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Appraisal of COVID-19 lockdown and unlocking effects on the air quality of North India

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ABSTRACT
The COVID-19 pandemic lockdown supposedly provided a ‘window’ of reinstatement to natural resources including the air quality, but the scenario after the phased unlocking is yet to be explored. Consequently, here we evaluated the status of air quality during the 8th phase of unlocking of COVID-19 lockdown (January 2021) at three locations of North India. The first site (S1) was located at Punjab Agricultural University, Ludhiana-PPCB; the second site (S2) at Yamunapuram, Bulandshahr-UPPCB; and the third site (S3) at Okhla Phase-2, Delhi-DPCC. The levels of PM2.5 showed a significant increase of 525.2%, 281.2%, and 185.0% at sites S1, S2, and S3, respectively in the unlock 8 (January 2021), in comparison to its concentration in the lockdown phase. Coherently, the levels of PM10 also showed a prominent increase of 284.5%, 189.1%, and 103.9% at sites S3, S1, and S2, respectively during the unlock 8 as compared to its concentration in the lockdown phase. This rise in the concentration of PM2.5 and PM10 could be primarily attributed to the use of biomass fuel, industrial and vehicular emissions, stubble burning considering the agricultural activities at sites S1 and S2. Site S3 is a major industrial hub and has the highest population density among all three sites. Consequently, the maximum increase (295.7%) in the NO2 levels during the unlock 8 was witnessed at site S3. The strong correlation between PM2.5, PM10, and CO, along with the PM2.5/PM10 ratio confirmed the similar origin of these pollutants at all the three sites. The improvements in the levels of air quality during the COVID-19 lockdown were major overtaken during the various phases of unlocking consequent to the initiation of anthropogenic processes.

1. Introduction
The rapid pace of industrialization towards exhaustive development has impacted the quality of natural resources across the globe (Dong et al., 2021; Shukla and Saxena, 2020d). The issue of air pollution has aggravated primarily due to the increasing population and their sustenance methods. Air pollution has a prominent impact on the economic development at all levels including local and regional scale, claiming ~5 trillion dollars yearly from the global economy (Cao et al., 2019; Hao et al., 2018; TERI, 2019). The changing lifestyles in developing nations including increased traffic on roadways has led to many Indian cities getting included in the list of most polluted cities around the world. India has undergone a multilateral transformation in the living conditions with modified individual habits and a fleet of industrial activities in the last two decades (Shukla and Saxena, 2020d). These activities have resulted into deterioration of air quality, which was also highlighted in a report confirming that 12.5% out of the total deaths in India...
are caused due to air pollution (India Today, 2019). The Indian air quality standards are less stringent in comparison to air quality standards around the world. This has led to continued ignorance towards various anthropogenic activities (biomass burning, stubble burning etc.,) being left unmonitored, and subsequently affecting the air quality, especially in northern India (HT, 2017; Mahato et al., 2020; TNIE, 2019).

Air pollution is the introduction of pollutants into the atmosphere which can damage and degrade the health of human beings and quality of environment (Iriti et al., 2020). Approximately, two million deaths associated with air pollution occur annually across the globe due to the health issues associated with air pollution, such as, damaged lungs, emphysema, respiratory diseases, chronic obstructive pulmonary disease (COPD), bronchitis, cancer etc. (Abdurrahman et al., 2020; Kim et al., 2015). Around 2.1 million deaths are caused due to the particulate matter (PM) in air. The airborne particulate matter is a diverse mixture of suspended particles in solid and liquid state with fluctuating composition and size (Shukla and Saxena, 2020a; Tripathi and Shukla, 2018). The chemical composition of PM particles is highly diversified, potentially including metals such as zinc, copper, nickel, iron, vanadium; organic compounds; biological compounds; nitrites; and sulphates (WHO, 2013). The ‘small particles’ include particles with diameter in the range of 2.5 μm–10 μm, and ‘fine particles’ with <2.5 μm diameter. Particulate matter can enter into air through both natural and anthropogenic activities and is a significant indicator of air pollution (Shah et al., 2013). The size, longevity (sustenance), and transportation of PM particles across huge distances through the atmosphere is directly associated with potential health issues in humans and reduction of human life (Antoniadis et al., 2019; Rinklebe et al., 2019; Shaheen et al., 2020). The impact of particle exposure on human health includes respiratory issues, cardiovascular ailments, cough, allergies, and premature deaths (Atkinson et al., 2011; Friedman et al., 2021; Kim et al., 2015; Meister et al., 2012). The incineration of cut stalks (stubbles) after crop harvesting can be defined as stubble burning. Stubble burning is one of the primary sources of air pollution across the globe. The emissions for stubble burning include both particulate and gaseous pollutants which severely harm the human health and quality of environment. The impact of stubble burning on the air quality of North India has been highlighted in a study by Abdurrahman et al. (2020). The study clearly stated that stubble burning was a major contributor towards gaseous pollutants including particulate matter (PM2.5 and PM10), carbon monoxide (CO), carbon dioxide (CO2), nitrogen oxides (NOx), sulphur oxides (SOx), and methane (CH4). Industrial emissions can be considered as the third most contributing factor after stubble burning and vehicular emissions towards the deteriorated air quality in India (Abdurrahman et al., 2020).

The SARS-CoV-2 virus, more commonly known as Coronavirus (COVID-19), affects the human health through zoonotic transmission (Bhattacharya et al., 2021). It has already infected more than 102 million people worldwide, with more than 2 million deaths (Worldometer, 2021). The spread of COVID-19 across both climatic variant nations (tropical and temperate) highlighted the highly resistant nature of the virus to a wide range of temperature and humid conditions (Ogen, 2020). India is the second most affected country with more than 10 million cases in a span of one year, after the first case being reported on January 30, 2020 (Worldometer, 2021). India, being the third largest democracy in the world with a population of ~1.3 billion, was under great risk considering the increasing number of cases of coronavirus and its rapid transmission. The cumulative cases and deaths due to COVID-19 in India from March 25, 2020 to January 31, 2021 have been illustrated in Fig. 1 using the data from (MoHFW, 2021).

India is one of the biggest economies with the second highest population across the globe. The inclusion of twenty-one Indian cities in the list of most polluted cities verifies the state of environmental pollution across the nation (Chakraborty et al., 2020). The probable direct proportionate relationship between mortality rate owing to COVID-19 and PM2.5 concentration has also been discussed in a study by Wu et al. (2020). Hence, the associated concerns of the potential coherence between PM particles and COVID-19 infectivity and mortality rate cannot be ignored (Ali and Islam, 2020). A nationwide lockdown was imposed by the Government of India on March 24, 2020 for the welfare and safety of a population of ~1.3 billion. The successful implementation of lockdown paved way towards normalization of human activities in phases with required restrictions. The various phases of lockdown and unlocking have been mentioned in Table 1. The industrial activities, regular vehicular movement, public gatherings, public transport, schools were shut down to prevent the outbreak of the disease. The measures taken by the authorities, corona warriors and immense cooperation from public paved the way towards the first phase of unlocking.

Reports about the positive impacts of COVID-19 lockdown on the environment gained immense attention from researchers across the globe (Khan et al., 2021a, 2021b). The excessive pace of urbanization and industrialization across the globe has led to depletion of natural resources without any time towards reinstatement (Khan et al., 2021c; Kumar et al., 2020; Yunus et al., 2020). The COVID-19 lockdown emerged as a reinstatement phase for nature highlighted in various studies (Aravinthasamy et al., 2021; CPCB, 2021; Dutta et al., 2020a; Karunadithi et al., 2021; Khan et al., 2021a, 2021b). The impact of COVID-19 lockdown gathered the attention of researchers across the globe (Bhattacharya et al., 2021; Kumar et al., 2020; Petrosino et al., 2021), but none of the studies has attempted to analyse the status of air pollution after the unlocking of COVID-19 lockdown. The average AQI values obtained for the post lockdown phase (January 2021) have been illustrated using ArcGIS for representation purpose (Fig. 2), which clearly signifies the declining status of air pollution during Unlock-8. Many studies (Aravinthasamy et al., 2021; Bhattacharya et al., 2021; Dutta et al., 2020b; Karunadithi et al., 2021; Selvam et al., 2020a, 2020b) have attempted to assess the impact of COVID-19 lockdown on natural resources but still none of the studies analysed the impact of unlocking in the various phases. The effectiveness of lockdowns in rejuvenating the quality of natural resources is praiseworthy but is it a permanent solution, considering the shrinking state of global economy? Thus, this study was taken up to assess the current state of pollution after the unlocking of various enterprises including industries, transportation, commercial activities. The relative changes during lockdown and unlock-8 have also been compared with the status of air quality during pre-lockdown phase. Furthermore, the correlation analysis, and bivariate relationships have also been analysed to assess the source of air quality parameters such as PM2.5, PM10 and NOx in the ambient atmosphere. Moreover, despite the imposed lockdown and subsequent decrease in global greenhouse emissions the target of SDG-13 fell short to limit the global warming to 1.5 °C (UNSDG, 2020). Hence, various recommendation towards management of air pollution without further deteriorating the economy and imposing complete lockdowns, are also suggested.

### 2. Materials and methods

#### 2.1. Studied sites

The monitoring sites were primarily chosen based on the population densities, nature of activities, geographical location, and availability of
data during all the phases (pre-lockdown, lockdown, and post-lockdown). The sites, S1 (Punjab Agricultural University, Ludhiana-PPCB), S2 (Yamunanapuram, Bulandshahr-UPPCB), and S3 (Okhla Phase-2, Delhi-DPCC) were chosen for assessing the air quality in Unlock 8 (January 2021) while comparing it with pre-lockdown (January 2020) and lockdown status (April 2020) in India. Based on the representative map of AQI in India (Fig. 2), two sites (i.e., S2 and S3) were chosen from ‘poor to severely’ affected zones and one site (S1) was chosen from ‘good to satisfactory’ zone of air quality. Hence, three monitoring stations of the Central Pollution Control Board representing three different locations of North India were selected for the present study, where the data was available for all the three phases. The sites were selected keeping in mind the different anthropogenic activities such as transportation, commercial activities, presence of industries, etc., for suitable comparison. The first site (S1) is in Ludhiana, a city in Punjab district, where agriculture activities are dominant and is classified as an industrial hub. The second site (S2) is in Bulandshahr, a town in the state of Uttar Pradesh where agricultural activities are the major source of income for the residents. The third site (S3) is in Okhla, which is one of the most important Industrial areas located in New Delhi, the capital city of India.

2.2. Studied parameters

The concentration of particles with diameter 2.5 μm and 10 μm i.e., PM2.5 and PM10 respectively, along with NO, NO2, NOx, NH3, O3, SO2, CO, C6H6, C2H6 were obtained from the website of Central Control Room for Air Quality Management (https://app.cpcbcr.com/ccr). Values of PM2.5, PM10, and NO2 were considered for the continuous assessment of air quality at all the sites and during all the selected phases, as these are one of the most critical and important parameters having a significant impact in human health (Cao et al., 2019; Friedman et al., 2021; Hao et al., 2018). However, the rest of the parameters were used for the Pearson’s correlation analysis to identify the sources of PM2.5, PM10, and NO2 in the ambient atmosphere.

2.3. Statistical analyses

The Pearson’s correlation matrix was prepared using Origin Pro 2020b software. The value of Pearson’s correlation coefficient, ‘r’ lies between –1 and +1. A ‘strong’ correlation exists, if ‘r’ lies between ±0.9 and ±1. A ‘good’ correlation exists, if values of ‘r’ ranges between ±0.51 and ±0.89, and a ‘poor’ correlation is said to exist when values of ‘r’ are less than ±0.50 (Batabyal, 2018; Shukla and Saxena, 2020b–d).

3. Results and discussion

3.1. Variation of PM2.5

The variation in the values of PM2.5 on 24-h basis in all three phases (pre-lockdown, lockdown, and post-lockdown) has been illustrated in Table 2 and Fig. 3. The highest average concentration (μg/m³) of PM2.5 in the pre-lockdown phase was recorded at S3 (174.0) exceeding the permissible limit of 60.0 μg/m³. The mean value of PM2.5 was 148.9 μg/m³ at S2 in the pre-lockdown phase and exceeded the permissible limit. While it remained within the permissible limits at S1 (44.8) highlighting the comparatively better status of the Ludhiana. The concentration of PM2.5 at S1 exceeded the permissible limit during 5 days of our assessment. While at S2 and S3, it exceeded the permissible limits on all days in the pre-lockdown phase. This status of PM2.5 concentrations clearly states the health hazards to which the inhabitants have been
The mean values of PM2.5 (μg/m³) in the lockdown phase at all three sites S1 (19.7), S2 (56.4) and S3 (43.3) witnessed a significant deterioration, signifying the positive impact of COVID-19 lockdown. The closure of anthropogenic activities (industrial enterprises, schools, colleges, public and private transport) significantly positively impacted the air quality as stated in various studies (Mahato et al., 2020; Selvam et al., 2020a, 2020b; Sharma et al., 2020).

The average value of PM2.5 (μg/m³) during the post-lockdown was the highest at S3 (238.3) followed by S2 (183.7) and S1 (50.1). The average values of PM2.5 at two sites (S2, and S3) exceeded the permissible limits and showed a steep increase after lockdown as well as pre-lockdown phase. The increase in the concentration of PM2.5 during the post-lockdown period highlighted the impact of the phased unlocking and the genesis of the current study. The industrial enterprises in the vicinity of S3 and their unlocking emerge as a major cause of PM2.5 pollution. The second site (S2) has a population density of 788 inhabitants per square kilometre being the 85th most populous district out of a total of 640 (Census, 2011). This site (S2) is a major agricultural district with huge quantities of grain production including wheat, maize etc. The distance of S2 is ~68 kms from S3 (industrialized location) signifying the relative impact of the air pollution of S3 on S2. The causes of the varying levels of PM2.5 have been further discussed in Section 3.4.

### 3.2. Variation of PM10

The variation in the values of PM10 on 24-h basis in all three phases (pre-lockdown, lockdown, and post-lockdown) has been illustrated in Table 2 and Fig. 4. The average concentration values (μg/m³) of PM10 in the pre-lockdown phase were 90.7 at S1, 203.8 at S2, and 262.4 at S3. The average concentration exceeded the permissible limit (100 μg/m³) at sites S2 and S3, while the value of PM10 at S1 remained within the permissible limit (Fig. 4).

The average concentration (μg/m³) of PM10 during the lockdown phase at S1, S2, and S3 showed significant deterioration with concentrations of 44.6, 152.8, and 100.8, respectively. It was noteworthy that...
the concentration of PM10 at site S2 and S3 remained above the permissible limit, despite the lockdown. Site S2 is an agricultural district with widespread use of biomass burning for household energy consumption. Hence, the probable impact of the emissions from power plants, biomass burning for food preparation needs to be considered due to their unstopped working even in the confinement period. Site S3 showed greater reduction in the PM10 levels than site S1 and S2 signifying the impact of factory shutdown. Site S3 previously also topped the list of 50 most polluted cities as mentioned in a study by Rodríguez-Urrego and Rodríguez-Urrego (2020).

The mean concentration of PM10 (μg/m³) in the post-lockdown phase at S1 (119.0), S2 (268.0), and S3 (349.5) exceeded the permissible limit (Fig. 4). The reopening of industrial enterprises, automobile mobilization probably contributed to the elevated levels of PM10 during Unlock 8. The associated reasons of such variation have been further discussed in Section 3.4.

### 3.3. Variation of NO₂

The variation in the atmospheric concentration of NO₂ on 24-h basis in all three phases (pre-lockdown, lockdown, and post-lockdown) has been illustrated in Table 2 and Fig. 5. The mean concentration of NO₂ (μg/m³) in the pre-lockdown phase was 26.5 at S1 48.5 at S2, and 48.2 at S3 (Table 2) and remained within the permissible limit (80 μg/m³) (Fig. 5). The maximum value of NO₂ at site S2 (88.1 μg/m³) exceeded the permissible limit only on one day (Fig. 5). The positive impact of COVID-19 lockdown on air quality could be clearly seen on the low concentration of NO₂ (μg/m³) with mean concentrations remaining within the permissible limits at S1 (19.9), S2 (16.1) and S3 (15.7) (Fig. 5).

The average concentration of NO₂ (μg/m³) during the post-lockdown phase increased to 31.5 at S1, 15.7 at S2, and to 55.2 at S3; however, the mean concentration of NO₂ at the three sites were remained within the permissible limit (Fig. 5). It is noteworthy that despite the mean concentration of NO₂ in the ambient atmosphere were found to be within the permissible limits, there was a significant rise in the NO₂ levels during the post-lockdown phase. This rise can be attributed towards an increase in transportation activities and resumption of industrial enterprises. The relative changes in the levels of NO₂ across the various phases have been discussed further in Section 3.4.

### 3.4. Phase-wise relative change

The relative change in the values of PM2.5, PM10, and NO₂ from pre-lockdown to lockdown phase and in the lockdown to post-lockdown phase has been illustrated in Fig. 6. A reduction in the concentration of PM2.5 was witnessed at site S3 (69.0%) > S2 (56.6%) > S1 (46.8%) in the lockdown phase signifying the impact of the closure of industries, and other enterprises (restricted vehicular movement) etc. A very steep increase in the values of PM2.5 at S3 (525.2%) > S2 (281.2%) > S1 (185.0%) was witnessed in the post lockdown (Unlock 8 i.e., January 2021).

The reduction in the concentration of PM10 was witnessed at site S3 > S1 > S2 (54.4%, 37.2%, and 15.0%, respectively) during the lockdown phase. While a very huge increase in the values of PM10 at site S3 > S1 > S2 (284.5%, 189.1%, and 103.9%, respectively) was observed in the Unlock 8 (post-lockdown phase). The reduction and elevation in the PM10 levels during lockdown and unlock confirm their correlation with closure and start of anthropogenic activities and movement.

The various efforts being made by the authorities including the National Clean Air Programme (NCAP) initiated by the Government of India which aims at reducing the Particulate Matter concentrations by 20%–30% and managing the air quality problems by the year 2024 are praiseworthy (PIB, 2020). Thus, the extensive implementation of policies and monitoring systems can prove to be very vital for improvement of air quality.

The values of NO₂ reduced at sites S3 > S2 > S1 in the lockdown (66.4%, 61.6%, and 3.9%, respectively) phase, while in the post-lockdown (Unlock 8) phase a steep increase was observed S3 > S1 > S2 (295.7%, 66.5%, and 4.1%, respectively). Although, the mean NO₂ levels remained within the permissible limits but, such increase in the concentration during Unlock 8 certainly raises the alarm and required

### Table 2

| Phase          | Site | Minimum | Maximum | Mean | Median | Standard deviation | n  |
|----------------|------|---------|---------|------|--------|--------------------|----|
| PM2.5          | Pre-Lockdown | S1 21.1 | 116.6   | 44.8 | 38.8   | 20.9               | 30 |
|                | S2 60.0 | 262.6   | 148.9   | 154.0| 52.4   | 86.4               | 30 |
|                | S3 74.4 | 475.2   | 174.0   | 149.0| 55.1   | 86.4               | 30 |
| Lockdown       | S1 9.2  | 36.8    | 16.7    | 18.8 | 6.0    | 21.2               | 30 |
|                | S2 26.0 | 101.4   | 56.4    | 55.1 | 21.2   | 30                 |    |
|                | S3 23.6 | 79.0    | 43.2    | 42.0 | 15.4   | 30                 |    |
| Post-Lockdown  | S1 20.3 | 94.2    | 50.1    | 53.9 | 18.1   | 30                 |    |
|                | S2 76.7 | 394.5   | 183.7   | 165.8| 74.7   | 30                 |    |
|                | S3 84.9 | 517.7   | 258.3   | 221.0| 108.8  | 30                 |    |
| PM10           | Pre-Lockdown | S1 37.1 | 251.2   | 90.7 | 76.4   | 45.6               | 30 |
|                | S2 79.7 | 343.0   | 203.8   | 203.2| 63.4   | 30                 |    |
|                | S3 139.4| 592.0   | 262.4   | 238.8| 111.2  | 30                 |    |
| Lockdown       | S1 25.1 | 85.8    | 44.6    | 37.8 | 15.0   | 30                 |    |
|                | S2 53.2 | 325.9   | 152.8   | 148.4| 61.3   | 30                 |    |
|                | S3 47.2 | 197.0   | 100.8   | 96.8 | 35.3   | 30                 |    |
| Post-Lockdown  | S1 36.4 | 225.8   | 119.0   | 121.9| 50.9   | 30                 |    |
|                | S2 92.9 | 530.0   | 268.0   | 251.8| 98.5   | 30                 |    |
|                | S3 124.7| 703.9   | 349.5   | 330.4| 142.0  | 30                 |    |
| NO₂            | Pre-Lockdown | S1 14.8 | 61.6    | 26.5 | 23.6   | 10.3               | 30 |
|                | S2 22.2 | 88.1    | 48.5    | 45.6 | 17.7   | 30                 |    |
|                | S3 31.5 | 70.6    | 48.2    | 48.4 | 9.5    | 30                 |    |
| Lockdown       | S1 15.2 | 71.5    | 19.9    | 15.6 | 11.4   | 30                 |    |
|                | S2 5.6  | 30.1    | 16.1    | 15.4 | 5.9    | 30                 |    |
|                | S3 7.3  | 25.4    | 15.7    | 15.5 | 5.0    | 30                 |    |
| Post-Lockdown  | S1 11.9 | 56.9    | 31.5    | 28.2 | 14.2   | 30                 |    |
|                | S2 2.8  | 37.8    | 15.7    | 12.8 | 10.9   | 30                 |    |
|                | S3 37.1 | 78.7    | 55.2    | 53.6 | 13.0   | 30                 |    |
precautionary measures. The health hazards include weakening of immune systems, bronchiolitis, focal pneumonitis, alveolar hyperplasia etc. The probable reaction of NO$_2$ with haemoglobin and resultant reduction of the oxygen carrying capacity of blood due to the formation of methaemoglobin or nitrosohemoglobin is a huge hazard and can more severely harm the COVID-19 patients (Chakraborty et al., 2020).

Fig. 3. Variation of PM 2.5 during (a) pre lockdown, (b) lockdown, and (c) post lockdown phase across sites S1, S2 and S3 respectively. Data Source: CPCB (2021)

Fig. 4. Variation of PM 10 during (a) pre lockdown, (b) lockdown, and (c) post lockdown phase across sites S1, S2 and S3 respectively. Data Source: CPCB (2021)
3.5. Correlation analysis

The Pearson’s correlation analysis was performed to assess the interdependability of various pollutants. The average atmospheric concentration across the three analysed phases (pre-lockdown, lockdown, and post-lockdown) for all the parameters (PM2.5, PM10, NO, NO2, NOx, NH3, O3, SO2, CO, C6H6, C7H8) was considered at all the three sites (Fig. 7). It can be observed that PM2.5 exhibits a very strong positive correlation with PM10, with \( r = 0.93 \) for S1, \( r = 0.91 \) for S2, and \( r = 0.97 \) for S3. This trend indicates that both PM2.5 and PM10 may have same originating source. To identify the probable source, the ratio of PM2.5 and PM10 has been used by many researchers (Chakraborty et al., 2020). In the present study, the values of PM2.5/PM10 ratio were calculated for all the phases and plotted in a box and whisker diagram for all the sites (Fig. 8). The mean values of the PM2.5/PM10 ratio were found to be very similar for all the three sites, indicating that the source of both PM2.5 and PM10 might be the same at the three locations. Since, the three locations are geographically different, and other factors such as industrial activities, atmospheric phenomenon such as dust storms etc. Cannot be the same, it can be concluded that both PM2.5 and PM10 originates from vehicular pollution, as the property of the fuel remains similar throughout the country.

Moreover, CO had a strong positive correlation (0.75 < \( r \) < 0.9) with both PM2.5 and PM10 at all the three sites. The primary source of CO in the air is emission from vehicles, which further confirms that vehicular emissions are the primary source of particulate matters in the studied locations (Ali and Islam, 2020; Dong et al., 2021; Katoto et al., 2021). Further, a positive correlation of PM2.5 with atmospheric NOx concentrations indicates that vehicular emission is the chief source of atmospheric NOx concentrations. NOx also had a good correlation with NO2 concentrations suggesting a similar origin, i.e., vehicular emissions for both these pollutants. Many previous studies have also indicated that emissions from transportation vehicles is the primary source of atmospheric NO2 concentrations (Chakraborty et al., 2020; Guttikunda et al., 2014). Further, benzene (C6H6) had a strong to very strong correlation with PM2.5 and PM10 at S2 and S3, whereas a poor correlation existed at S1. Emission from paint manufacturing industries is the primary source of benzene in atmosphere. This finding conforms to the study area also, as many paint industries are there near S2 and S3 is an industrial hub with varying type of industries present in the area. These finding also suggests that industrial emissions have a small contribution towards atmospheric concentrations of PM2.5 and PM10.

4. Conclusions and environmental implications

Assessment of the analysed data confirmed the prominent impact of COVID-19 lockdown and unlocking on the air quality through three air quality monitoring stations across North India. The variations in the levels of PM2.5, PM10, and NO2 across pre-lockdown, lockdown, and
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post-lockdown (Unlock 8) phases could be correlated to the normal and confinement time. The positive impact of COVID-19 lockdown on the air quality consequent to the restricted mobility of vehicles, industrial shutdown was confirmed in the study with PM2.5 levels reducing by 69.0%, 56.6%, and 46.8% at sites S3, S2, and S1, respectively in comparison with the pre-lockdown concentrations. Similarly, a major impact of automobile demobilization was also witnessed in the confinement period with a significant reduction in the NO\textsubscript{2} levels i.e., 66.4%, 61.6%, and 3.9% at site S3, S2, and S1, respectively. The scenario after the phase of reinstatement (lockdown) emerged to be very severe and needs immediate authoritarian intervention. The various parameters showed significant increase in the post-lockdown (Unlock 8) phase highlighting the contribution of factories, road dust, stubble burning towards the dilapidated air quality.

Based on our study and the source apportionment of various air pollutants the following recommendations can act as an insight towards the measure required for improving the current air quality in the ambient atmosphere.

➢ The implementation of lockdowns in modified forms (partial, temporary, no private vehicles on holidays etc.) considering the positive impact of COVID-19 lockdown can prove to be effective in improvement of air quality.

➢ A comprehensive real-time air quality monitoring system at local, regional, and national level is required to recognize the various sources of air pollutants. The identification of sources can prove to be a very effective step towards accurate monitoring of emissions at all levels. Further, the absence of real time monitoring systems at many locations and consequent lack of data about the levels of air pollutants needs to be managed.

➢ The continuous upgradation and maintenance of these real-time monitoring systems currently installed across the globe is very crucial and must be looked after rigorously especially keeping an eye in the industrial hubs.

➢ The awareness towards environment friendly technologies and the importance of individual contribution in children must be created at school levels itself.

➢ The continuous upgradation and maintenance of these real-time monitoring systems currently installed across the globe is very crucial and must be looked after rigorously especially keeping an eye in the industrial hubs.

➢ The introduction of stricter norms, regulations by relevant authorities can prevent the release of gaseous emissions without proper treatment by industrial enterprises. Creation of ‘Carbon Negative’ zones near the major industrial hubs could prove to be crucial for reinstating the air quality in the ambient atmosphere.

➢ Various multispectral awareness programmes for developing understanding in farmers engaged in stubble burning should be initiated. The programmes should include the ill effects of various emissions during the stubble burning (PM2.5, PM10 etc.) on human health.

➢ Farmers should be motivated towards modern eco-friendly techniques through promotion of incentive measures associated with such methodologies.

➢ Prevention of stubble burning by farmers can be also attained through utilization of crop stubble by power generation units, construction sector, pulp and paper industries etc. Through proper recycling channel. However, the implementation of this recommendation requires governmental intervention through various norms for industries to employ.

➢ Promotion and utilization of public transportation system instead of private vehicles, car-pooling, opting for green fuels (compressed natural gas, electricity etc.) can prove to be a boon towards improving the air quality.

➢ The intra and inter boundary transportation of pollutants among cities, states, and nations should be dealt by collaborative approaches of governments at all levels, with a common objective of sustainable development.

➢ The objective of a healthy environment can be attained successfully through a collaborative coordination between all the stakeholders including residents, NGOs, and governing bodies.

➢ Hence, this study upraises the urgent need of policies and measures on a coherent platform while maintaining balance between the economic development and giving time to natural resources to reinstate. This study will also act as a database for the future studies, residents, and governing authorities in the study area to promote suitable measures to improve the air quality and safeguard the human health.

Credit author statement

Saurabh Shukla: Research idea, concept, methodology, writing the
original draft of the manuscript, correction, and editing. **Ramsha Khan**: Concept, analysis, writing, data collection, writing the original draft of the manuscript creating figures, correction, and editing. **Abhishek Saxena**: Supervision and writing the original draft of the manuscript. Selvam Sekar: writing the original draft of the manuscript, and corrections. Esmat F. Ali: Correction and editing. Sabry M. Shaheen: writing the original draft of the manuscript, review, correction, editing and proof reading, and corresponding.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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