COVID-19 lockdown induced air pollution reduction over India: A lesson for future air pollution mitigation strategies

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Air pollution is one of the biggest problems worldwide and needs to be addressed potentially with the implementation of updated stringent policies and legislative laws. The nationwide lockdown imposed to prevent the COVID-19 outbreak, has given us a unique opportunity to understand the contribution of anthropogenic emissions to the total atmospheric pollutant burden on a global as well as regional scale. Thus, in the present study, we try to investigate the impact of COVID-19 induced lockdown on common ambient air pollutants (i.e., PM_{2.5}, NO₂, and SO₂) concentration over 22 cities in India using in-situ measurement under a network of Centre Pollution and Control Board (CPCB). A significant reduction in the mean mass concentration of all the studied air pollutants (i.e., PM_{2.5}, NO₂, and SO₂) (nearly 10–70%) is found during different phases of lockdown which reached within the National Ambient Air Quality Standard (i.e., NAAQS). The reduction in studied air pollutants is more prominent during the first phase of lockdown (mainly NO₂) which could be due to the complete shutdown of industrial activities. The outcome of the present study will be helpful for policymakers to design cost-effective and accurate air pollution mitigation strategies for the development of a sustainable environment. The study also suggests that well-planned short-term and periodical lockdown could be an alternative effective tool of air pollution mitigation.

Keywords. PM_{2.5}; lockdown; COVID-19; air pollution; mitigation.

1. Introduction

Air pollution is one of the most vulnerable and serious issues throughout the world during the last few decades; particularly in developing countries like China, India, and Brazil, due to the rapidly increasing trend in urbanization, industrialization as well as population and associated energy demands (Li and Lin 2015; Srivastava *et al.* 2017; Chen *et al.* 2018a, b). It has severe

impacts on air quality, atmospheric visibility reduction, human health as well as climate change (Cai *et al.* 2017; Chen *et al.* 2017, 2018a, b). It has one of the greatest health risks today and ranked at 4th position on the cause of millions of premature death worldwide (Lelieveld *et al.* 2015). Recent studies reported that nearly more than half a million premature deaths over the Indian region are associated with air pollution (Ghude *et al.* 2016; Chowdhury and Dey 2016). In

addition to this, Guo *et al.* (2017) also reported approximately one million deaths in 2015, mainly due to particulate matter pollution in India. Particulate matter (PM) is one of the major constituents of air pollution and is mainly emitted from vehicles, residential, energy, and industrial emissions (Tiwari *et al.* 2016; Guo *et al.* 2019). Recently, World Health Organization (WHO) reported that nearly 90% of the world population is exposed to polluted air due to exceeding of PM_{2.5} exposure guideline ($\sim 35 \mu\text{g}/\text{m}^3$) (WHO BoD 2018). In addition to this, Indian cities continuously ranked in the top 20 most-polluted cities of the world for the past few years (Kota *et al.* 2018; Mukherjee and Agrawal 2018).

The spread of Coronavirus disease 2019 (COVID-19) was initially identified at the beginning of December 2019 at Wuhan, China, and the ongoing outbreak of COVID-19 spread rapidly worldwide resulting in a pandemic declared by the World Health Organization (WHO 2020). The COVID-19 is a virus infection having a median incubation period of nearly 5 days (Lauer *et al.* 2020) which generates a severe acute respiratory syndrome with serious clinical symptoms like fever, dry cough, dyspnea, respiratory disorders, pneumonia (Guo *et al.* 2019) and causes progressive respiratory failure and even death (Chen *et al.* 2020; Sohrabi *et al.* 2020). As of May 31st, 2020, outbreak of COVID-19 has infected over 6.24 million people worldwide and the death toll has reached approximately 3,79,369. Since specific medication and treatment for COVID-19 are not yet reported, the number of cases of infection is still increasing at a high rate causing serious damage to the economy and a threat to humankind (Cortegiani *et al.* 2020). In India, the first confirmed COVID-19 case was reported on January 30th, 2020 and now India is facing the biggest challenge with an alarmingly increasing rate of COVID-19 patients across the country which has caused situations like health emergency. As of 31st May 2020, nearly 2286 people were died due to COVID-19, while almost 190,648 people confirmed COVID-19 positive (<https://www.covid19india.org/>). Thus, considering the severity of the COVID-19 pandemic and the need to control alarming increasing COVID-19 cases, the first nationwide lockdown had been declared for 14 hrs on March 22nd, which was followed up to 31st May 2020 in four different phases, i.e., from March 24th to April 14th 2020 (Phase-I), April 15th to 3rd May 2020 (Phase-II), May 4th to May 17th 2020 (Phase-III) and May 18th to 31st May 2020 (Phase-IV).

This complete lockdown and self-quarantine measures enforce constraints to human activities resulted in the shutdown of all the industrial activities and businesses like markets, shops, tourism, hotels and restaurants, construction work, mining, and other activities as well. The transport sector was almost suspended for private and public transport. Only personnel employed in essential services like the medical sector were allowed to commute. However, the energy sector was allowed to execute with a limited number of employees as it comes under the essential services. The complete lockdown nationwide drastically reduced the air pollution in India as well as in the whole world (Bao and Zhang 2020; Chauhan and Singh 2020; Pani *et al.* 2020; Saadat *et al.* 2020; Sharma *et al.* 2020). Thus, the worldwide lockdown condition provides a rare research opportunity to evaluate the impact of anthropogenic activities on air quality, greenhouse concentration along with their impacts (Saraswat and Saraswat 2020) on a global as well as regional-scale, which will be useful for policymakers for sustainable development and air quality mitigation (Sharma *et al.* 2020).

Thus, with the above objectives, in the present study, we analyzed the variation of most common ambient air pollutants concentration (i.e., PM_{2.5}, NO₂, SO₂) along with meteorological parameters (mainly relative humidity) for March, April, and May for the year 2018–2020, over 22 different cities across India. The dataset in the present study is obtained from the Central Pollution Control Board (CPCB) (CPCB: <https://app.cpcbcr.com/ccr/#/caaqm-dashboard-all/caaqm-landing/data>); a network of air quality monitoring stations which is discussed in detail in the upcoming section.

2. Site description, dataset, and methodology

To investigate the impact of COVID-19 induced nationwide lockdown on air pollution reduction, air pollutants data from the 22 different cities across the country (figure 1) were analyzed. Based on the United Nations Department of Economic and Social Affairs (World Urbanization Prospects 2019), the selected cities were categorized into three different types, i.e., megacities, urban, and suburban. The megacities (having populations > 10 million) include Delhi, Mumbai, Kolkata, Bengaluru, Hyderabad, and Chennai,

Figure 1. Location map of 22 different cities studied in the present study. The colour scale represents the number of confirmed COVID-19 cases at the study locations on 31st May 2020.

while the urban sites are Ahmedabad, Kanpur, Agra, Udaipur, Jaipur, Varanasi, Nagpur, Nasik, Pune, and Kota. The suburban sites are Gurugram, Amritsar, Patiala, Jalandhar, Muzaffarpur, and Gaya. The megacity Mumbai is the most affected city by COVID-19 than any other cities followed by Delhi and Chennai. These three megacities have nearly 20.81% (Mumbai), 10.40% (Delhi), and 7.76% (Chennai) contribution of total confirmed cases in India (up to 31st May 2020). The location map of selected cities and the number of COVID-19 confirmed cases are given in figure 1. Among the selected cities, most of the cities are located in the Indo-Gangetic Basin (IGB), which is one of the most populated and highly polluted river basins in the world (Tiwari *et al.* 2016). During the pre-monsoon season, the entire IGB experience very high aerosol loading attributed mainly because of the frequent occurrence of dust storms (Tiwari *et al.* 2019), wheat crop residue burning (Kaskoutis *et al.* 2014; Chauhan *et al.* 2017; Rajput *et al.* 2017), and extensive anthropogenic activities (Kumar *et al.* 2015; Pratap *et al.* 2020; Kumar *et al.* 2020; Tiwari *et al.* 2020). The daily mean mass concentration of the three most common ambient air pollutants, i.e., $\text{PM}_{2.5}$, NO_2 , SO_2 (in $\mu\text{g}/\text{m}^3$) were obtained from the Centre Pollution Control Board (CPCB: <https://app.cpcbcr.com/ccr/#/caaqm-dashboard-all/caaqm-landing/data>) from March to May months of the year 2018, 2019,

and 2020. The CPCB has deployed different types of instruments fitted with sensors certified by world meteorological organizations to collect various real-time air pollutants data (CAAQMS Guidelines 2019). The USEPA (United States Environmental Protection Agency) approved $\text{PM}_{2.5}$ monetarizing analyzer is used for the measurement of $\text{PM}_{2.5}$ particles, which works on the principle of β -ray attenuation. Particulate sampled through the instrument were collected on fiberglass filter tape and an internal micro-processor automatically calculated the concentration of $\text{PM}_{2.5}$. The airflow rate of the sampler is maintained at 16.7 l/min and has the PM concentration range of 0–1000 $\mu\text{g}/\text{m}^3$ having $\pm 1\%$ uncertainties (CAAQMS Guidelines 2019). For measurement of NO_2 , ambient oxides of nitrogen analyzer are used which has 0–2000 ppb range and works on the principle of chemi-luminescence with the lowest detectable limit ~ 1 ppb, noise level 0.5 ppb and having $\pm 1\%$ uncertainties (CAAQMS Guidelines 2019). Moreover, an ambient sulfur dioxide analyzer is used for monitoring SO_2 , which works on the principle of UV fluorescence and has a range of 0–200 ppb with a noise level of 0.5 ppb and $\pm 1\%$ uncertainties. Further technical details about the measurements like instrument model number, calibration method, and calibration frequency are discussed elsewhere (CPCB 2019; CAAQMS Guidelines 2019).

3. Results and discussions

3.1 Changes in mass concentration before and during the lockdown period

The temporal variation of ambient pollutants, i.e., $\text{PM}_{2.5}$, NO_2 , and SO_2 (in $\mu\text{g}/\text{m}^3$) from March 1st to 31st May 2020 is shown in figures 2–4. The figure clearly shows a large variation in all three studied air pollutants with a significant reduction at all the sites but more prominent over highly populated and industrialized places like megacities and urban areas (figures 2 and 3). The mean mass concentration of $\text{PM}_{2.5}$ was found to be in the range of 25–84 $\mu\text{g}/\text{m}^3$ before the lockdown over the studied sites which reduced up to 71% and was found to be in the range of 11–109 $\mu\text{g}/\text{m}^3$ during the different phases of lockdown. During the first phase of lockdown, reduction in the mean mass concentration of air pollutants is observed over all the megacities (table 1). The maximum reduction in $\text{PM}_{2.5}$ was found during the first two phases of lockdown; however, a sharp increase in $\text{PM}_{2.5}$ ($\sim 40\%$) during the end of the first and start of the second phases of lockdown at Delhi is mainly due to the dust storm that occurred on 14th May 2020. Earlier studies also reveal that dust storm causes

enhancement in particulate matter into the atmosphere (Singh *et al.* 2016; Tiwari *et al.* 2019). However, enhancement in $\text{PM}_{2.5}$ over Mumbai after the first phase of lockdown may be mainly due to the mass migration of workers towards the villages, which causes the dust resuspension into the atmosphere. Source apportionments study over Mumbai also suggests that road dust contributes nearly 71% of the emission load of particulate matter (<https://indianexpress.com/article/cities/mumbai/road-dust-responsible-for-71-emission-load-of-pm-in-mumbai-finds-neeri-study-7211641/>). The mean mass concentration of air pollutants at megacities, urban and suburban sites before and during different phases of lockdown are summarized in tables 1–3, respectively. Apart from this, enhancement of $\text{PM}_{2.5}$ at other locations over IGB (like Amritsar, Jalandhar, Patiala) during the third and fourth phases may be attributed to the wheat crop residue burning. In an earlier study, Sharma *et al.* (2017) also reported a significant contribution of agricultural biomass burning in total particulate matter loading over Patiala. One of the other possible reasons for slight enhancement in $\text{PM}_{2.5}$ concentrations during the third and fourth phases of lockdown over IGB sites may be associated with an increase in intense convective activity

Figure 2. Temporal variation of daily mean concentration (in $\mu\text{g}/\text{m}^3$) of $\text{PM}_{2.5}$, $\text{NO}_{2.5}$ and SO_2 at different megacities from 1st March 2020 to 31st May 2020.

Figure 3. Similar to figure 2, but for urban locations.

Table 1. Mean mass concentration of air pollutants before and during lockdown 2020 over megacities.

Cities	Pollutants	Mean mass concentration				
		Before lockdown	During lockdown			
			Phase-I	Phase-II	Phase-III	Phase-IV
Delhi	PM _{2.5}	77.86	56.57	109.30	76.12	71.47
	NO ₂	36.82	21.80	20.25	25.00	37.29
	SO ₂	14.67	13.55	13.16	10.55	6.26
Mumbai	PM _{2.5}	24.80	18.23	31.96	48.26	50.76
	NO ₂	54.29	11.49	3.58	–	5.80
	SO ₂	16.88	23.53	44.42	62.86	23.51
Chennai	PM _{2.5}	32.35	21.81	10.76	16.41	19.22
	NO ₂	11.56	13.38	6.38	5.31	6.63
	SO ₂	4.86	3.75	4.08	3.71	3.61
Kolkata	PM _{2.5}	50.95	32.90	16.46	17.58	16.38
	NO ₂	54.68	15.30	11.40	11.99	12.15
	SO ₂	12.98	11.51	8.67	6.83	4.39
Hyderabad	PM _{2.5}	33.99	31.32	24.74	25.41	34.71
	NO ₂	25.36	16.06	16.34	17.07	18.08
	SO ₂	9.41	9.86	7.85	7.38	16.20
Bengaluru	PM _{2.5}	31.24	27.18	31.27	26.50	27.56
	NO ₂	30.64	18.34	19.82	23.72	25.36
	SO ₂	7.59	6.56	6.88	7.89	6.66

resulting in uplifting of soil dust which transported from one region to another. Earlier studies also reported a higher concentration of particulate matter during April and May months, particularly over the north Indian region (Tiwari *et al.* 2013, 2019; Yadav *et al.* 2014). In addition to this, other important air pollutants, i.e., NO₂ and SO₂

also decreased significantly (up to ~93% and ~76%) during the different phases of lockdown (figures 2–4). The most significant reduction among studied pollutants was observed for NO₂, which is commonly known as a primary tracer for industrial activity and urban air pollution, mainly emitted from high-temperature combustion processes. The

Figure 4. Similar to figure 2, but for suburban locations.

massive reduction in NO_2 emission is found over the megacities like Delhi and Mumbai (79.3% and 89.3%) during the second phase of lockdown (table 1). Kolkata witnessed a reduction of up to 76% in NO_2 concentrations due to restrictions on industrial activities and almost no traffic during the lockdown. In Chennai, NO_2 level reduced up to 54%, whereas Hyderabad and Bengaluru faced up to 40% reduction of NO_2 in its ambient air. Recently, Ajay *et al.* (2021) reported a reduction (>60%) in fossil fuel emitted black carbon (a constituent of $\text{PM}_{2.5}$) concentration over Bengaluru during the first phase of lockdown. On the other hand, industrialized major urban cities like Ahmedabad and Kanpur, also witnessed a significant reduction in NO_2 concentration which reached up to 49% and 65%, respectively. Other cities in this category also showed a significant reduction in NO_2 confirming the positive aspect of lockdown on the environment. A slight enhancement in NO_2 was observed over the North Indian cities (like Amritsar, Patiala, Gurugram, etc.) during the third and fourth phases of lockdown that may be attributed to the intensive stubble burning from the wheat field, which produced a significant amount of NO_2 and other co-emitter pollutants in the atmosphere. Earlier studies also reported a sufficient amount of ambient air pollutants emission from the crop residue burning over Indian region (particularly over Indo-Gangetic Basin) (Kaskaoutis *et al.* 2014;

Sharma *et al.* 2017; Liu *et al.* 2018; Sarkar *et al.* 2018; Grover and Chowdhary 2019; Chawala and Sandhu 2020 and references therein) as well as other parts of the world (Chen *et al.* 2017; Kang *et al.* 2019; Paralovo *et al.* 2019). A higher concentration of NO_2 together with NH_3 is also reported in biomass burning plumes, which enhance the sulfate formation through the aqueous phase reaction (Chen *et al.* 2017). Similarly, a significant reduction in SO_2 is also observed over most of the studied sites. An enhancement in NO_2 after the first phase of lockdown over Gaya could be mainly attributed to biomass combustion for domestic heat production (Ozgen *et al.* 2021). Similarly, a large reduction in SO_2 (up to 75%) is also observed over almost all the studied sites during the first phase of lockdown except Mumbai, where a significant enhancement is observed during all phases of lockdown (table 1). The reduction in air pollutants during March to May 2020 in different phases of lockdown is tabulated in tables 1, 2, and 3 for megacities, urban and suburban sites. Apart from this, a few spikes were also observed in the mass concentration of SO_2 during the different phases of lockdown. The enhancement in SO_2 during lockdown could be due to the no-restrictions of power plants and the use of coal energy, an essential commodity during the lockdown. Since, sulfur is mostly emitted from diesel, coal, or heavy fuel oil, the transport sector can be neglected as NO_2 is not increased. Further,

Table 2. Mean mass concentration of air pollutants before and during lockdown 2020 over urban cities.

Cities	Pollutants	Mean mass concentration				
		Before lockdown	During lockdown			
			Phase-I	Phase-II	Phase-III	Phase-IV
Ahmedabad	PM _{2.5}	50.08	32.51	28.37	25.68	27.15
	NO ₂	35.44	28.02	18.10	18.19	21.24
	SO ₂	46.82	27.83	25.48	11.26	–
Jaipur	PM _{2.5}	31.72	19.68	25.02	29.18	42.34
	NO ₂	29.72	11.49	11.31	15.82	19.63
	SO ₂	12.52	11.29	10.88	9.33	10.01
Kanpur	PM _{2.5}	59.81	41.91	49.26	44.04	50.92
	NO ₂	42.67	14.67	20.09	22.49	37.06
	SO ₂	14.51	15.20	15.01	11.70	9.91
Nagpur	PM _{2.5}	29.94	22.67	23.46	20.41	23.40
	NO ₂	48.91	22.92	20.45	17.75	20.20
	SO ₂	6.30	1.75	1.79	2.22	2.43
Agra	PM _{2.5}	55.81	43.06	49.39	44.13	59.53
	NO ₂	50.27	45.40	39.38	29.34	29.79
	SO ₂	26.79	26.41	28.54	29.96	26.51
Nasik	PM _{2.5}	34.06	32.73	23.60	21.88	16.89
	NO ₂	30.79	22.06	20.33	18.33	12.96
	SO ₂	3.88	2.68	2.36	2.17	1.87
Pune	PM _{2.5}	48.26	30.53	27.51	87.03	42.41
	NO ₂	15.32	11.60	10.45	33.07	16.12
	SO ₂	42.72	24.25	22.30	21.03	23.57
Varanasi	PM _{2.5}	60.23	57.21	32.57	38.13	38.81
	NO ₂	19.56	32.62	31.67	29.50	24.28
	SO ₂	27.50	32.65	32.70	34.49	57.54
Amritsar	PM _{2.5}	30.74	20.42	18.27	31.06	38.39
	NO ₂	11.51	11.35	16.49	17.00	14.07
	SO ₂	13.15	7.15	8.98	9.48	17.40
Kota	PM _{2.5}	38.62	28.21	27.52	28.90	35.52
	NO ₂	31.41	12.91	12.16	22.05	7.84
	SO ₂	9.43	10.07	8.35	8.83	8.63

a comprehensive study is needed to investigate possible reasons behind the enhancement in SO₂ during the lockdown.

3.2 Inter-comparison of pollutants concentration with previous years

To investigate the impact of COVID-19 induced lockdown on air pollutants burden, we also compared the mean mass concentration of air pollutants in 2020 with the same period of two successive previous years, i.e., 2018 and 2019. Significant depreciation in the mean mass and concentration of ambient air pollutants, during different phases of lockdown, is found in the year 2020 as compared to 2018 and 2019 (tables 4, 5, 6)

due to restricted anthropogenic activities to avoid the spread of the COVID-19. The imposed lockdown caused a drastic change in air quality standard overall studied cities as PM_{2.5} concentrations at most of the places found were within the permissible limits of National Ambient Air Quality Standard (i.e., NAAQS, PM_{2.5} = 60 µg/m³) during 2020 except Delhi, where PM_{2.5} concentrations seemed to be found near the boundary of permissible limits which is not common for the past few years. Among all the studied megacities, Delhi followed by Chennai witnessed a maximum reduction in PM_{2.5} concentrations. In addition, other pollutants, i.e., NO₂ and SO₂ also showed a maximum reduction at Delhi due to complete lockdown with no traffic and industrial activities.

Table 3. Mean mass concentration of air pollutants before and during lockdown in year 2020 over suburban cities.

Cities	Pollutants	Mean mass concentration				
		Before lockdown	During lockdown			
			Phase-I	Phase-II	Phase-III	Phase-IV
Udaipur	PM _{2.5}	37.96	25.92	27.05	31.06	36.31
	NO ₂	18.43	6.12	7.04	9.65	11.69
	SO ₂	12.49	8.81	6.53	10.29	8.05
Gurugram	PM _{2.5}	56.07	35.79	44.49	55.86	49.99
	NO ₂	17.05	10.76	10.36	22.79	15.09
	SO ₂	43.82	32.50	27.49	32.63	30.55
Jalandhar	PM _{2.5}	42.34	22.39	33.00	42.73	49.02
	NO ₂	8.42	9.63	7.55	6.21	8.26
	SO ₂	9.56	9.26	6.70	8.93	
Patiala	PM _{2.5}	25.82	15.28	23.19	25.46	39.81
	NO ₂	6.80	2.93	6.07	6.93	11.87
	SO ₂	5.93	4.42	5.67	6.64	13.61
Muzaffarpur	PM _{2.5}	82.24	67.86	28.43	39.16	23.14
	NO ₂	24.12	24.10	24.12	24.07	24.06
	SO ₂	21.85	25.05	17.68	17.24	14.78
Gaya	PM _{2.5}	54.13	47.59	40.13	43.31	48.06
	NO ₂	4.59	2.75	16.85	16.78	23.36
	SO ₂	14.21	14.38	14.86	15.55	16.26

Delhi experienced up to ~50% diminution in PM_{2.5} levels during different phases of lockdown in the earlier two years, i.e., 2018, 2019, whereas up to 80% and 50% reduction in the case of NO₂ and SO₂ concentrations, respectively during the same period (table 4). Almost similar results were also found for other megacities, i.e., Kolkata, Mumbai, Chennai, Hyderabad, and Bengaluru. Mahato *et al.* (2020) also reported >50% reduction in PM_{2.5} and PM₁₀ concentration during the lockdown as compared to the pre-lockdown phase over megacity Delhi. Kolkata witnessed PM_{2.5} concentration reduction range from 7 to 61% during 2020 in comparison to 2019. On the other hand, NO₂ concentration reduced during the first (51%) and second phases (62%), while enhancement during the third and fourth phases of lockdown could be mainly due to the anthropogenic activities for essential services. A significant reduction in PM_{2.5} mean mass concentration was found during the first phase of lockdown, while enhancement in mass concentration during the second and third phases of lockdown is mainly attributed to the resuspension of road dust as discussed earlier. On the other hand, the mean mass concentration of NO₂ reduced throughout the different phases of lockdown with different magnitudes. In contrast, over Mumbai,

the mean mass SO₂ concentration was found high (up to 3 times) during different phases of 2020 than the year 2019. Similarly, the reduction in PM_{2.5} concentrations were found in the range of 12–64% (6–66%) at Chennai, 14–44% (20–64%) at Bengaluru, and 18–44% (26–45%) at Hyderabad as compared to the year 2018 (2019), respectively. Recently, Gogoi *et al.* (2021) also found a reduction (nearly 10–40%) in mean black carbon (a most common constituent of PM_{2.5}) concentration over the entire mainland during the first phase of lockdown and even more pronounced over IGB (>60%) during the second phase of lockdown. Similarly, the maximum reduction in NO₂ is found in Delhi, while Mumbai experienced a maximum enhancement in SO₂ concentration among all the megacities, during different phases of lockdown as compared to the previous year. Further details about the air pollutants during 2018, 2019, 2020 for different phases of lockdown and their percentage changes are given in table 4. On the other hand, among the urban sites, the maximum reduction in PM_{2.5} concentration was observed at Ahmedabad (up to 72%), while the minimum at Kanpur (up to 42%) followed by Agra (up to 44%) as compared to the previous years. The maximum reduction in NO₂ mass concentration was observed at Kanpur (78%) followed by

Table 4. Mean mass concentration of $PM_{2.5}$, NO_2 and SO_2 over megacities during different phases of lockdown period in 2018, 2019, 2020 and respective percentage change in 2020.

Cities	Pollutants	Mean value of pollutants											
		2018				2019				2020			
		I	II	III	IV	I	II	III	IV	I	II	III	IV
Delhi	$PM_{2.5}$	109.12	116.42	119.78	110.98	109.03	91.78	148.43	76.52	54.78	109.29	76.12	71.46
	NO_2	105.51	102.27	95.48	123.01	86.43	93.99	94.59	111.67	21.05	20.24	25.00	37.28
	SO_2	15.24	10.20	9.36	11.49	26.44	26.30	22.13	15.05	13.35	13.16	10.54	6.26
Mumbai	$PM_{2.5}$	-	-	-	-	24.70	20.51	14.59	15.41	17.99	31.96	48.25	50.75
	NO_2	-	-	-	-	18.40	22.34	14.45	12.74	10.61	3.58	5.79	5.79
	SO_2	-	-	-	-	23.43	21.96	22.14	14.32	23.58	44.41	62.85	23.51
Chennai	$PM_{2.5}$	45.06	30.46	18.67	17.92	23.73	31.89	37.99	27.33	21.79	10.76	16.40	19.21
	NO_2	10.94	47.22	13.32	12.44	15.43	5.85	13.41	14.26	13.36	6.37	5.31	6.63
	SO_2	5.36	6.06	5.76	4.402778	4.75	4.96	4.93	5.20	3.70	4.07	3.71	3.61
Kolkata	$PM_{2.5}$	-	-	-	-	35.64	31.57	45.72	34.62	33.13	16.46	17.57	16.38
	NO_2	-	-	-	-	31.156	30.07	6.08	4.84	15.12	11.39	11.99	12.1125
	SO_2	-	-	-	-	6.93	7.63	1.34	2.182	11.42	8.66	6.83	4.391
Bengaluru	$PM_{2.5}$	31.66	56.22	42.68	48.29	69.94	74.27	74.37	34.85	26.93	31.26	26.49	27.55
	NO_2	13.01	25.51	33.79	36.95	22.03	25.22	31.58	27.16	18.20	19.82	23.71	25.36
	SO_2	4.3	5.75	5.62	5.07	2.54	2.09	2.82	4.70	6.54	6.87	7.88	6.66
Hyderabad	$PM_{2.5}$	49.00	44.36	35.57	42.55	45.12	39.37	46.20	47.00	31.55	24.73	25.41	34.70
	NO_2	29.705	28.40	23.21	23.74	24.23	24.77	29.55	25.48	16.15667	16.34	17.07	18.07
	SO_2	9.68	9.6	7.67	6.93	5.01	6.38	9.47	7.22	9.977619	7.85	7.38	16.19
% Change in 2020													
Cities	Pollutants	w.r.t. 2018				w.r.t. 2019				w.r.t. 2019			
		I	II	III	IV	I	II	III	IV	I	II	III	IV
Delhi	$PM_{2.5}$	50	6	36	35	49	-19	48	6	-19	78	48	6
	NO_2	80	80	73	69	75	78	73	66	49	49	52	66
	SO_2	12	-29	-12	45	27	-55	-230	58	-55	-230	-230	58
Mumbai	$PM_{2.5}$	-	-	-	-	42	83	100	54	83	100	100	54
	NO_2	-	-	-	-	-0.6	-102	-183	-64	-102	-183	-183	-64
	SO_2	-	-	-	-	8	66	56	29	66	56	56	29
Chennai	$PM_{2.5}$	51.6	64.6	12.1	-7	13	-8	60	53	-8	60	60	53
	NO_2	-22	86.4	60.1	46	22	17	24	30	17	24	24	30
	SO_2	30.9	32.7	35.6	18	7	47	61	52	47	61	61	52
Kolkata	$PM_{2.5}$	-	-	-	-	51	62	-97	-150	62	-97	-97	-150
	NO_2	-	-	-	-	-64	-13	-408	-101	-13	-408	-408	-101
	SO_2	-	-	-	-	61	57	64	20	57	64	64	20
Bengaluru	$PM_{2.5}$	14	44	38	43	17	21	24.9	6	21	24.9	24.9	6
	NO_2	-39	22	30	31	-157	-228	-179	-41	-228	-179	-179	-41
	SO_2	-52	-19	-40	-31	30	37	45	26	37	45	45	26
Hyderabad	$PM_{2.5}$	35	44	28	18	33	34	42	29	34	42	42	29
	NO_2	45	42	26	23	-99	-23	22	-124	-23	22	22	-124
	SO_2	-3	18	3	-133	-99	-23	22	-124	-23	22	22	-124

Ahmedabad (74%), while the minimum was at Agra (26%) and Nagpur (52%). However, the mean mass concentration of SO_2 was shown (both enhancement and reduction) during 2020 as compared to the previous years, which could be due to the continuous operation of coal-based power plants under essential services (Sharma *et al.* 2020) and needs to be studied further in detail. The mean mass concentration of air pollutants during a different phase of lockdown in the year 2018, 2019, 2020 along with percentages is summarised in tables 5 (for urban sites) and 6 (for suburban sites). Additionally, in the suburban category, Gaya and Gurugram were sought to be most beneficial in the context of $\text{PM}_{2.5}$ concentrations where it reduced to more than twice as compared to previous years while in terms of gaseous pollutants (NO_2 , SO_2) maximum reduction observed at Patiala followed by Muzaffarpur (table 6). Recently, Sharma *et al.* (2020) conducted a study over different stations of India and observed an overall reduction of 43% and 31% in $\text{PM}_{2.5}$ and PM_{10} mass concentrations, respectively as compared to the same period of the past 4 years. Srivastava *et al.* (2020) have also found similar results, i.e., a substantial improvement in ambient air quality over two capital cities (Delhi and Lucknow). A similar trend was observed in three metro cities (Delhi, Mumbai, and Chennai) of the country (Jain *et al.* 2020; Sharma *et al.* 2020). Kumar (2020) reported that during the lockdown period in India, aerosols and NO_2 reduced sharply with a maximum drop of about 60 and 45%, respectively. Jain *et al.* (2020) also reported ~41% and 14% decline in $\text{PM}_{2.5}$ levels over Delhi and Chennai, respectively, during the lockdown period as compared to the pre-lockdown period. Wang *et al.* (2020) in a recent analysis of $\text{PM}_{2.5}$ over Beijing, Shanghai, Guangzhou, and Wuhan cities during the lockdown period reported significant improvement in air quality as a result of reduced industrial activities and lesser public transport and use of personal vehicles. Xu *et al.* (2020) conducted a study over three cities of China during the lockdown and reported a decline in the levels of pollutants like $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO, and NO_2 . In another study, Nakada and Urban (2020) also reported reduced concentrations of NO, NO_2 , and CO, in the city of São Paulo, Brazil during the partial lockdown in February to April 2020 in comparison to the five-year (2015–2020) average of the same months. Similarly, decline in air pollution has been reported by many researchers all over the world. For example, Tobías *et al.* (2020) reported

improved air quality during the lockdown in Barcelona using the Copernicus tropospheric monitoring service data. They have reported a reduction of 31% in particulate matter and also a 51% reduction in NO_2 during the lockdown period as compared to previous months. Similarly, Zambrano-Monserrate *et al.* (2020) also assessed the air quality over China and observed 20–30% reduction in February 2020 as compared to the same timeline of past 3 years. In an important study conducted over important cities of the world, Chauhan and Singh (2020) have observed improved air quality in respect of $\text{PM}_{2.5}$ concentrations. Thus, a comparative phase-wise air pollutant reduction, discussed in an earlier section indicates that lockdown improved air quality at all the study sites, providing us baseline statistics for these pollutants, which may be further useful for policymakers to define new goals to achieve a clean and sustainable environment. However, a strong possibility of enhancement in air pollution concentration after the uplifting of lockdown will again reduce the air quality.

3.3 Lessons for future mitigation of air quality in India

The novel coronavirus disease (COVID-19) poses a serious threat to the economy of the world and human health as well. To control the spread of this pandemic, the Government of India imposed a lockdown in the entire country in different phases and state governments also started acting collaboratively to grapple with this unprecedented crisis. Due to this complete lockdown, a huge economic loss is reported worldwide, and recently, the Government of India declared a negative growth rate (i.e., -23.9%) of gross domestic product (GDP), which is mainly attributed to the restriction of almost all the anthropogenic activities during the lockdown. As a positive consequence of lockdown, various places in India showed a significant improvement in their air quality which is reflected from various research works done dealing with air quality improvement in the lockdown period. But this may not be the permanent solution as it has rather more negative effects on our economy. Thus, in the present scenario, Environment Pollution (Prevention and Control) Authority, India should come up with some scientific approach through which air quality at highly populated

Table 5. Mean mass concentration of $PM_{2.5}$, NO_2 and SO_2 over megacities during different phases of lockdown period in 2018, 2019, 2020 and respective percentage change in 2020.

Cities	Pollutants	Mean value of pollutants											
		2018				2019				2020			
		I	II	III	IV	I	II	III	IV	I	II	III	IV
Ahmedabad	$PM_{2.5}$	110.76	65.39	50.88	55.05	86.85	102.69	46.07	44.17	32.53	28.36	25.68	27.15
	NO_2	90.13	47.66	30.38	36.60	71.85	70.71	72.81	90.34	28.21	18.10	18.18	21.23
	SO_2	64.49	38.63	61.71	56.48	23.70	62.39	89.15	105.00	26.98	25.48	11.26	98.7
Jaipur	$PM_{2.5}$	47.92	53.85	54.93	57.59	39.90	44.3	57.77	36.79	19.27	25.02	29.17	42.33
	NO_2	32.30	31.63	32.14	27.57	38.33	41.67	37.90	47.60	11.09	11.30	15.82	19.63
	SO_2	8.93	7.83	7.77	12.02	12.69	10.92	8.53	10.67	11.13	10.88	9.33	10.01
Kanpur	$PM_{2.5}$	54.45	53.49	62.10	86.13	70.55	63.03	68.54	60.68	39.97	49.25	44.04	50.91
	NO_2	54.51	64.53	53.73	58.645	62.78	60.07	68.27	56.01	14.05	20.091	22.48	37.06
	SO_2	9.63	11.58	8.35	9.68	7.58	11.62	21.93	17.68	15.07	15.00	11.69	9.90
Nagpur	$PM_{2.5}$	49.43714	37.42	50.09	48.00	53.29	44.81	37.52	42.98	22.50	23.46	20.40	23.4
	NO_2	40.45	38.36	32.92	30.95	47.58	39.02	20.25	39.40	22.94	20.44	17.74	20.19
	SO_2	16.61	16.38	16.83	13.88	19.82	18.08	10.58	13.42	1.75	1.79	2.21	2.42
Agra	$PM_{2.5}$	74.55	70.65	80.44	82.55	75.87	68.90	76.19	50.31	42.62	49.38	44.12	59.53
	NO_2	44.94	41.66	36.01	40.13	29.21	37.84	35.03	39.11	45.44	39.38	29.34	29.78
	SO_2	6.58	8.41	9.54	8.41	10.90	12.86	28.85	14.37	26.66	28.53	29.96	26.51
Nasik	NO_2	–	–	–	–	17.66	24.56	32.96	25.69	21.76	20.32	18.33	12.95
	SO_2	–	–	–	–	5.531	6.06	3.27	3.59	2.51	2.36	2.16	1.87
	$PM_{2.5}$	–	–	–	–	52.32	54.88	45.94	49.32	30.61	27.51	23.32	32.42
Varanasi	NO_2	–	–	–	–	12.26	11.82	17.27	16.8	11.63	10.45	8.86	14.41
	SO_2	–	–	–	–	25.036	24.02	35.95	35.43	23.95	22.29	21.02	23.57
	$PM_{2.5}$	75.57	75.29	78.34	90.33	97.74	96.96	91.70	93.85	57.10	32.57	38.12	38.80
Amritsar	NO_2	92.03	79.21	60.68	41.62	70.97	69.54	74.96	58.99	32.62	31.67	29.50	24.28
	SO_2	27.20	27.72	23.93	23.46	33.62	32.01	31.59	36.45	32.79	32.69	34.48	57.53
	$PM_{2.5}$	47.91	47.95	64.79	73.72	57.64	46.57	62.32	40.12	20.12	18.27	31.05	38.39
Kota	NO_2	23.49	10.63	8.24	8.40	32.43	15.99	30.75	22.69	11.37	16.48	16.99	14.06
	SO_2	4.65	5.76	5.53	5.71		55.71	25.01	20.60	7.11	8.98	9.47	17.403
	$PM_{2.5}$	67.46	61.33	71.98	83.98	68.01	68.02	45.48	42.43	27.71	27.52	28.9	35.52
	NO_2	12.28	9.79	9.96	7.61	32.53	32.53	21.5	16.74	12.74	12.15	22.05	7.84
	SO_2	17.65	8.41	9.99	10.92	10.82	8.84	7.90	9.82	10.08	8.34	8.82	8.62
% Change in 2020													
Cities	Pollutants	w.r.t. 2018				w.r.t. 2019							
		I	II	III	IV	I	II	III	IV				
Ahmedabad	$PM_{2.5}$	70	56	46	26.49	62	72	49	– 15				
	NO_2	68	62	50	42	60	74	58	76				
	SO_2	58	34	– 20	16.71	– 13	59	– 9	6				
Jaipur	$PM_{2.5}$	59	54	47	26	51	44	50	– 6				
	NO_2	65	64	51	29	71	73	58	58				
	SO_2	– 24	– 39	– 20	17	12	0	– 9	1				

Table 5. (Continued)

Cities	Pollutants	% Change in 2020							
		w.r.t. 2018				w.r.t. 2019			
		I	II	III	IV	I	II	III	IV
Kanpur	PM _{2.5}	27	8	29	41	43	22	36	16
	NO ₂	74	69	58	37	78	67	67	34
	SO ₂	− 56	− 30	− 40	− 2	− 99	− 29	47	44
Nagpur	PM _{2.5}	54	37	59	51	58	48	46	46
	NO ₂	43	47	46	35	52	48	12	49
	SO ₂	89	89	87	83	91	90	79	82
Agra	PM _{2.5}	43	30	45	28	44	28	42	− 18
	NO ₂	− 1	5	19	26	− 56	− 4	16	24
	SO ₂	− 305	− 239	− 214	− 215	− 144	− 122	− 4	− 84
Nashik	NO ₂	−	−	−	−	− 23	17	44	50
	SO ₂	−	−	−	−	55	61	34	48
	PM _{2.5}	−	−	−	−	41	50	49	34
Varanasi	NO ₂	−	−	−	−	5	12	49	14
	SO ₂	−	−	−	−	4	7	42	33
	PM _{2.5}	24	57	51	57	42	66	58	59
Amritsar	NO ₂	65	60	51	42	54	54	61	59
	SO ₂	− 21	− 18	− 44	− 145	2	− 2	− 9	− 58
	PM _{2.5}	58	62	52	48	65	61	50	4
Kota	NO ₂	52	− 55	− 106	− 67	65	− 3	45	38
	SO ₂	− 53	− 56	− 71	− 204		84	62	16
	PM _{2.5}	59	55	60	58	59	60	36	16
	NO ₂	− 4	− 24	− 121	− 3	61	63	− 3	53
	SO ₂	43	1	12	21	7	6	− 12	12

and fast-growing cities should be sustainable and achievable.

Municipalities have been involved in implementing mitigation strategies. Several nations are implementing municipal climate mitigation policies to deal with the growing urban traffic as well as with the energy sector. Climate change adaptation and mitigation could be seen as complementary and thus, the scientific community has thought of merging these two aspects which could be jointly called as ‘adaptation institutionalisation’ (Göpfert *et al.* 2019). However, there is lack of systematic approach to envisioning this joint institutionalisation of climate change mitigation and adaptation. Thus a model of three-dimensional cities has been proposed, according to which star-shaped cities could serve as a better approach to climate mitigation than radially symmetric cities (Pierer and Creutzig 2019). In India also, several air pollution mitigation policies and legislative laws are implemented to achieve “National Clean Air Program (NCAP)” goal. For example, successful implementation of the latest policies for the power sector

(MoEFCC 2015) will reduce total national SO₂ emission by 50% in 2030, while the introduction of BS-VI in 2020 for new “all on-road vehicle categories” followed by for non-road machinery (for example, agricultural tractors, industrial and forestry machinery, etc.) in 2024 will also help in the reduction of air pollutant from the transport sectors (MoRTH 2016). In addition, the Government of India also launched several schemes to reduce the PM_{2.5} emissions from the residential sectors. For example, in 2016, Pradhan Mantri Ujjwala Yojana was launched under which nearly 80 million Liquid Petroleum Gas (LPG) connections to Below Poverty Line (BPL) households are targetted (Sankhyayan and Dasgupta 2018).

Therefore, the current situation provides us a rare opportunity to capture baseline data for various environmental metrics which could be very useful for the policymakers to build sustainable models. The closure of industrial and commercial establishments and shutdown of traffic seen during the lockdown, can perhaps also be used at times of extremely poor air quality situations; however,

Table 6. Mean mass concentration of $PM_{2.5}$, NO_2 and SO_2 over megacities during different phases of lockdown period in 2018, 2019, 2020 and respective percentage change in 2020.

Cities	Pollutants	Mean value of pollutants												% Change in 2020							
		2018				2019				2020				w.r.t. 2018				w.r.t. 2019			
		I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
Udaipur	$PM_{2.5}$	34.74	72.14	43.77	65.6	58.45	41.70	43.93	43.93	15.08	23.18	25.46	39.80	53	61	56	38	17	12	12	7
	NO_2	23.15	36.01	39.48	81.87	76.02	29.85	27.62	19.91	2.87	6.07	6.93	11.86	79	71	65	53	74	66	52	31
	SO_2	60.35		8.50	2.81	6.99	7.06	9.91	10.23	4.39	5.67	6.64	13.61	24	33	17	43	35	43	15	27
Gurugram	$PM_{2.5}$	73.66	83.42	82.67	92.66	72.60	81.97	108.1	76.52	34.67	44.48	55.85	49.98	53	47	32	46	52	46	48	35
	NO_2	23.78	34.40	19.76	32.76	8.39	25.45	27.42	30.06	10.72	10.35	22.79	15.09	55	70	-15	54	-28	59	17	50
	SO_2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Jalandhar	$PM_{2.5}$	44.61	53.5	67.24	61.01	44.47	41.35	44.40	42.35	22.43	32.99	42.73	49.02	50	38	36	20	50	20	4	-16
	NO_2	9.67	7.78	27.12	13.25	22.02	18.39	30.81	27.17	9.87	7.55	6.20	8.26	-2	3	77	38	55	59	80	70
	SO_2	12.87	6.8	6.03	7.84	12.18	10.83	19.98	20.79	9.10	6.70	8.93	-	29	1	-48	100	25	38	55	100
Patiala	$PM_{2.5}$	34.74	72.14	43.77	65.69	58.45	41.70	39.38	43.93	15.08	23.18	25.46	39.80	57	68	42	39	74	44	35	9
	NO_2	23.15	36.01	39.48	81.87	76.02	29.85	27.62	19.91	2.87	6.07	6.93	11.86	88	83	82	86	96	80	75	40
	SO_2	60.35	-	8.50	2.81	6.99	7.06	9.91	10.23	4.39	5.67	6.64	13.61	93	-	22	-383	37	20	33	-33
Muzaffarpur	$PM_{2.5}$	71.47	52.58	46.17	46.46	75.94	57.71	72.57	52.84	66.48	28.42	39.16	23.13	7	46	15	50	12	51	46	56
	NO_2	80.46	36.2	41.64	49.11	34.80	2.66	3.80	4.00	24.10	24.12	24.06	24.05	70	33	42	51	31	-805	-532	-500
	SO_2	64.36	93.56	108.1	99.79	19.34	20.16	19.98	19.38	25.14	17.6	17.24	14.78	61	81	84	85	-30	12	14	24
Gaya	$PM_{2.5}$	168.5	117.1	83.00	90.31	67.93	62.49	63.02	62.11	47.57	40.1	44.10	47.24	72	66	47	48	30	36	30	24
	NO_2	40.65	23.6	28.99	26.90	24.91	19.04	20.03	20.29	2.74	16.85	16.96	25.38	93	29	41	6	89	12	15	-25
	SO_2	6.30	2.96	4.30	5.24	13.57	13.86	13.84	11.15	14.40	14.85	15.61	16.22	-128	-401	-263	-209	-6	-7	-13	-45

partial lockdown in stages could be incorporated as an emergency action plan which comes into action when AQI (Air Quality Index) is severe/poor/moderate for a short duration (for example, Haze episode during winters in Delhi). Reductions in NO₂ and SO₂ from traffic and manufacturing sectors have long been considered as the normal protocol in implementing regulatory policies. The recent results showed that such a protocol achieves only limited effects on PM, NO₂, and SO₂, and other air pollutant levels, without simultaneous emission controls from big power plants and heavy manufacturing and chemical industry (Le *et al.* 2020). Therefore, it is suggested to make a more comprehensive regulation of precursor gases from all possible sectors when developing an emission control strategy.

In addition, like COVID-19, we need to communicate with people using a separate portal to share pollution levels, the actions taken, and health precautions/advisory for the vulnerable people in society on a large scale. There is also a need for social awareness and behavioural shifts in local people with a focus on sustainable means such as the use of public transportation, cleaner fuels, abiding by regulations, and reduced stubble burning.

4. Conclusion

In our study, we have examined the most common ambient air pollutants concentration over 22 cities across the whole country distinguished by three different categories, i.e., megacity, urban and sub-urban, during and before the lockdown period imposed due to COVID-19 outbreak. At all the places, there is a significant reduction in levels of air pollutants (PM_{2.5}, NO₂, and SO₂) and at most of the sites, air pollutants concentration is found within the National Ambient Air Quality Standard (i.e., NAAQS). All the cities included in the study boast of a significant reduction in PM_{2.5} levels ranging from 10% to 70% during 2020 as well as up to 72% compared to the previous two years. In addition, a significant reduction in gaseous pollutants (NO₂ and SO₂) was also found during the different phases of lockdown; however, enhancement (particularly highly industrialized sites or sites in IGB) was found during the second phase of lockdown onwards. In general, the whole country has witnessed slashed air pollution due to imposed lockdown but the situation could be reversed due

to the uplifting of lockdown similar to the pre-lockdown phase with an increased level of pollutants. However, the complete lockdown situation has allowed policymakers to make a balance between environmental and anthropogenic activities to mitigate the air pollution in ambient air by promoting e-governance and work from home policy for corporate offices. A well-planned and short-term lockdown (for a maximum of 5–7 days) in a periodical manner (after every 6–9 months) could be an alternative effective tool for future air pollution mitigation policies.

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Author statement

Vineet Pratap: Writing – Original draft and software. Shani Tiwari: Methodology, conceptualization, data curation, supervision, and reviewing and editing. Akhilesh Kumar: Visualization and plotting. Abhay Kumar Singh: Writing – reviewing, supervision and editing.

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