

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

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Abstract

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 twenty-two 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 (Srivastava *et al.* 2017; Li *et al.* 2015; Chen *et al.* 2018). It has severe impacts on air quality, atmospheric visibility reduction, human health as well as climate change also (Cai *et al.* 2017; Chen *et al.* 2018; 2017). It has one of the greatest health risks today and ranked at 4th position on the cause of premature death resulting in millions of per-mature deaths 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 the 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 (Guo *et al.* 2019; Tiwari *et al.* 2016). Recently, World Health Organisation (WHO) reported that nearly 90% of the world population is exposed to polluted air due to exceeding of PM_{2.5} exposure guideline (~35 µg/m³) (WHO BoD, 2018). In addition to this, Indian cities continuously ranked in the top twenty 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 five 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 a result in progressive respiratory failure and even death also (Sohrabi *et al.* 2020; Chen *et al.* 2020). As of May 31st, 2020, an outbreak of COVID-19 has infected over 6.24 million people worldwide and the death toll has reached approximately 3,79,369. The number of new cases of infection is still increasing at a high rate causing serious damage to the economy of the whole world and a serious threat to humankind as well since no specific medication and pharmacological treatment for COVID-19 yet reported (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 in the country. As of 31st May 2020, nearly 2286 peoples were died due to COVID-19 while almost 190648 people confirmed COVID -19

positive (<https://www.covid19india.org/>). Thus, considering the severity of the COVID-19 pandemic and to control alarming increasing COVID-19 cases, the first nationwide lockdown had been declared for fourteen hours 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 different businesses like markets, shops, tourism, hotels and restaurants, construction work, mining, and other activities as well. The transport sector was also almost suspended as very little communication was allowed both 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-wide drastically reduced the air pollution in India as well as in the whole world (Sharma *et al.* 2020; Chauhan *et al.* 2020; Bao and Zhang, 2020; Saadat *et al.* 2020; Pani *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 the 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 of the year 2018–2020, over twenty-two 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 details in the upcoming section.

2. Site description, data set, and methodology:

To investigate the impact of COVID – 19 induced nationwide lockdown on air pollution reduction, air pollutants data from the twenty – two 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) includes Delhi, Mumbai, Kolkata, Bengaluru, Hyderabad, and Chennai while the urban sites are Ahmedabad, Kanpur, Agra, Udaipur Jaipur, Varanasi, Nagpur, Nashik, Pune, Kota however, the suburban sites are,

Gurugram, Amritsar, Patiala, Jalandhar, Muzaffarpur, and Gaya. The megacity Mumbai is mostly affected 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; Rajput *et al.* 2017; Chauhan *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. PM_{2.5}, NO₂, SO₂ (in µg/m³) 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 (the United States Environmental Protection Agency) approved PM_{2.5} Monetizing analyzer is used for the measurement of PM_{2.5} particles which works on the principle of β-ray attenuation. Particulate sampled through the instrument and collected on fiberglass filter tape and an internal microprocessor automatically calculates the concentration of PM_{2.5}. The airflow rate of the sampler is maintained at 16.7 liters/minute and has the PM concentration range of 0-1000 µg/m³ having ± 1% uncertainties (CAAQMS Guidelines, 2019). For measurement of NO₂, ambient oxides of nitrogen analyzer are used which has range 0-2000 ppb and works on the principle of Chemi-luminescence with the lowest detectable limit ~ 1 ppb, noise level 0.5 ppb and having ± 1% uncertainties (CAAQMS Guidelines, 2019). Moreover, an ambient sulfur dioxide analyzer is used for monitoring SO₂ which works on the principle of UV Fluorescence and has a range 0-200 ppb with a noise level of 0.5 ppb and having ± 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. PM_{2.5}, NO₂, and SO₂ (in µg/m³) from March, 1st to 31st May 2020 is shown in Figure 2 - 4. The figure clearly shows a large variation in all three

studied air pollutants with a significant reduction in air pollutants and which more prominent over highly populated and industrialized places like megacities and urban areas (Figure 2 and Figure 3). The mean mass concentration of PM_{2.5} was found to be in the range of 25 – 84 µg/m³ before the lockdown over the studied sites which reduced up to 71% and was found to be in the range of 11 – 109 µg/m³ 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 PM_{2.5} was found during the first two phases of lockdown however, a sharp increase in PM_{2.5} (~40%) during the end of the first and start of the second phase 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 (Tiwari *et al.*, 2019; Singh *et al.*, 2016). However, enhancement in 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. The mean mass concentration of air pollutants at megacities, urban and sub-urban sites before and during different phases of lockdown are summarized in Table 1 – 3 respectively. Apart from this, enhancement of PM_{2.5} at other locations over IGB (like Amritsar, Jalandhar Patiala) during the third and fourth phase 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 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 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 month, particularly over the north Indian region (Tiwari *et al.* 2019, 2013; 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 a high-temperature combustion process. The massive reduction in NO₂ 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 NO₂ concentrations due to restriction on industrial activities and almost no traffic during the lockdown phase. In Chennai, NO₂ level reduced up to 54% whereas Hyderabad and Bengaluru faced up to 40 % reduction of NO₂ in its ambient air. Recently, Ajay *et al.*, (2020) reported a reduction (> 60%) in fossil fuel emitted black

carbon (a constituent of PM_{2.5}) concentration over Bengaluru during the first phase of lockdown. While on the other hand industrialized major urban cities like Ahmedabad, Kanpur, also witnessed a significant reduction in NO₂ concentration which reached up to 49 % and 65 % respectively. Other cities in this category also showed a significant reduction in NO₂ confirming the positive aspect of lockdown on the environment. A slight enhancement in NO₂ was observed over the Northern 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 NO₂ and other co-emitter pollutants into 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; Sarkar *et al.* 2018; Grover and Chowdhary 2019; Liu *et al.* 2018; Chawala and Sandhu. 2020 and references therein) as well as other parts of the world also (Chen *et al.* 2017; Paralovo *et al.* 2019; Kang *et al.* 2019). A higher concentration of NO₂ together with NH₃ 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 SO₂ is also observed over most of the studied sites. An enhancement in NO₂ 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 SO₂ (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 SO₂ during the different phases of lockdown. The enhancement in SO₂ 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 the diesel, coal or heavy fuel oil, and the transport sector can be neglected as NO₂ is not increased. Further, 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, 2019. Significant depreciation in the mean mass concentration of ambient air pollutants, during different phases of lockdown, is found in the year 2020 as compared to 2018 and 2019 (Table 4, 5, 6) due to restricted anthropogenic activities to avoid the spread of the COVID – 19.

The imposed lockdown causes a drastic change in air quality standard overall studied cities as PM_{2.5} concentrations at most of the places found 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 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 which caused merely no traffic and industrial activities. Delhi experienced up to ~ 50% diminution in PM_{2.5} levels during different phases of lockdown concerning earlier two years i.e. 2018, 2019 whereas up to 80% and 50% reduction in NO₂ and SO₂ concentrations respectively during different phases of the lockdown (Table 4). Nearly, 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 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 phase 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 phase 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 magnitude. In contrast, over Mumbai, the mean mass SO₂ concentration was found high (up to 3 times) during different phases of 2020 than the previous year 2019. Similarly, the reduction in PM_{2.5} concentrations 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 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 observed at Kanpur (78%) followed by Ahmedabad (74%) while the minimum at Agra (26%) and Nagpur (52%). However, the mean mass concentration of SO₂ showed (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 study further in details. The mean mass concentration of air pollutants during a different phase of lockdown in the year 2018, 2019, 2020 along with percentages is summarized in Table 5 (for urban sites) and Table 6 (for sub-urban sites). Additionally, in the suburban category, Gaya and Gurugram were sought to be most beneficial in the context of PM_{2.5} concentrations where it reduced to more than twice as compared to previous years while in terms of gaseous pollutants (NO₂, SO₂) 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 PM_{2.5} and PM₁₀ mass concentrations respectively as compared to the same period of the past four 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 NO₂ reduced sharply with a maximum drop of about 60 and 45 %, respectively. Jain *et al.* (2020) also reported ~ 41 % and 14 % decline in 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 PM_{2.5} over Beijing, Shanghai, Guangzhou, and Wuhan cities during the lockdown period and 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 PM_{2.5}, PM₁₀, SO₂, CO, and NO₂. In another study, Nakada and Urban (2020) also reported reduced concentrations of NO, NO₂, 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, Tobias *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 nitrogen dioxide 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 three years. In an important study conducted over important cities of the world, Chauhan *et al.*

(2020) have observed improved air quality in respect of 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 both: 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 very scientific approach through which air quality at highly populated 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 a lack of a 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 reduction in 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 targeted (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, 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 behavioral 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 twenty-two 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) was observed, and at most of the sites air pollutants concentration found within the National Ambient Air Quality Standard (i.e. NAAQS). All the cities included in the study boasts 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 also 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 5 – 7 days) in a periodical manner (after every six to nine months) could be an alternative effective tool for the future air pollution mitigation policies.

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Caption to Figures:

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

Figure 2: Temporal variation of daily mean concentration (in $\mu\text{g}/\text{m}^3$) of PM_{25} , NO_2 and SO_2 at different Megacities during 1st March 2020 to 31st May 2020.

Figure 3: Similar to Fig 2 but for Urban locations.

Figure 4: Similar to Figure 2 but for Sub-urban locations .

Caption to Tables:

Table 1: Mean mass concentration of air pollutants before and during lockdown 2020 over mega cities

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

Table 3: Mean mass concentration of air pollutants before and during lockdown in year 2020 over sub-urban cities

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

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

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

Figures:

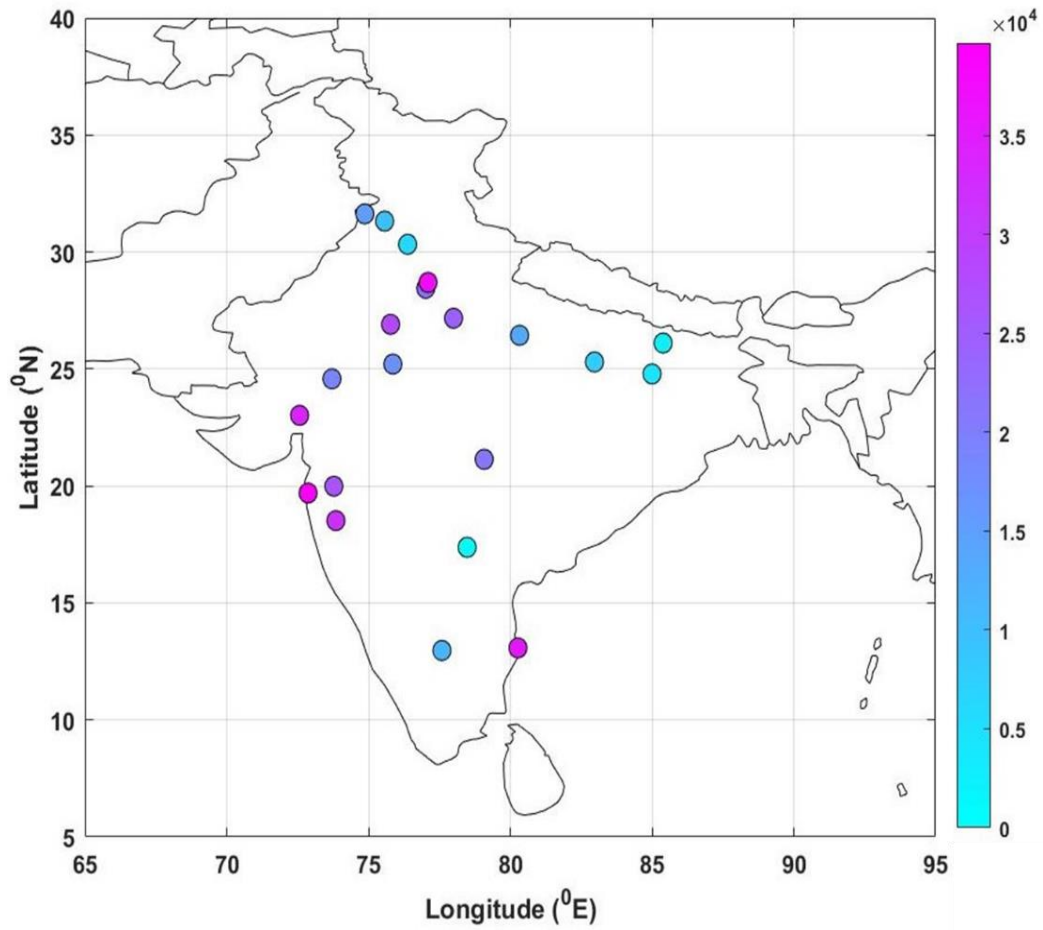


Figure 1: Location map of twenty-two different cities studied in the present study. The color scale represents the number of confirmed COVID – 19 cases at the study locations on 31st May 2020.

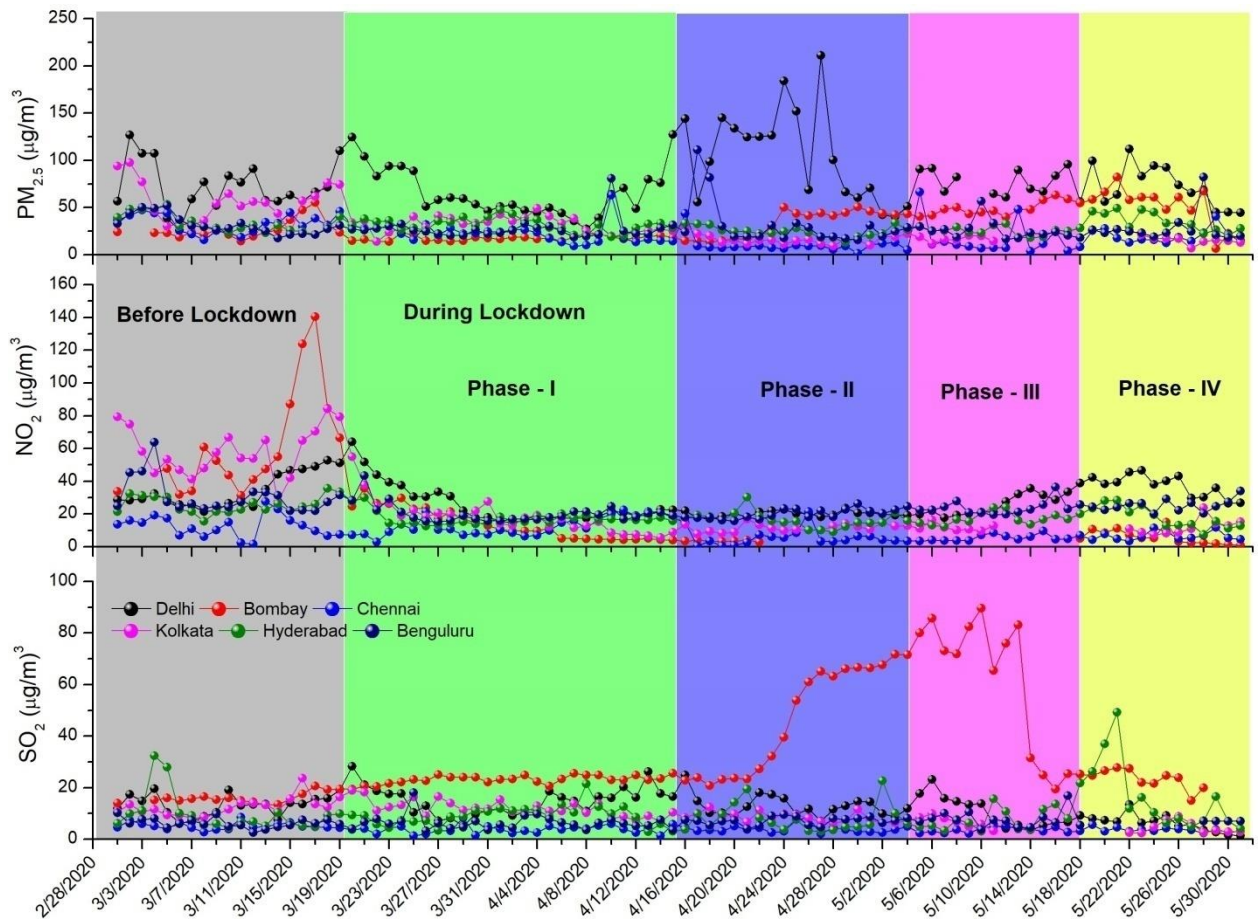


Figure 2: Temporal variation of daily mean concentration (in $\mu\text{g}/\text{m}^3$) of $\text{PM}_{2.5}$, NO_2 , and SO_2 at different Megacities from 1st March 2020 to 31st May 2020.

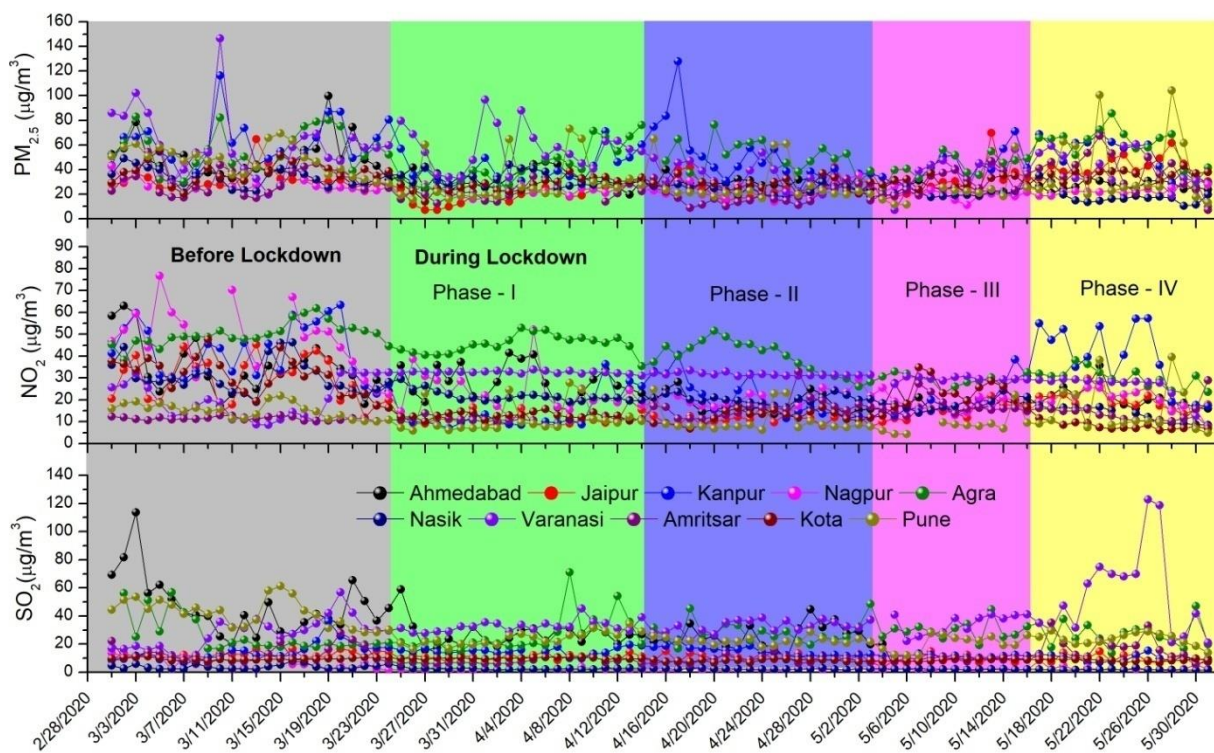


Figure 3: Similar to Figure 2 but for Urban locations.

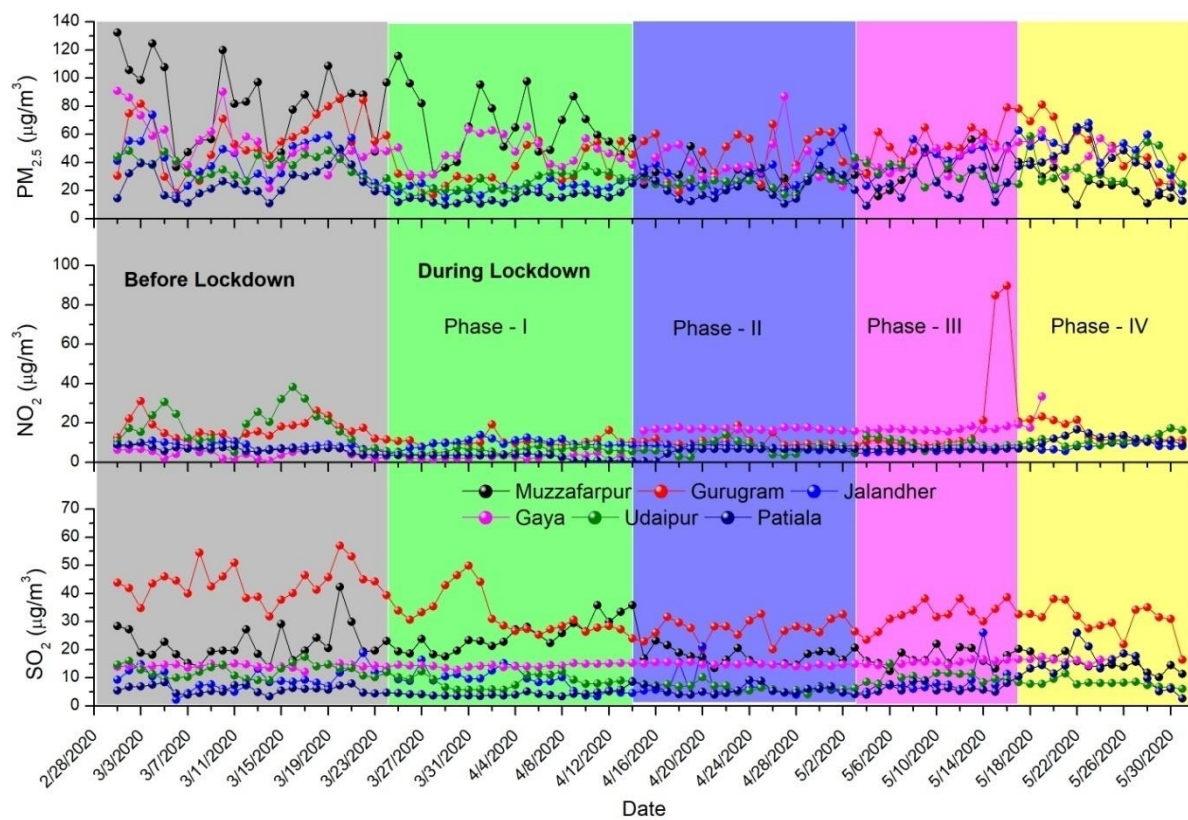


Figure 4: Similar to Figure 2 but for sub-urban locations.

Table 1: Mean mass concentration of air pollutants before and during lockdown in year 2020 over mega cities

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

Table 2: Mean mass concentration of air pollutants before and during lockdown in year 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
Nashik	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

Table 3: Mean mass concentration of air pollutants before and during lockdown over in year 2020 sub - urban 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

Table 4: Mean mass concentration of PM_{2.5}, NO₂ and SO₂ 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	I	I	II	II	I
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	50	6	36	3 5	49	- 1 9	48	6
	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	80	80	73	6 9	75	7 8	73	6 6
	SO ₂	15. 24	10. 20	9.3 6	11.4 9	26. 44	26. 30	22. 13	15. 05	13.35	13. 16	10. 54	6.26	12	- 29	- 12	4 5	49 .5	4 9	52	5 8
Mum bai	PM _{2.5}	----	----	----	----	24. 70	20. 51	14. 59	15. 41	17.99	31. 96	48. 25	50.75	---	---	---	-- --	27	- 5 5	- 23 0	- 2 9
	NO ₂	----	----	----	----	18. 40	22. 34	14. 45	12. 74	10.61	3.5 8	5.79	---	---	---	-- --	42	8 3	10 0	5 4	
	SO ₂	----	----	----	----	23. 43	21. 96	22. 14	14. 32	23.58	44. 41	62. 85	23.51	---	---	---	-- --	- 0. 6	- 1 0 2	- 18 3	- 6 4

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	51.6	64.6	12.1	-7	8	6	56	2
	NO₂	10.94	47.22	13.32	12.44	15.43	5.85	13.41	14.26	13.36	6.37	5.31	6.63	-22	86.4	60.1	46	13	-8	60	5
	SO₂	5.36	6.06	5.76	4.402778	4.75	4.96	4.93	5.20	3.70	4.07	3.71	3.61	30.9	32.7	35.6	18	22	17	24	3
Kolkata	PM_{2.5}	----	----	----	----	35.64	31.57	45.72	34.62	33.13	16.46	17.57	16.38	---	---	---	--	7	4	61	5
	NO₂	----	----	----	----	31.156	30.07	6.08	4.84	15.12	11.39	11.99	12.1125	---	---	---	--	51	62	-97	-1
	SO₂	----	----	----	----	6.93	7.63	1.34	2.182	11.42	8.66	6.83	4.391	---	---	---	--	-64	-13	-408	-1
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	14	44	38	43	61	57	64	2
	NO₂	13.01	25.51	33.79	36.95	22.03	25.22	31.58	27.16	18.20	19.82	23.71	25.36	-39	22	30	31	17	21	24.9	6
	SO₂	4.3	5.75	5.62	5.07	2.54	2.09	2.82	4.70	6.54	6.87	7.88	6.66	-52	-19	-40	-31	-157	-2	-179	-41

																			2			8
Hyder	PM_{2.5}	49.	44.	35.	42.5	45.	39.	46.	47.		24.	25.		35	44	28	1	30	3	45	2	
abad		00	36	57	5	12	37	20	00	31.55	73	41	34.70				8		7		6	
	NO₂	29.	28.	23.	23.7	24.	24.	29.	25.	16.15	16.	17.		45	42	26	2	33	3	42	2	
		705	40	21	4	23	77	55	48	667	34	07	18.07				3		4		9	
	SO₂	9.6		7.6		5.0	6.3	9.4	7.2	9.977	7.8	7.3		-3	18	3	-	-	-	22	-	
		8	9.6	7	6.93	1	8	7	2	619	5	8	16.19				1	99	2		12	
																	3	3	3		4	

Table 5: Mean mass concentration of PM_{2.5}, NO₂ and SO₂ over urban cities 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
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	7.0	5.6	4.6	26.49	6.2	72	49	-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	6.8	6.2	5.0	42	6.0	74	58	76
	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	5.8	3.4	-2.0	16.71	-1.3	59	-9	6
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	5.9	5.4	4.7	26	5.1	44	50	-6
	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	6.5	6.4	5.1	29	7.1	73	58	58
	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	-2.4	-3.9	-2.0	17	1.2	0	-9	1
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	2.7	8	2.9	41	4.3	22	36	16

	NO₂	54.5 1	64.5 3	53. 73	58.6 45	62.7 8	60.0 7	68. 27	56.0 1	14. 05	20.0 91	22. 48	37.0 6	7 4	6 9	5 8	37 8	7 8	67	67	34
	SO₂	9.63	11.5 8	8.3 5	9.68	7.58	11.6 2	21. 93	17.6 8	15. 07	15.0 0	11. 69	9.90	- 5 6	- 3 0	- 4 0	-2 9 9	- 9 9	-29	47	44
Nagpur	PM_{2.5}	49.4 3714	37.4 2	50. 09	48.0 0	53.2 9	44.8 1	37. 52	42.9 8	22. 50	23.4 6	20. 40	23.4	5 4	3 7	5 9	51 8	5 8	48	46	46
	NO₂	40.4 5	38.3 6	32. 92	30.9 5	47.5 8	39.0 2	20. 25	39.4 0	22. 94	20.4 4	17. 74	20.1 9	4 3	4 7	4 6	35 2	5 2	48	12	49
	SO₂	16.6 1	16.3 8	16. 83	13.8 8	19.8 2	18.0 8	10. 58	13.4 2	1.7 5	1.79	2.2 1	2.42	8 9	8 9	8 7	83 1	9 1	90	79	82
Agra	PM_{2.5}	74.5 5	70.6 5	80. 44	82.5 5	75.8 7	68.9 0	76. 19	50.3 1	42. 62	49.3 8	44. 12	59.5 3	4 3	3 0	4 5	28 4	4 4	28	42	-18
	NO₂	44.9 4	41.6 6	36. 01	40.1 3	29.2 1	37.8 4	35. 03	39.1 1	45. 44	39.3 8	29. 34	29.7 8	-1	5	1 9	26	- 5 6	-4	16	24
	SO₂	6.58	8.41	9.5 4	8.41	10.9 0	12.8 6	28. 85	14.3 7	26. 66	28.5 3	29. 96	26.5 1	- 3 0 5	- 2 3 9	- 2 1 4	- 21 5 4	- 1 4	-122	-4	-84
Nashik	NO₂	----	----	----	----	17.6 6	24.5 6	32. 96	25.6 9	21. 76	20.3 2	18. 33	12.9 5	-- --	-- --	-- --	---	- 2 3	17	44	50
	SO₂	----	----	----	----	5.53 1	6.06	3.2 7	3.59	2.5 1	2.36	2.1 6	1.87	-- --	-- --	-- --	---	5 5	61	34	48

	PM_{2.5}	----	----	----	----	52.3 2	54.8 8	45. 94	49.3 2	30. 61	27.5 1	23. 32	32.4 2	-- --	-- --	-- --	--- -	4 1	50	49	34
Varanasi	NO₂	----	----	----	----	12.2 6	11.8 2	17. 27	16.8	11. 63	10.4 5	8.8 6	14.4 1	-- --	-- --	-- --	--- -	5	12	49	14
	SO₂	----	----	----	----	25.0 36	24.0 2	35. 95	35.4 3	23. 95	22.2 9	21. 02	23.5 7	-- --	-- --	-- --	--- -	4	7	42	33
	PM_{2.5}	75.5 7	75.2 9	78. 34	90.3 3	97.7 4	96.9 6	91. 70	93.8 5	57. 10	32.5 7	38. 12	38.8 0	2 4	5 7	5 1	57	4 2	66	58	59
Amritsar	NO₂	92.0 3	79.2 1	60. 68	41.6 2	70.9 7	69.5 4	74. 96	58.9 9	32. 62	31.6 7	29. 50	24.2 8	6 5	6 0	5 1	42	5 4	54	61	59
	SO₂	27.2 0	27.7 2	23. 93	23.4 6	33.6 2	32.0 1	31. 59	36.4 5	32. 79	32.6 9	34. 48	57.5 3	- 2	- 1	- 4	- 14	2 5	-2	-9	-58
	PM_{2.5}	47.9 1	47.9 5	64. 79	73.7 2	57.6 4	46.5 7	62. 32	40.1 2	20. 12	18.2 7	31. 05	38.3 9	5 8	6 2	5 2	48	6 5	61	50	4
Kota	NO₂	23.4 9	10.6 3	8.2 4	8.40	32.4 3	15.9 9	30. 75	22.6 9	11. 37	16.4 8	16. 99	14.0 6	5 2	- 5	- 1	- 67	6 5	-3	45	38
	SO₂	4.65	5.76	5.5 3	5.71		55.7 1	25. 01	20.6 0	7.1 1	8.98	9.4 7	17.4 03	- 5	- 5	- 7	- 20		84	62	16
	PM_{2.5}	67.4 6	61.3 3	71. 98	83.9 8	68.0 1	68.0 2	45. 48	42.4 3	27. 71	27.5 2	28. 9	35.5 2	5 9	5 5	6 0	58	5 9	60	36	16

	NO₂	12.2 8	9.79	9.9 6	7.61	32.5 3	32.5 3	21. 5	16.7 4	12. 74	12.1 5	22. 05	7.84	-4	- 2 4	- 1 2 1	-3	6 1	63	-3	53
	SO₂	17.6 5	8.41	9.9 9	10.9 2	10.8 2	8.84	7.9 0	9.82	10. 08	8.34	8.8 2	8.62	4 3	1	1 2	21	7	6	-12	12

Table 6: Mean mass concentration of PM_{2.5}, NO₂ and SO₂ over sub-urban cities 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	-	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	-	12	14	24
	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

Gaya	NO₂	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
	SO₂	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