).

There have been several epidemiological research studies which have related air pollution with human health and have highlighted the increase in morbidity and mortality due to air pollution (Brunekreef & Forsberg, 2005; Dockery et al., 1993; Karthik et al., 2017; Yao et al., 2015). The adversity of exposure to air pollution is it can result in several kinds of cardio-pulmonary diseases and various types of cancers particularly in a vulnerable population of society which includes in particular infants and aged people (Ganguly et al., 2015; Prasad & Sanyal, 2016). In a recent study conducted by Singh, Mhawish et al. (2020), Singh, Dey et al. (2020), Singh Singh and Biswal (2020c), Singh et al. (2020d)) highlighted the effects of multiple air pollutants (BC, PM_{2.5}, PM₁₀, NO₂) on all-cause non-accidental mortality in Varanasi, a air pollution hotspot in Indo-Gangetic Plain. Samoli et al. (2011) reported that a rise of 10 µg/m³ PM₁₀ concentrations increased the cases of paediatric asthma by 2.54% in a study conducted in Athens, Greece. Pollutants like sulphur and nitrogen oxides, ground-level ozone, volatile organic compounds (VOCs), carbon monoxide, polycyclic aromatic hydrocarbons (PAHs) are detrimental to human as they can cause afflictions of the respiratory system such as chronic obstructive pulmonary diseases (COPD), bronchitis, lung carcinoma, breakdown of the central nervous system and even epidermal diseases (Karthik et al., 2017; Manisalidis et al., 2020). Prolonged exposure to degraded air quality creates a potential risk to human health (Brunekreef & Holgate, 2002). This leads to a rise in fatality and illness rates which affect the existing public health system and also hike in medical costs for individuals. Thus, the affected efficiency of the skilled workforce due to air pollution can sooner or later hamper the economic growth of the country (World Bank report: "The cost of air pollution", 2016). It was also reported in the same report that India incurred losses equivalent to 7.69% of India's gross domestic product (GDP) due to air quality degradation.

Most of the South Asian cities are facing challenges in maintaining air quality standards. The air quality in these cities is highly deteriorated, due to high concentration levels of particulates and other criteria pollutants such as NO_x, SO₂ (Kanawade et al. 2020; Gurjar et al. 2016). Developing countries like India have also been experiencing population explosion, industrial development, urbanization and energy usage which is detrimental to the overall environment and air quality (Gurjar et al., 2016). Indian metropolitans like Delhi, Kolkata, Mumbai and other such cities are massively overpopulated and still growing, which have stressed the functioning of the basic civic and environmental utilities.

Hence, these cities fail in meeting the health-based standards particularly due to adversity of air pollution occurring due to traffic and industrial emissions (Ganguly et al., 2019; Gurjar et al., 2010; Kumar et al., 2015; Wenzel et al., 2007).

Novel coronavirus disease, more commonly known as COVID-19, broke out in Wuhan city located in Hubei province of China in late 2019 and has been declared as a pandemic by the World Health Organization in March 2020 (Kumar & Morawska, 2019). Till 3 February 2021, total COVID-19-related cases reported globally are about 105 million, out of which 2.28 million deaths have been recorded. Entire and partial lockdowns have been observed in most of the affected countries around the world. India has also been experiencing the challenges and problems analogous to other countries in the world. In India, COVID-19 cases are rising rapidly and figures stand at 10.8 million with 155,000 deaths as of 3 February 2021 (MoHFW 2021). A 14-h voluntary public curfew was organized on March 22 following which a complete lockdown was ordered by the Indian government on March 24. First phase of lockdown was implemented in the country, starting from 25 March till 14 April 2020. This led to the suspension of all public and private transports with exemption to the essential services as well as the closure of offices, institutions and universities, shopping malls and restaurants. Observing the severity of the situation and increasing cases, phase 2 of lockdown was implemented from 15 April to 3 May 2020 with conditional relaxations.

The present study provides a detailed analysis for lengthened duration to cover the extended phase of lockdown in Delhi, Mumbai and Kolkata. In addition to the consideration of increased lockdown phase, the present study also presents the variation in levels of pollutants at the background and urban monitoring stations of the city which are considerably low emission zones and air pollution hotspots in the cities. Moreover, the inadequacy of monitoring stations in different cities of India has been mentioned which is a possible hindrance in precise quantification of the ambient air quality of these cities.

Further, we have assessed the impacts of lockdown on air quality at three Indian metropolitan cities namely Delhi, Mumbai and Kolkata and discussed strategies that can help tackle the degrading air quality in India in post-COVID-19 environments. The study focusses on the short-term change in air quality observed due to the implementation of the lockdown policy of the GoI. Thus, the objectives of this work are to (i) provide the insights on plight of Indian metropolitan cities in the context of air pollution; (ii) analyse and compare the air quality of Delhi, Kolkata and Mumbai cities; and (iii) assess the impact of the two phases of lockdown on three megacities of India.

2 Literature review

Rising rates of morbidity and mortality are the primary concern of COVID-19. Restrictions on economic activities during the lockdown has hampered the local as well global economy significantly, worst affected the daily wage earners and migrant labourers. However, it has been observed that the ban on vehicular movement and industrial activities has significantly improved air quality across the globe (Bao & Zhang, 2020; Jain & Sharma, 2020; Kumar et al., 2020).

Recent studies and researches conducted during the lockdown period have reported the decline in concentrations of air pollutants as a result of decreased traffic and industrial emissions. Nakada and Urban (2020) reported the impacts of partial lockdown on air quality in São Paulo– Brazil. Tobias et al. (2020) observed approximately 31% decrease in

particulate matter and 51% reduction in NO_2 in Barcelona during the two-week lockdown in Spain. Xu et al. (2020) investigated the change in air quality during the lockdown in Chinese cities of Wuhan. Travaglio et al. (2020) explored the potential association between air quality and COVID mortality in England. Fattorini and Regoli (2020) analysed the role of degraded air quality as a potential risk in COVID 19 outbreak in Italy. The same study suggested that mitigation of prolonged atmospheric pollution problems can improve human health, thereby reducing the risk of an epidemic outbreak. Han et al. have highlighted the association of $\text{PM}_{2.5}$ concentrations with the rate of a number of confirmed COVID cases in Wuhan, China. Further, Singh, Mhawish, et al. (2020), Singh, Dey, et al. (2020), Singh Singh, and Biswal (2020c), Singh et al. (2020d)) reported a significant linkage between short-term $\text{PM}_{2.5}$ exposure and daily COVID-19-confirmed cases.

Similar trends have also been observed in India. Jain and Sharma (2020) assessed the overall socio-economic impact of lockdown in five megacities of India. Mahato et al. (2020) reported the impact of lockdown on air quality for Delhi city. The following paragraph summarizes some of the results of the studies conducted during the implementation of lockdown due to COVID.

In addition to the above, various studies have been conducted in India demonstrating the variations in air quality due to implementation of lockdown due to COVID -19. To prevent the spread of COVID-19, lockdowns imposed were somewhat helpful in containing the pandemic, but significantly improved the air quality (Girdhar, 2020; Srivastava, 2020). Table 1 highlights the results of some recent studies conducted in India for the assessment of air quality during the lockdown period. It can be observed from these studies that there has been a substantial reduction in major air pollutants (e.g. PM_{10} , $\text{PM}_{2.5}$, CO, NO_2), attributed to the decline in anthropogenic activities particularly vehicular and industrial (Kumar et al. 2020; Mahato et al. 2020; Sharma et al., 2020). Biswas and Ayantika (2020) used satellite data to explore the effect of lockdown on NO_2 , formaldehyde (HCHO), SO_2 and AOD over India and showed large-scale decrease in all the measured parameters spanning almost the entire Indian landmass. Further, Sharma et al. (2020) used a WRF-AERMOD model to highlight an overall decline of 43, 31, 10 and 18% in levels of $\text{PM}_{2.5}$, PM_{10} , CO, and NO_2 during the lockdown period in comparison to similar period in previous years. Navinya et al. 2020 have highlighted that greater reductions in air pollutants have been observed in northern region of country compared to the other parts of the country. Similarly, Mahato et al. (2020) reported greater than 50% reduction in $\text{PM}_{2.5}$ and PM_{10} concentrations in Delhi city. Delhi, Kolkata and Mumbai have greater population and are among the highly industrialized areas within the country, where ambient concentrations of particulates (PM_{10} and $\text{PM}_{2.5}$) are generally above the annual guideline values of 10 (for $\text{PM}_{2.5}$) and 20 (for PM_{10}) $\mu\text{g m}^{-3}$ as prescribed by WHO (Kumar et al. 2020; WHO, 2016). Acharya et al. (2021) used satellite observations to analyse the aerosol optical depth (AOD), NO_2 and SO_2 for Southeast Asia, Europe and USA and observed significant reductions in AOD and NO_2 emissions due to imposition of lockdowns due to COVID. However, same study showed increase in SO_2 concentrations due to increase in emissions from power plants due to rise in energy demand because of people staying and working from homes. Another study conducted by Biswal (2020b), have mentioned that coal-based power plants continued to be air pollution hotspots during the lockdown. In India, work-place-related mobility reduced drastically in India due to implementation of lockdown, which is one of the major reasons of the short-term but significant improvement in air quality in regions across the country which on usual days are highly polluted (Sannigrahi et al., 2020). Around 17.5% reduction in mean concentrations of particulate matter

Table 1 Summary of the recent studies on assessment of air quality during lockdown in India

Study	Study area	Major Outcomes
Biswal et al. (2020a)	India	Analysed the NO ₂ concentrations in India for lockdown period (25 March–14 April 2020) using satellite data Results showed a reduction of almost 12% in tropospheric concentration of NO ₂ in India
Biswal et al. (2020b)	India	Estimated the changes in NO ₂ concentrations in India for lockdown period (25 March–3 May 2020) using satellite data There was a substantial reduction in NO ₂ levels in urban areas, and it was directly proportional to urban size and population density
Biswas and Ayanika (2020)	India	Used satellite data to explore the effect of lockdown on NO ₂ , HCHO, SO ₂ and AOD Greatest reduction was observed in NO ₂ , followed by SO ₂ and HCHO
Dumka et al. (2020)	Delhi NCR	Examined particulate matter concentrations and air pollutants (NO _x , SO ₂ , CO, NH ₃ and O ₃) at 63 stations in Delhi-national capital region Reductions recorded were: PM ₁₀ (–46 to –58%), PM _{2.5} (–49 to –55%), NO ₂ (–27 to –58%), NO (–54 to –59%), CO (–4 to –44%), NH ₃ (–2 to –38%)
Jain and Sharma (2020)	Delhi, Mumbai, Chennai, Kolkata and Bangalore	Evaluated the spatiotemporal variations in five megacities of India 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) A significant decline was observed in all megacities for all pollutants PM _{2.5} reduced by ~41% during lockdown in Delhi when compared to lockdown, PM ₁₀ by 52%, NO ₂ by 51% and CO by 28%. Similar reductions were observed for other megacities
Kumar et al. (2020)	Chennai, Delhi, Hyderabad, Kolkata and Mumbai	Assessed the trends of fine particulate matter (PM _{2.5}) from 2015–2020 for lockdown period in five cities Substantial reductions were observed in PM _{2.5} particularly in Delhi city
Mahato et al. (2020)	Delhi	Analysed seven criteria pollutants (PM ₁₀ , PM _{2.5} , SO ₂ , NO ₂ , CO, O ₃ and NH ₃) in Delhi for pre-lockdown periods and during the lockdown Particulates (PM ₁₀ and PM _{2.5}) showed maximum reduction (> 50%) with respect to pre-lockdown period

Table 1 (continued)

Study	Study area	Major Outcomes
Navinya et al. (2020)	17 Indian cities	PM ₁₀ , PM _{2.5} , SO ₂ , NO ₂ and CO were used to quantify the change in air quality during the lockdown period Northern region showed greater decline for all the measured pollutants Meteorological changes observed were minimal, while pollution levels reduced significantly Estimated the change in air quality during lockdown period (24 March–20 April 2020) compared to pre lockdown period (1 January–23 March 2020) by analysing PM ₁₀ , PM _{2.5} , SO ₂ , NO ₂ , CO, and O ₃ in Gujarat state The concentrations of PM _{2.5} , PM ₁₀ and NO ₂ were reduced by 38–78%, 32–80% and 30–84%, respectively Moreover, there was a reduction of 3–55% in CO, while O ₃ improved by 16–48%
Selvam et al. (2020)	Gujarat	Analysed six criteria pollutants (PM ₁₀ , PM _{2.5} , SO ₂ , NO ₂ , CO and O ₃) during March 16 to April 14 from 2017 to 2022 in 22 cities covering different regions of country There was a decrease of around 43, 31, 10 and 18% in PM _{2.5} , PM ₁₀ , CO and NO ₂ , while O ₃ increased by 17% in India during lockdown period compared to previous years Performed the six-year trend and exceedance analysis of PM _{2.5} for five metropolitan cities of India
Sharma et al. (2020)	22 cities in different regions of India	Delhi was observed to be the highest polluted cities among the cities considered for study followed by Kolkata, Mumbai, Hyderabad and Chennai The six-year trend analysis performed for five cities showed a statistically significant decreasing trend ranging from 1.5 to 4.19 µg/m ³ (2%–8%) per year
Singh et al. (2020c)	Chennai, Kolkata, Hyderabad, Mumbai and New Delhi	Temporal and diurnal changes of six criteria air pollutants (PM _{2.5} , PM ₁₀ , NO ₂ , O ₃ , CO, SO ₂) were analysed for lockdown period across regions of India Four pollutants except SO ₂ and O ₃ reduced significantly in all the regions SO ₂ and O ₃ showed mixed variations
Singh et al. (2020d)	India	

(PM₁₀ and PM_{2.5}) was observed in city of Kolkata during lockdown particularly due to reduced human mobility (Bera et al., 2020). Closing of markets, industries and transport resulted in decline in concentrations of PM_{2.5} in major cities around the world including Delhi and Mumbai (Chauhan & Singh, 2020). Singh et al. (2020c) estimated the temporal and diurnal changes of criteria pollutants like PM_{2.5}, PM₁₀, NO₂, CO, O₃ and SO₂ for regions across India by using real-time monitoring data from CPCB and observed significant reductions in particulate pollutants, NO₂ and CO, while the results of SO₂ and O₃ showed mixed variation. In a recent study presented by Dumka, 2020 used WRF-CHIMERE model and observed that reductions in PM₁₀, PM_{2.5}, NO₂ during lockdown in Delhi NCR region ranged between 27 to 59%. Similarly, Biswal et al. (2020a, 2020b) observed decrease in NO₂ concentrations during lockdown period compared to last year using satellite-based ozone monitoring instrument sensor data for India. Table 1 highlights very recent studies conducted in India for the assessment of air quality during the lockdown period. It can be observed from these studies that there has been a substantial reduction in major air pollutants (e.g. PM₁₀, PM_{2.5}, CO, NO₂), attributed to the decline in anthropogenic activities particularly vehicular and industrial (Kumar et al., 2020; Mahato et al., 2020; Sharma et al., 2020).

3 Materials and methods

The following section presents an outline on the considered pollutants including their monitoring techniques to determine their concentrations. The section also highlights the selection and availability of the monitored data for the study period and the different methods used to show their effects. Overall, the methodology of the study is shown in Fig. 1.

Fig. 1 Schematic representation of the methodology of the study

3.1 Monitored parameters

We assessed the air quality of the three Indian metropolitan cities by studying the levels of particulate matter (PM₁₀) pollutant and a gaseous pollutant (NO₂). The selected pollutants have been the global concern in terms of damage caused to the human health and the environment. Pant et al. (2018) have reported deterioration of air quality due to PM₁₀ in Indian cities, particularly located in north and central part of the country. The issue rising trend of oxides of nitrogen in urban regions of India have been mentioned by Gurjar et al. (2016) and Goel and Guttikunda (2015). Further, they have been listed as criteria pollutants in the National Ambient Air Quality Standards (Gorai et al. 2018) which leads to further credence in their selection. The monitoring operation involving these pollutants at all the three study locations complies with the methodology and the guidelines as framed by CPCB. Methods used for measurement of pollutants considered for analysis are mentioned in Table 2.

To summarize, the NO₂ concentrations are determined using the modified Jacob and Hochheiser method, while chemiluminescence analyser is used for automatic measurements. Similarly, tapered element oscillating membrane (TEOM) or beta attenuation is used for real-time detection of particulate matter, wherein a respirable dust sampler (RDS) fitted with a cyclonic connector as used to determine the PM₁₀ concentrations. The average flow rate of air in the RDS is generally maintained at about 1.1 m³/min. The particulate matter is collected on a filter paper, and the mass of the particulate matter collected is determined in the laboratory which is divided by the volume of air sampled and being reported in ppm units. The details of methods and techniques used by CPCB for measurement of pollutant have been mentioned in report specifying guidelines for manual and real-time sampling and analysis of pollutants (Ganguly et al., 2019; CPCB 2013).

3.2 Data Collection and Analysis

The study for understanding the impact of lockdown was conducted in three metropolitan cities of India namely, Delhi, Mumbai and Kolkata. The daily air pollutant concentration data (measured in µg/m³) for PM₁₀ and NO₂ was downloaded from the online repository of CPCB (<https://app.cpcbcr.com/>) for the above-noted three metropolitan cities of India. The data were procured for the time period of March 25 to May 3 for year 2019 and 2020 to analyse the relative change in concentrations which might have eventually occurred due to emission reductions during lockdown. The list of air quality monitoring stations installed across the various locations in three cities are highlighted in Fig. 2. The quality of data is ensured by the CPCB, Indian Meteorological Department and State Pollution

Table 2 Methods of measurements of different pollutants considered for study

Pollutant	Method of Measurement
Nitrogen dioxide (NO ₂) µg/m ³	Modified Jacob and Hochheiser (Na-Arsenite)
	Chemiluminescence
Particulate matter (size less than 10 µm) PM ₁₀ µg/m ³	Gravimetric
	TOEM
	Beta attenuation

Fig. 2 Map of India showing geographic locations of three metropolitan cities of India along with the air quality monitoring network

Control Boards by regular calibrating of the air quality monitors (Hama et al. 2019; Kumar et al. 2014). However, it was observed that data for some stations were unavailable. For example, pollutant reading for four stations were missing from the data set for Delhi. However, observing the number of monitoring stations installed in three metropolitan cities, this study also noted the inadequacy of monitoring stations represent the air quality of Mumbai and Kolkata city according to IS 5182: part 14 (2000).

The relative change in daily concentrations of pollutants observed during lockdown in comparison with the pre-lockdown period (14 February–24 March) and same period in year 2019, respectively, was calculated. Furthermore, a statistical inferential tool “*paired t test*” was used to validate the significance of changes observed in two phases of lockdown. Dewulf et al. (2016) used paired *t* test to check the differences between various scenarios (hourly vs daily pollutant concentration, week vs weekend days etc.) undertaken in study for assessment of air quality, and hence, this statistical test is widely used for interpretation of results.

Daily exceedance was calculated for the entire study period to record the frequency of these pollutants exceeding the national standards. In this context, the concept of exceedance factor was utilized. *Exceedance factor* is the ratio of the mean concentration of a selected pollutant to its standard value. It is represented as follows (Kumar et al. 2014):

$$\text{Exceedance Factor} = \frac{\text{Measured concentration of pollutant}}{\text{Standard Concentration of pollutant}}$$

Thus, air quality with respect to EF can be classified into four different levels (a) critical pollution (when $EF > 1.5$); (b) high pollution (when EF is between 1 and 1.5); (c) moderate pollution (When EF lies between 0.5 and 1); (d) low pollution when $EF < 0.5$) (Kumar et al. 2014).

Further, to assess the change in overall air quality, we determined the air quality index (AQI) which is a comprehensive tool specifically employed to disseminate the information regarding the ambient air quality to the general public. It helps in understanding the quality of air by providing the definite number expressing the measured air quality in respect of its human health impacts (Ganguly and Kumar, 2018). CPCB uses the formula based on “linear segmented principle” for determination of AQI (National Air Quality Index, CPCB report):

$$I_p = \left[\frac{I_{HI} - I_{LO}}{C_{HI} - C_{LO}} \right] (C_p - C_{LO}) + I_{LO}$$

where I_p = the AQI for pollutant p , C_p = the actual ambient concentration of pollutant p , C_{hi} = the concentration breakpoint given in Table 3 that is $\geq C_p$, C_{lo} = the concentration breakpoint given in Table 3 that is $\leq C_p$, I_{HI} = the sub-index value corresponding to C_{HI} , I_{LO} = the sub-index value corresponding to C_{LO} . The AQI is calculated for all of the measured pollutants, and the uppermost value is considered to be the overall AQI.

To elaborate further, we have also assessed and compared the background and urban contributions, respectively. Background sites in all three cities were assumed to be the monitoring stations which recorded the lowest concentrations observed across the study period. In principle, the monitoring locations Aya Nagar, Borivali East and Bidhannagar were selected as background sites for Delhi, Mumbai and Kolkata, respectively, and have been marked in colour red in Fig. 2. The individual concentrations of pollutants at urban sites were averaged to study the combined effect of these sites on air quality of the respective cities. Diurnal profiles were also prepared separately for lockdown and pre-lockdown period to understand the changes in day-night concentrations of PM_{10} and NO_2 .

Table 3 AQI category, sub-index and breakpoint pollutant concentrations as per CPCB

AQI Category, Pollutants and Health Breakpoints								
AQI Category (Range)	PM_{10} 24-hr	$PM_{2.5}$ 24-hr	NO_2 24-hr	O_3 8-hr	CO 8-hr (mg/m^3)	SO_2 24-hr	NH_3 24-hr	Pb 24-hr
Good (0-50)	0-50	0-30	0-40	0-50	0-1.0	0-40	0-200	0-0.5
Satisfactory (51-100)	51-100	31-60	41-80	51-100	1.1-2.0	41-80	201-400	0.5 – 1.0
Moderately polluted (101-200)	101-250	61-90	81-180	101-168	2.1- 10	81-380	401-800	1.1-2.0
Poor (201-300)	251-350	91-120	181-280	169-208	10-17	381-800	801-1200	2.1-3.0
Very poor (301-400)	351-430	121-250	281-400	209-748*	17-34	801-1600	1200-1800	3.1-3.5
Severe (401-500)	430 +	250+	400+	748+*	34+	1600+	1800+	3.5+

*One hourly monitoring (for mathematical calculations only)

The meteorological aspect in our research was not considered as it has been reported in Sharma et al. (2020), that no significant variations in meteorological conditions were observed particularly during the lockdown period in India. Similarly, Nakada et al. (2020) conducted in São Paulo, Brazil, noted that reduction in pollutants during lockdown was not influenced by changes in meteorological and dispersion conditions. In a recent study conducted by Dumka et al. 2020 for the region of Delhi NCR also reported that drastic change in pollutant concentrations during lockdown period could be attributed to limited anthropogenic emissions and effect of meteorological conditions were minimum. Hence, based on the above literature, it was assumed that the role of meteorological parameters in reduction of pollutant concentrations was minimum.

4 Case Study

The impact of the lockdown measures on air quality has been examined for the metropolitan cities of India namely Delhi, Mumbai and Kolkata. The observations from air quality networks have been analysed, focussing on particulate matter (PM₁₀) and nitrogen dioxide (NO₂). Further the description of study area and methodology adopted for the study has been explained in this section.

The most common anthropogenic sources of pollution observed in the three cities are traffic and industry generated emissions, open burning of waste and combustion of fossil fuels (Bottle et al., 2020; Gurjar et al., 2016; Hama et al., 2019; Mukherjee et al., 2012). However, the contributions of sources in degrading the air quality amongst these metropolitan cities are different.

Delhi is the capital of India, spread over an area of 1483 km². It is one of the highly densely populated cities in the world, with a population density of 11,297 persons /km² with an average growth rate of 1.92%. It is situated within geographical coordinates of 28.24°N to 28.53°N and 76.50°E to 77.20°E. In particular, dust particles emanating from Thar desert and biomass burning from neighbouring state of Punjab significantly affect the air quality in the capital during pre-monsoon season. Additionally, the rise in population and ultimately the growth of traffic are the main reasons for Delhi being one of the cities having worst air quality (Hama et al., 2019; Kumar et al., 2013, 2017). In Delhi, dust generated from soil, road and construction followed by industrial and transport sector has significant influence on deteriorating the air quality of Delhi (TERI's report on Delhi's source apportionment, 2018). Further, prevailing meteorology and geographic location of Delhi (being landlocked) plays a major role in aggravating the air quality scenario of the city (Kumar et al., 2015). Concentrations are highest in Delhi due to peculiarity in its topography wherein windblown dust significantly contributes to the particulate load (Gurjar et al., 2016). Increase in aerosol and gaseous loading can be also attributed to the burning of crop residue in the neighbouring states of Haryana, Punjab and UP (Cursworth, 2018).

Mumbai is the financial capital of India and is the most populated city in India. The total area of the city is 603.4 km² with almost 28,000 persons/km² population density, with a growth rate of 12.05% as per 2011 census (Census Report of India, 2011). The city has a humid tropical climate and extends from 18° 55' N latitudes and 72° 54' E longitudes. The continual traffic in Mumbai has impacted the air quality of city by the generation of vehicular exhaust emissions thus, significantly deteriorating the ambient air quality, also degrading the public health (Siva and Ahire, 2017). CPCB (2010) have reported the emission load

of Mumbai city in detail, which highlights that power plants, road dust and landfill open burning to be the highest emitters of particulates.

Kolkata is the third-highest populated city of the country with a population of 14.1 million (Census Report of India, 2011) with a very high population density of about 24,000 persons/km². Rapid industrialization and population burst in the city has put a tremendous burden on the city infrastructure which has caused degradation of various elements of the environment, air quality being one of them (Das et al., 2015). However, residential sector which comprises of domestic and commercial combustion is the largest contributor to the particulate generated pollution, followed by vehicular generated emissions in Kolkata city (Majumdar et al., 2019). The city has been experiencing particulate pollution due to the rise in daily vehicular emission, which can affect the health of citizens of Kolkata (Haque & Singh, 2017).

Mumbai and Kolkata being the coastal cities experience coastal breezes which strongly affect the dispersion and transportation of gaseous and aerosol loads in the air (Anand et al., 2019; Spiroska, 2011). The flow of clean coastal winds towards city disperses the air pollutants thus, improving the air quality, while the reversal coastal winds lead to accumulation of pollutants (Anand et al., 2019).

5 Results and discussions

The nationwide lockdown resulted in significant reduction in levels of pollutants in the three cities. In this context, the following section discusses the decline observed in the concentrations of PM₁₀ and NO₂ using different techniques to understand the possible causes for this trend including an overall discussion and the need for additional monitoring stations.

5.1 Trend analysis of PM₁₀ and NO₂ concentration during lockdown

The nationwide lockdown imposed from 24 March 2020 resulted in significant reduction in levels of pollutants in the three cities. Figure 3 and Table 4 show the trends of daily mean variations of PM₁₀ and NO₂ observed in Delhi, Mumbai and Kolkata during the lockdown period and in 2019 for the same period. The analysis revealed that there was a significant decline in concentrations of both the pollutants in metropolitan cities considered for the study. The extent of variations witnessed in the levels of pollutants

Fig. 3 Trends of daily mean concentrations of PM₁₀ and NO₂ for 25 March–3 May 2019 and 2020, i.e. the first two phases of lockdown

Table 4 Descriptive statistics of pollutants in all three cities

M.S		A		B		C	
		PM10	NO2	PM10	NO2	PM10	NO2
Delhi	Mean	229.81	48.48	165.52	41.79	98.14	19.90
	S.D	81.75	26.27	71.47	21.17	41.97	13.86
Mumbai	Mean	87.93	20.28	136.73	38.36	62.28	7.79
	S.D	28.49	8.27	61.11	28.79	19.52	5.53
Kolkata	Mean	96.04	34.62	127.29	42.94	50.61	10.96
	S.D	57.94	19.22	61.58	22.60	25.98	5.67
A	March 25–May 3, 2019						
B	Feb 14–March 24, 2020						
C	March 25–May 3, 2020

Fig. 4 Trends of daily mean concentrations of PM₁₀ and NO₂ for pre-lockdown (February 14–March 24) and Lockdown period (March 25–May 3) **Fig. 5** Relative change in PM₁₀ and NO₂ for period (A-25 March–3 May 2019, B-14 Feb–24 March 2020 and C- 25 March–3 May 2020)

is different in all three cities. For example, PM₁₀ concentrations during lockdown were 98 ± 42 µg/m³ (Delhi), 62 ± 20 µg/m³ (Mumbai) and 51 ± 26 µg/m³ (Kolkata), which were reduced by 57%, 29% and 47% when compared with PM₁₀ levels observed in year 2019 for same period (Fig. 5). The maximum dip of about 57% was observed in PM₁₀ levels in Delhi compared to other two cities. Similarly, the reduction in levels of NO₂ during lockdown was significant. The reductions observed in NO₂ concentrations in three cities ranged between 59 and 68%, with maximum reduction observed in the city

of Kolkata. Further, the reductions observed in concentrations of both the pollutants by comparing their levels in pre-lockdown and lockdown period (Fig. 4). PM_{10} levels reduced by 41–60% in all three cities, with greater decline in Kolkata. However, the maximum decline was observed in NO_2 concentrations in all cities, with highest percentage reduction observed in Mumbai. In this context, it is important to mention that in general important rural background concentrations of atmospheric particulates generally originate from non-urban sources thereby their reduction is generally less important as for NO_2 , which is a typical urban pollutant. Similar results were also presented in a similar study reported for the European continent during the spring 2020 lockdown period (Zerefos et al., 2020).

Delhi exhibits the highest concentrations of PM_{10} and NO_2 even in the lockdown compared to the other two cities. Traffic and residential pollution are the significant factors influencing the air quality of Delhi city (Gulia et al. 2018). The majority of the pollution of Delhi city has been attributed primarily to vehicular and industrial sources (Hama et al. 2019). The paired *t* test results also verified the significant decline (*p-values* vary from 1.29642E-14 to 5.78334E-21) in concentrations of the pollutants during lockdown in comparison with the same period in 2019. Similarly, hypothesis testing performed for pre-lockdown vs lockdown period also highlighted the substantial difference (*p-values* range between 5.86923E-06 to 2.53974E-16) observed in the concentrations of PM_{10} and NO_2 . This can be attributed to the lockdown imposed by the government during which transportation, industrial and construction activities were halted.

The decrease in concentrations of pollutants considered was also witnessed in other two cities, namely Mumbai and Kolkata (Figs. 3 and 4). The Mumbai city is facing severe degradation in air quality due to the high rate of urbanization, unplanned infrastructural and industrial developments and rising vehicular emissions (MPCB report, 2019). Moreover, the city has been the worst-hit metropolitan city due to COVID-19 and cases are still rising.

Police et al. (2018) performed the source apportionment for particulates in Bombay and reported the six dominant sources namely, crustal material, sea salt spray, biomass combustion, fuel oil combustion, road traffic and metal industry. The lockdown imposed by the government have restricted the movement and activities of the general public with all transportation, industrial and construction activities have ceased. This has led to a reduction in the generation of emissions due to anthropogenic activities during the post-lockdown period. Figure 5 highlights the significant reductions (*p-values* between 4.91139E-05 and 1.31539E-11) in PM_{10} and NO_2 in lockdown, 2020 compared with similar period in 2019. Furthermore, the percentage reductions in lockdown in comparison with pre-lockdown period for PM_{10} and NO_2 was found to be 54% and as high as 80%, respectively. The air pollution problem in Kolkata is due to particulate concentrations which generally originates from vehicular and industrial emissions, road dust, waste incineration and combustion of fossil fuels (Das et al., 2015; Mukherjee et al., 2012). Therefore, 47–60% reduction in PM_{10} levels compared to 2019 and pre-lockdown period in Kolkata can be particularly related to the reduction in emission load, generated by road dust, construction and industries. There was a significant (*p* value = 3.77313E-11) decline of 60% in NO_2 levels compared to 2019 and 74% compared to the pre-lockdown period.

Despite, the suspension of emission generating anthropogenic activities (particularly industrial and vehicular activities), almost half of concentrations of the different air pollutants still continue to persist in these cities. This may be attributed to the emissions generated from sources like residential biomass burning, roadside waste or municipal solid waste landfills, thermal power plants, electricity generators (Hama et al., 2020; Kumar et al., 2020).

Table 5 Percentage exceedance calculated based on the number of days exceeding the E.F. > 1

City	PM10			NO ₂		
	A	B	C	A	B	C
Delhi	95	87.5	45	0	0	0
Mumbai	22.5	80	0	0	0	0
Kolkata	30	67.5	0	2.5	0	0
A	March 25–May 3, 2019					
B	Feb 14–March 24, 2020					
C	March 25–May 3, 2020					

Fig. 6 Percentage number of days with E.F. > 1 for PM₁₀ for period (A–25 March–3 May 2019, B–14 Feb–24 March 2020 and C–25 March–3 May 2020)

5.2 Percentage Exceedance and AQI

The exceedance factor was used to check whether the pollutants violated the permissible limits during the study period. Further, we calculated the frequency of violations observed in three cities by calculating the percentage number of days for which the E.F. > 1, i.e. violation of the permissible limits. Table 5 and Fig. 6 show the percentage number of days exceeding the national standards of 100 $\mu\text{g}/\text{m}^3$ for PM₁₀ and 80 $\mu\text{g}/\text{m}^3$ for NO₂ (i.e. Exceedance Factor > 1). Delhi had the worst air quality among three cities with concentrations of PM₁₀ pollutant exceeding the National Ambient Air Quality Standards (NAAQS). The frequency of PM₁₀ exceedance in Delhi during 2019 and pre-lockdown period was 95% and 88% which reduced to 45% during the lockdown period. Further, standards of PM₁₀ were violated for 68% and 80% of days in Kolkata and Mumbai city during pre-lockdown period. However, the concentrations remained under permissible limits during the lockdown period. It was also observed that the standards for gaseous pollutant NO₂ in the three cities were not exceeded for entire study period.

The levels of particulates in Delhi are very high compared to the other two cities (Gurjar et al., 2016); therefore, the levels of pollution remained somewhat high in the city which can be attributed to the additional sources such as residential burning of biomass, thermal power plants, etc. (Kumar et al., 2020, Hama et al., 2019). Mumbai and Kolkata are coastal cities; thus, it is quite possible that sea breezes may help in dispersion of the city emission leading to reduced concentrations (Kumar et al., 2015).

The effects of the COVID-19 on the movement of the public as well transportation was discernible post the advisories and notices issued by central and several state governments. In order to understand the change in overall air quality scenario in lockdown in three cities, we calculated the air quality index (AQI). The air quality index calculated for

the different periods considered in study are displayed in Table 6 along with the relative change observed in it during lockdown with respect to two different scenarios. During the six weeks of lockdown, air quality was observed to be satisfactory (AQI=91), while it was moderately polluted during the same period in 2019 (AQI=150) and pre-lockdown period (AQI=193). Air quality in Mumbai city during lockdown improved to satisfactory as index value reduced to 54 from 141 in 2019. While AQI in Kolkata even attained good category showing significant improvement in air quality from moderately polluted during same period in 2019. Therefore, it can be said that the strict lockdown measures implemented in the megacities lead to a short-term improvement in air quality due to switch off of huge emission load sources such as industrial, vehicular and commercial sources.

A comparative assessment of our results showed agreement with similar other studies conducted during the lockdown for regions across India. For example, Selvam et al. (2020) used AQI to illustrate the improvements in air quality during lockdown in the state of Gujarat and observed an overall improvement of 58% compared to previous year. Mahato et al. (2020) displayed the reductions in air pollutants (PM_{2.5}, PM₁₀, NO₂, SO₂ and NH₃) during lockdown using AQI data from 34 monitoring stations of Delhi city.

5.3 Background vs urban concentrations

Table 7 highlights the trends of concentrations at the background and urban sites in three cities. The monitoring station located at Aya Nagar was considered as the background site for Delhi city, owing to the lowest mean concentrations of air pollutants that were observed at this site over the whole study period. The concentrations of PM₁₀ at this site indicated the influence of regional pollution and local sources. Mundaka monitoring site which has been selected as the urban site is an industrial area located in the North region of Delhi. The overall mean PM₁₀ concentrations at the background site were almost 50% less compared to the urban mean concentrations during the pre-lockdown period. Similarly, NO₂ concentrations at urban sites are almost double than background site. However, after the lockdown was imposed, concentrations of PM₁₀ declined from $310 \pm 82 \mu\text{g}/\text{m}^3$ in pre-lockdown period to $121 \pm 47 \mu\text{g}/\text{m}^3$ during lockdown at urban site and from $148 \pm 37 \mu\text{g}/\text{m}^3$ to $74 \pm 27 \mu\text{g}/\text{m}^3$ at background site, which is almost a decrease of 60 and 50% (Table 8). The reductions in concentrations of NO₂ at the background site were not significant. However, the effect of lockdown at the urban site was discernible, where a reduction of greater than 45% in levels of NO₂ was observed in comparison with the same period in 2019 and the pre-lockdown period.

The prohibition on the vehicular movement and reduction in other associated anthropogenic activities during lockdown could be the possible reason behind such high reduction

Table 6 Air quality index along with the relative change observed the in index

City	A	B	C
Delhi	150	193	91
Mumbai	141	86	54
Kolkata	114	90	50
A	March 25-May 3 2019		
B	Feb 14-March 24 2020		
C	March 25-May 3 2020		

Table 7 Background vs urban concentrations

City	Station type	Station name		A		B		C	
				PM10	NO2	PM10	NO2	PM10	NO2
Delhi	Background	Aya Nagar	Mean	143.62	18.45	148.20	16.79	73.76	13.72
			S.D	47.30	9.16	37.23	6.26	27.53	1.29
	Urban	Mundaka	Mean	302.35	39.01	310.06	38.23	120.65	20.52
			S.D	100.43	8.58	81.69	11.02	46.65	7.04
Mumbai	Background	Borivali East	Mean	-	-	90.28	12.85	52.56	1.76
			S.D	-	-	23.73	3.87	18.52	0.75
	Urban	Sion	Mean	-	-	229.72	71.42	79.55	11.03
			S.D	-	-	77.01	20.83	17.38	3.12
Kolkata	Background	Bidhannagar	Mean	-	-	99.29	26.66	46.68	6.67
			S.D	-	-	38.98	11.32	19.91	1.70
	Urban	Rabindra Bharti Uni- versity	Mean	129.60	38.59	173.30	56.81	51.35	20.11
			S.D	60.10	22.47	94.78	20.95	29.18	4.31
A	March 25-May 3 2019								
B	Feb 14-March 24 2020								
C	March 25-May 3 2020								

Table 8 Relative change in background and urban concentrations

City	Station type	Station name	Relative Change in C w.r.t A		Relative change in C w.r.t B	
			PM10	NO2	PM10	NO2
Delhi	Background	Aya Nagar	- 48.64	- 25.64	- 50.23	- 18.28
	Urban	Mundaka	- 60.10	- 47.40	- 61.09	- 46.32
Mumbai	Background	Borivali East	-	-	- 41.78	- 86.30
	Urban	Sion	-	-	- 65.37	- 84.56
Kolkata	Background	Bidhannagar	- 63.48	- 62.73	- 64.88	- 62.25
	Urban	Rabindra Bharti University	-	-	- 71.15	- 85.33
A	March 25-May 3 2019					
B	Feb 14-March 24 2020					
C	March 25-May 3 2020					

in the concentration of air pollutants. Moreover, urban site selected for the study is very highly populated, and thus, poor infrastructure and residential pollution may be the reason for high concentrations of PM₁₀ even during the lockdown even though substantial reductions were observed. Similar analysis was also performed for the other two cities, Mumbai and Kolkata. Borivali East was selected as the background site for the city of Mumbai since minimum concentrations of air pollutants were recorded at this site for almost the entire study period. Unlike Delhi, PM₁₀ concentrations at the background site were already below the permissible limits which highlight the quality of air in the area. The background

site is located in the vicinity of Sanjay Gandhi Biodiversity Park which could be possible reason of reduced concentrations. Urban vegetation is known to positively affect the concentrations of air pollutants and improve air quality (Abhijith et al., 2017; Escobedo et al., 2011; Kumar et al., 2019). While, the urban location Sion has heavy pollution load due to unplanned infrastructure, super heavy vehicular congestion and high biomass burning (Report by TERI on Air quality status of Maharashtra, 2019). The concentrations of PM_{10} and NO_2 at urban site during the pre-lockdown period were $230 \pm 77 \mu\text{g}/\text{m}^3$ and $71 \pm 21 \mu\text{g}/\text{m}^3$ which declined to $80 \pm 17 \mu\text{g}/\text{m}^3$ and $11 \pm 3 \mu\text{g}/\text{m}^3$ after the enforcement of lockdown. The levels of PM_{10} reduced from $90 \pm 24 \mu\text{g}/\text{m}^3$ to $53 \pm 18 \mu\text{g}/\text{m}^3$ at background site. Further, levels of NO_2 declined to almost $2 \pm 1 \mu\text{g}/\text{m}^3$ at the background site. Similarly, concentrations at Rabindra Bharti University, the urban site for Kolkata substantially declined as high as 70% for PM_{10} and 60% for NO_2 during lockdown compared to the pre-lockdown period. Therefore, the restriction on industrial, construction activities and on vehicular movement during the whole month of April lead to the great reduction in air pollutants in Kolkata city.

The greater reduction observed in urban sites which are the primary air pollution hot-spots of the three megacities highlights the influence of the particular anthropogenic activities which lead to high emission load and thereby deterioration of air quality in these areas during the routine circumstances and conditions. In a similar study conducted in south-east Asia and Malaysia (Kanniah, 2020) revealed larger reductions in urban/industrial sites compared to suburban and rural sites due to large reductions in primary pollutants emissions from source like traffic, heating, industries in the industrial and/or in traffic sites. Moreover, the reduction in background areas can be justified with the combined effect of reduction in urban areas.

5.4 Diurnal variation of pollutant concentrations

The diurnal variation of PM_{10} and NO_2 for Delhi, Mumbai and Kolkata is presented in Fig. 7 across the pre-lockdown and lockdown period. To analyse the impact of lockdown on the diurnal behaviour of the two pollutants, we calculated the averaged diurnal concentrations at the selected background and urban sites which recorded the highest and lowest concentrations at all the three cities. Then, the diurnal cycle of pre-lockdown period (represented by 14 February–24 March 2020) and lockdown period (25 March–3 May 2020) was developed for all the three cities.

Figure 7 highlights the diurnal pattern of PM_{10} and NO_2 pollutant at Aya Nagar and Mundaka which are the representative stations recording the lowest and highest pollutant concentrations in the city of Delhi. Hourly variations of particulate and gaseous pollutant exhibited a substantial variation with minimum variations observed during the day for both the pollutants. Two peaks were observed for PM_{10} , in the morning between 08:00 and 09:00 h and between 20:00 and 21:00 in evening. Similarly, two peaks were observed for NO_2 . The lowest concentrations of both the pollutant witnessed during the day time can be attributed to the dilution effect of fully developed Planetary Boundary Layer (PBL) (Chen et al., 2019). The photochemical reactions and emissions generated from vehicular fleet lead to primary and secondary peaks of NO_2 during morning and evening (Tyagi et al., 2016). The diurnal pattern of pollutant concentrations at Mundaka (which is influenced by both industrial and vehicular emissions) is much clearer than the Aya Nagar. It can be observed that although there was a significant reduction in pollutant concentrations, the

Fig. 7 Diurnal trends of PM₁₀ and NO₂ at background and urban sites of three metropolitan cities of India

diurnal pattern during the lockdown months was similar to that of pre-lockdown period, although the curve was flattened.

The diurnal pattern for the station with least (Borivali East) and the highest (Sion) pollutant concentrations are displayed in Fig. 7 for Mumbai city. A peculiar trend of particulate matter concentration was observed at the site with minimum average concentrations i.e. Borivali East, where hourly concentrations reached peak in late morning hours and remained relatively high on the contrary to Sion monitoring station where day time concentrations were least. Household emissions and traffic sources along with the local meteorology could be the possible explanation for this peculiar observation. Similar observations have been reported by Bathmanabhan and Madanayak (2010), which attributed the elevated concentrations during daytime to the vehicular load in Chennai city. The trend of NO_2 was similar to that of Delhi, which showed primary and secondary peaks during morning and evening hours; however, there were variations in peak timings. For example, primary peak at Borivali east was noted in the morning, while hourly concentrations of NO_2 reached a peak during evening time. The diurnal pattern for both the pollutants remained identical for pre-lockdown and lockdown period, however, with reduced concentrations (flattened curve) during lockdown. The hourly concentrations of pollutants at Sion monitoring stations seems to be affected by the lockdown, where the curve has flattened significantly and almost constant levels of pollutant concentrations with least variations over day and night.

Similarly, the diurnal cycle of PM_{10} and NO_2 was studied for Bidhannagar (site with least concentrations of pollutants) and Rabindra Bharti University (site with maximum concentrations of pollutants). Keeping aside the extent of PM_{10} levels, the diurnal pattern (Fig. 7) at Bidhannagar has been almost identical to the pattern observed at Rabindra Bharti University. A similar trend has been observed for NO_2 pollutant as well. Peak observed in evening time between 19:00–20:00 can be attributed particularly to the emissions released from the vehicular movement. The impact of halted anthropogenic activities is apparent for the lockdown curves which have flattened compared to the pre-lockdown period.

In particular, it is observed that for the urban sites the "vanish" of the morning traffic peak during the lockdown period, especially in Mumbai and Kolkata, while in Delhi the lockdown diurnal patterns of both PM_{10} and NO_2 follow those of the pre-lockdown period, although the much lower values. Overall, it was observed that diurnal curve of the PM_{10} and NO_2 flattened during the lockdown period due to the suspension of the daily generating anthropogenic activities which reduced the hourly emissions.

5.5 Overall summary of variation in air quality during the lockdown period

In general, NO_2 levels were observed to be lower in Kolkata and Mumbai than Delhi as the public movement in the former two cities are more dependent on mass transportation than personal vehicles as in case of Delhi (Gurjar et al., 2016). Kumar et al. (2011) have reported that Delhi has the highest number of motor vehicles (i.e. 6.93 million) which is likely to rise to 25.6 million by 2030. The concentrations of the particulate and gaseous pollutant decreased in all the three analysed cities. Kolkata witnessed the highest decline in concentrations of PM_{10} and NO_2 pollutants during the lockdown months, followed by Mumbai and Delhi. The findings reported in this study are similar to assessments made by Nakada et al. (2020) wherein the study conducted reported greater than 50% reduction in NO , NO_2 and CO concentrations in urban areas of São Paulo, Brazil. The dwindling concentrations of pollutants have also been recorded by Xu et al. (2020) which reported

30–70% reduction in concentrations of PM_{10} , NO_2 , CO and O_3 for three cities of Wuhan, Jingmen and Enshi in China. We have observed that the reduction in NO_2 concentrations has been greater in comparison with PM_{10} concentrations. This observation is similar to that of Tobías et al. (2020), who have highlighted an improvement in the air quality of Barcelona city due to lockdown where there was 28–31% reduction in PM_{10} levels and 51% reduction in NO_2 concentrations. These results are in agreement with the results observed for our study. In general, it is important to note that when comparing the NO_2 and (PM_{10}) reductions during the lockdown, it is important to note that rural background concentrations of atmospheric particulate originate from non-urban sources thereby their reductions are generally less than NO_2 , which is an urban pollutant. Similar results were reported in another study conducted in Europe (Zerefos et al., 2020).

Kumar et al., 2020 assessed the variation in levels of particulates ($PM_{2.5}$) in five Indian cities (Chennai, Delhi, Hyderabad, Kolkata and Mumbai) using the long-term data from 2015 to 2020. There was substantial reduction in $PM_{2.5}$ concentrations, ranging from 19–43% in Chennai, 41–53% in Delhi and so on. The short-term analysis conducted by us corroborates with the long-term trend analysis of Kumar et al. (2020) highlighting the reduction in pollutants. PM_{10} being the most predominant pollutant in Indian cities showed the highest reduction indicating the need of strategies which should particularly address the particulates. Moreover, we analysed two pollutants to provide an altogether better scenario of the improvement in air quality due to the reduction in pollution load with respect to last year.

The study primarily focuses on the short term effects of the lockdown process, and hence, it is difficult to infer whether such impacts on air quality are a one-time assessment due to forced changes in peoples attitude. It may be highlighted that in principle, with the resumption of daily normal routine the acquired improvements in the air quality due to the lockdown will be offset in the longer period. Similar concerns in this aspect had been raised by (Koundal, 2020) in a newspaper article published in April 2020. Follow-up news articles published in the months of June 2020 (Deepika, 2020; News18 Graphics 2020) showed severe deterioration in air quality of Bangalore city and increase in $PM_{2.5}$ concentrations in some of the major cities in India. Though not a direct correlation, it may be presumed that any possible health benefits arising due to improved air quality may be cancelled out due to anxiety and health issues arising from the economical breakdown due to the lockdown conditions. This will have a significant influence on the long-term health of the population. It may be highlighted that the implementation of the lockdown measures, in essence is the reduction of emission levels of various sources including vehicular.

5.6 Design of additional monitoring station

It has also been observed that only Delhi conform to the population-wise recommended number of monitoring stations as mentioned in IS (5182): part 14 (2000), which are highlighted in Table 9. Delhi has one of the best air quality monitoring network in the country with 38 monitoring stations installed across the city which provides great spatial coverage. The reliability of Kolkata (only 7 continuous monitoring stations) and Mumbai (only 10 continuous monitoring stations) based on the above standards can be considered inadequate. The impact of increasing vehicular emissions and industrialization can be only assessed by establishing new monitoring stations for better representation of air quality (Ganguly et al. 2019). According to IS 5182: part 14 (2000), we calculated the number of monitoring stations required for the two cities and are highlighted in Table 10. There is a

Table 9 Recommended minimum number of stations, population-wise as per IS 5182: part 14 (2000)

Pollutant	Population of evaluation area	Minimum no. of ambient air quality monitoring stations
SPM (Hi-Vol)	< 100,000	4
	100,000–1,000,000	4 + .6 per 100,000 population
	1,000,000–5,000,000	7.5 + .25 per 100,000 population
	> 5,000,000	12 + .16 per 100,000 population
SO ₂ (bubbler)	< 100,000	3
	100,000–1,000,000	2.5 + .5 per 100,000 population
	1,000,000–10,000,000	6 + .15 per 100,000 population
	> 10,000,000	20
NO ₂ (bubbler)	< 100,000	4
	100,000–1,000,000	4 + .6 per 100,000 population
	> 1,000,000	10

Table 10 Required number of stations in Mumbai and Kolkata, population-wise as per IS 5182: part 14 (2000)

City	Population (according to Census Report of India, 2011)	Pollutant	Minimum no. of M.S. required	Number of M.S. present	Deficit
Mumbai	18,394,912	SPM (Hi-Vol)	16	10	6
		NO ₂ (bubbler)	10	10	0
Kolkata	14,035,959	SPM (Hi-Vol)	12	7	5
		NO ₂ (bubbler)	10	7	3

deficit of 6 monitoring stations in Mumbai. There is a requirement of 5 additional monitoring stations in Kolkata for better representation of ambient air quality in these cities.

Therefore, there's a need to address the requirement of additional monitoring stations in Mumbai and Kolkata. The existing number of monitoring stations might not be able to provide a complete coverage of ambient air quality of the areas. With non-availability of proper air quality data due to lack of appropriate monitoring stations, it is likely possible that residents of the city might be exposed to greater levels of pollutants.

6 Policy and managerial implications

This study documented the short-term reduction in air pollution due to COVID-19 lockdown in which most of the anthropogenic activities were halted. Although ceasing the anthropogenic activities due to the lockdown may be impractical economically, however, such a scenario enabled us to understand the ability of cities to achieve good air quality levels if appropriate reforms and plans are implemented. Thus, there is a certain need to integrate the plans of boosting economy with environmental management for planning a sustainable and stable future. The decline in oxides of nitrogen and particulate concentration

particularly due to reduction in transportation activities justifies the need of promoting increased public transportation vehicles running on cleaner fuels, improved intra-city public transport systems, reducing non-essential travel including total cordoning of those designated air quality (AQ) hotspots areas from individual vehicular travel, identifying and implementing low emission zones (LEZ) in these cities, improved greenery in cities with increase in natural parks and encouraging pedestrian and cycling activities. Moreover, to achieve a clean and healthy atmosphere in the urban cities, the use of cleaner and sustainable fuel needs to be encouraged in transportation, industries and even in the households.

Additionally, some of the important concepts proposed in the National Clean Air Program in April 2018 (NCAP, 2018) could be highly helpful. For example, one of the major proponents in the NCAP programme is source apportionment studies. An appropriate source apportion studies conducted before, during and after lockdown, will significantly help in identifying both natural and anthropogenic sources and the role they play in generation of AQ hotspots. Since the role of anthropogenic sources will be almost reduced to none, during the lockdown period, background and natural sources will be the major cause of pollutants during such time, the concentrations of which will be significantly less. In the same context, another major suggestion included in the NCAP could be utilized effectively. This includes the proposal of installation of additional monitoring stations in the cities to determine additional AQ hotspots. This proposal of need of installation of additional monitoring stations as per NCAP has already been corroborated in the present study.

7 Conclusions

The study presents and compares the spatiotemporal variations of particulate (PM_{10}) and gaseous (NO_2) pollutant in three metropolitan cities of India namely, Delhi, Mumbai and Kolkata. Results highlighted that capital city Delhi had the worst air quality among three cities, with particulate pollutant (PM_{10}) being the dominant pollutant. There has been a significant decline in concentrations of PM_{10} and NO_2 in all three cities, with greater PM_{10} reduction in Kolkata and NO_2 in Mumbai. Moreover, the comparison of background and urban sites highlighted the greater reduction in pollutants observed at urban sites, which shows the substantial short-term impact of ceasing the emission producing activities. Particularly, ensuring the better technology for industries and vehicles can reduce the overall emission load.

The diurnal pattern of pollutants analysed for sites having lowest and highest pollution levels for the pre-lockdown and lockdown period showed that the hourly concentrations of pollutants became nearly invariable during lockdown period, due to complete stoppage of all associated anthropogenic activities. In overall sense that the reduction in NO_2 concentrations was higher than PM_{10} concentrations similar to other reported scientific literature.

COVID-19 has hindered the growth of the whole world taking, but this unwanted situation has improved the various environmental systems globally including air quality as evidenced by this study. However, repercussions of the pandemic will also be observed in post-lockdown period. Reviving the global and national economy will be a great challenge to the countries. This might lead to the consumption of more natural resources thereby, degrading the environment which has been partially restored. This will also lead to depletion of restored air quality in the long run.

Social distancing has been considered as an important preventive measure for COVID-19. However, to maintain this people might prefer to buy personal vehicles, instead of using

public transportation for conveyance. This may lead to an increase in the on-road vehicular emissions, consequently raising the pollutant concentrations. Although short-term reductions were obtained during the lockdown; however, it also showed that cleaner environments are possible but that would require a great deal of planning and policies that can make a balance between the economic revival and the environmental degradation. Since we have observed the impact of prohibiting and reducing the vehicular movement, imposing lockdown every month on a particular weekend can be as a matter of further research.

At last, it may be concluded from the study that cities like Mumbai and Kolkata may require additional continuous monitoring stations for adequately representing the variations in air quality.

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