Impact of lockdown and crop stubble burning on air quality of India: a case study from wheat-growing region

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Abstract The emergence of COVID-19 has brought the entire planet to a halt. Many countries, including India, were compelled to shut down most urban, industrial, social and other activities as a result of the pandemic. Due to a series of complete lock-downs imposed in India from March 24 to May 17, 2020, and state-wise local level restrictions afterward, have resulted in significant reduction of emissions of numerous atmospheric pollutants. The objective of this study is to analyse the change in concentration of various pollutants such as nitrogen oxide (NO₂), carbon monoxide (CO) and aerosol optical depth (AOD) due to lockdown and also to quantify the contribution of crop stubble burning to air pollution. The Sentinel-5P based NO₂ and CO observations for 2019 and 2020 and Moderate Resolution Imaging Spectroradiometer (MODIS)-based AOD observations for 2016–2020 were used for detecting the variations. The obtained results showed a significant decrease in NO₂ levels during various stages of lockdown. Small decrease in CO levels was observed across most part of the India. With a few exceptions, such as coastal and desert regions, there was a moderate decrease in AOD levels. Furthermore, to study the contribution of NO₂, CO and AOD from crop stubble burning, MODIS observations on active fire events were obtained from Visible Infrared Imaging Radiometer Suite (VIIRS). The burning of crop stubble increased NO₂ emissions by 22 to 80%. CO levels, on the other hand, have risen by 7 to 25%. A considerable variation in AOD was reported, ranging from 1 to 426%.

Keywords Crop stubble burning · COVID-19 · Air pollution · Sentinel 5P · MODIS

Introduction and motivation

The year 2020 began with the discovery of a new coronavirus known as SARS-CoV-2 or COVID-19 (Lal et al., 2020). The outbreak started in Wuhan, China (Lu et al., 2020; Chen et al., 2020) and spread around the world via a human-to-human transmission (Bogoch et al., 2020). COVID-19 was declared a “Public Health Emergency of International Concern (PHEIC)” on January 30, 2020, due to the virus’s high infectivity, undetermined incubation time and global mortality rate (World Health Organization, 2020a, b). On January 30, 2020, the first case of COVID-19 was reported in the Indian state of Kerala. In February, there were no large instances reported, but this began to change in early March. India has reported 90,927 cases, 2872 deaths from the virus, and 34,109 people have been recovered as of May 17, 2020 (MoHFW, 2020). Due to an increase in COVID-19 infections recorded in early March, the Indian government
enforced the first nationwide lockdown between March 24 and April 14, 2020 (hereafter referred to as Lockdown 1.0). All activities were prohibited during Lockdown 1.0, except for essential and medical emergencies. The government has also declared two more lockdowns, one from 15 April to 3 May 2020 (Lockdown 2.0) and the other from 4 to 17 May 2020 (Lockdown 3.0) with conditional relaxation of specific activities related to travel and industry.

The COVID-19 lockdown had a tremendous impact on air quality, which is certainly improved in the major cities of India, which was felt by individuals and documented in CPCB Report 2020. It was also discovered that in megacities such as Delhi, where the energy footprint is huge, the lockdown has improved air quality on a larger scale (Mahato et al., 2020). Mandal and Pal (2020) reported decrease in PM10 concentration from 189–278 to 50–60 g/m³ after 18 days of lockdown in their investigations on air quality of four selected stone crushing clusters in the Dwarka river basin of eastern India. Research studies have looked into the influence of air pollution on the Indian population and their health in the past. The techniques for managing urban air quality were developed, with a focus on emission inventories, control strategies, a monitoring network and public participation (Gulia et al., 2015). Significant reductions in PM 2.5, PM 10 and NO₂ levels were observed during the lockdown as a result of a combination of fewer vehicles on the road, the operation of only essential commercial units and the weather conditions. During the lockdown, there was a 46% reduction in particulate matter (PM) 2.5 and a 50% reduction in PM10. The reductions in PM 10 and PM 2.5 were mostly due to combustion and industrial sources, which are common to both fractions of particulate matter (CPCB Report, 2020). The particulate matter and other contaminants have significant impact on the human health. According to the World Health Organization press release dated May 2, 2018, around 7 million people die across the globe each year as a result of fine particles in contaminated air (WHO, 2018). The environment in India was severely deteriorated due to various pollutants and the air quality index well beyond the acceptable limits. Transportation, factories, power plants, construction activities, biomass and residue burning, road dust re-suspension and residential activities are the major contributors to air pollution (Angelevska et al., 2020; Gibergans Bąguena et al., 2020; Kansoh et al., 2020). Furthermore, activities that contribute to air pollution are Diesel Generator set operation, restaurant operations and landfill fires (CPCB Report, 2020). Aerosols and pollutant concentrations rise as a result of emissions from automobiles and industries in metropolitan areas, as well as agricultural stubble burning. Aerosols contribute to climate change in a variety of ways, both directly and indirectly (Huang et al., 2014; Menon et al., 2002). Aerosols in the atmosphere primarily disrupt the scattering and absorption of solar energy, causing precipitation and atmospheric instability (Jiang et al., 2016).

The burning of agricultural stubble after harvest is a normal practice in the intensive rice–wheat farming system of India’s northern states. Stubble burning for land removal may be quick and cost-effective, but it adds a lot of aerosols, particulate matter and other gases including nitrogen oxides and carbon monoxide to the atmosphere (Badarinath et al., 2009; Vadrevu et al., 2013). Besides environmental pollution, it causes health problems such as asthma, cough, bronchitis, skin disorders and conjunctivitis, among others. Increased NO₂ levels have also been linked to disorders including bronchoconstriction, breathing or respiratory problems (Goings et al., 1989). The key questions are (1) What if some of the causal activities are stopped for a brief amount of time? (2) How much of a change will there be in the levels of harmful air pollutants? (3) How to identify the percentage contribution of a specific activity like crop stubble burning?

Numerous studies have been conducted to determine the impact of COVID-19 on overall pollution levels in various cities and states across India (Kumari & Toshiwal, 2020; Aman et al., 2020) and the globe (Tobias et al., 2020; Dantas et al., 2020). Studies have focused on either single city or couple of cities, and analysis has been done to study the impact of COVID-19 on pollution levels. However, none of these studies have focused on considering the levels of restrictions imposed in various lockdowns and the corresponding periods when there were no restrictions to study the emission of various pollutants. No detailed countrywide investigation was performed to see the impact of COVID-19 on pollutants levels. Therefore, there is a scope for determining the impact of various activities on pollutant concentrations. Furthermore, one of the key causes of rising NO₂, CO, AOD and other pollutants in the Delhi, Punjab, Haryana states of India is the burning of stubble following...
the rice–wheat harvest. Air pollution in India’s capital Delhi and surrounding region is a major problem resulting into economic and social distress. Every year, increase in the air pollution during the months of rice harvest (October to December) and wheat harvest (March to May) has been caused due to stubble burning and other factors such as vehicular emissions and construction. As restrictions imposed during lockdown have significantly stopped the urban and industrial activities; hence, stubble burning is the only major source of pollution during April–May 2020 in the region of Delhi, Punjab, Haryana. The lockdown imposed to curb spread of COVID-19 provided us the rare opportunity to study the quantitative impact of stubble burning on the levels of key pollutants. Very few studies have provided insights on the effects of stubble burning. However, there are no studies that quantified the influence of stubble burning on the levels of key pollutants. The overall objective of this study is to understand the variations in air pollution during the lockdown. The particular goals are to (1) compare the change in major pollutants such as nitrogen dioxide (NO₂), carbon monoxide (CO) and aerosol optical depth (AOD) during lockdowns 1.0, 2.0 and 3.0, and (2) quantify the contribution of NO₂, CO and AOD from crop stubble burning.

This paper is organized in six sections; details about the study area and duration of lockdowns imposed throughout India are described in “Study area”. “Datasets used in this study” describes the various data sources and detailed information about the data analysis methods. The results cover the impact of various lockdowns on concentration of key pollutants in “Impact of multiple lockdowns on levels of atmospheric pollutants”. “Case study on the impact of crop stubble burning on air quality of major wheat producing regions of India during COVID-19 lockdown” presents a detailed case study on the impact of crop stubble burning on air pollution around Delhi and surrounding region. Finally, conclusions are covered in “Conclusions”.

Study area

The COVID-19 pandemic has brought the world’s economies to a halt. The current research was conducted in India to determine the impact of lockdown on levels of several air pollutants. India, located in South Asia, is the world’s second-most populous country. In India, air pollution is one of the most important health concerns. Industrial pollution is responsible for 51% of air pollution, cars for 27%, crop stubble burning for 17% and Diwali fireworks for 5% (Indian Express, 2019). In urban regions, emissions from automobiles and industrial operations are the primary causes of pollution, but, in rural areas, crop stubble, such as rice, wheat and sugarcane stubble, as well as biomass burning for cooking, contribute significantly to air pollution. For effective analysis and interpretation of air pollution results, India was divided into six major regions: north, south, east, west, central and northeast. Table 1 lists the states and their related regions (Miller, 2014). Figure 1 depicts the study area and the several regions that were considered.

Timeline of lockdowns imposed in India

The Government of India has imposed numerous lockdowns, beginning on March 24, 2020, to reduce the impact and spread of COVID-19. From the 24th of March to the 14th of April, Lockdown 1.0 was in effect. Similarly, the second (2.0) and third (3.0)
lockdowns took place from April 15 to May 3, 2020 and May 4 to 17, 2020, respectively (Table 2). During Lockdown 1.0, all travel and industry operations were prohibited; however, during Lockdown 2.0, limited exceptions were made. Some industries with very limited capacity, as well as essential travel, were authorised under Lockdown 3.0. The post-monsoon agricultural season in India starts from

Table 2 Timeline of lockdowns, relaxations and farm activities

| Lockdown       | Pre-lockdown | Lockdown 1.0 | Lockdown 2.0 | Lockdown 3.0 | Source                          |
|----------------|--------------|--------------|--------------|--------------|--------------------------------|
| Duration       | 4–15 Mar     | 16–23 Mar    | 24 Mar–4 Apr | 15–25 Apr    | 26 Apr–3 May                   | a,b,c                          |
| Rabi wheat     | Wheat growing| Wheat growing| Harvest      | Harvest      | Harvest                        | (Singh, 2018)                  |
| Stubble burning|              |              | Slight burning| Moderate burning| Severe burning                | (Yadav et al., 2014)          |
| Relaxation     | Full         | Full         | No           | No           | Conditional relaxation (Essential travel + industries with very limited staff and due approvals) | b,c                            |

*a* [https://www.nytimes.com/2020/03/24/world/asia/india-coronavirus-lockdown.html]

*b* [https://www.livemint.com/news/india/pm-modi-announces-extension-of-lockdown-till-3-may-11586839412073.html]

*c* [https://www.ndtv.com/india-news/nationwide-lockdown-over-coronavirus-extended-for-two-weeks-beyond-may-4-2221782]
November–December and ends in March and April (locally called Rabi cropping season). Table 2 shows the Rabi Wheat harvest aligned with the Lockdown 1.0 and 2.0. Also, the crop stubble burning is aligned with the Lockdown 1.0, 2.0 and some parts of 3.0.

Datasets used in this study

The macro-level perspective of dangerous pollutants is provided by atmospheric remote sensing observations. Sentinel-5 Precursor (Sentinel-5P), Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) observations were used to provide spatiotemporal insights into the research area.

Sentinel 5 Precursor

The Sentinel-5 Precursor (Sentinel-5P) satellite, launched by the European Space Agency, collects data that can be used to analyse air quality (ESA, 2020). On October 13, 2017, the satellite was successfully launched. This satellite is equipped with a multispectral TROPOspheric Monitoring Instrument (TROPOMI) sensor that captures reflectance data for measuring ozone, methane, formaldehyde, aerosol, carbon monoxide, nitrogen dioxide and sulphur dioxide concentrations in the atmosphere (Veefkind et al., 2012). With daily repeat coverage, the data has a spatial resolution of 0.01 arc degree. Spatiotemporal fluctuations in pollutants during lockdown were studied using CO and NO2 measurements. NO2 is a significant trace gas in the atmosphere. NO2 emissions are mostly caused by the combustion of fossil fuels and biomass, as well as natural activities such as wildfire, lightning and soil microbiological processes (Veefkind et al., 2012). The NO2 data is given in mol/m^2 as a total vertical column density. CO is estimated using TROPOMI radiance measurements in the short-wave infrared (SWIR) region of the sun spectrum with a 2.3-µm spectral range. The information is presented in the form of a vertically integrated column density in mol/m^2. CO emissions are primarily caused by the combustion of fossil fuels and the burning of agricultural residue/biomass. NO2 and CO Sentinel-5P level-3 data available between March 4 and May 17 for the years 2019 and 2020 was accessed from the Google Earth Engine (GEE) platform and used in the analysis (Gorelick et al., 2017).

MODIS MCD19A2.006

This product provides land Aerosol Optical Depth (AOD) generated from Moderate Resolution Imaging Spectroradiometer Terra and Aqua combined Multi-angle Implementation of Atmospheric Correction (MAIAC) (Lyapustin & Wang. 2018). The data is available at a spatial resolution of 1 km with a daily revisit frequency. The GEE has a collection of MCD19A2 version 6 data (MCD19A2.006). The dataset mainly provides blue band AOD at 0.47 µm and green band AOD at 0.55 µm. The data in blue band AOD available from the 4th of March to the 17th of May for the years 2016 to 2020 was used in the analysis.

VIIRS FIRMS data

The Visible Infrared Imaging Radiometer Suite (VIIRS) is one of the key instruments on board the Suomi National Polar-Orbiting Partnership (Suomi NPP) spacecraft (Changyong et al., 2013). The VIIRS consist of a multi-spectral instrument with five spectral channels at 375 m (I-bands), 16 spectral channels at 750 m (M-bands) and a light-sensitive day-and-night band at 750 m (DNB). The VIIRS active fire detection products are developed using instruments 375 m (I-bands) and 750 m (M-bands). A fire detection algorithm was developed using five 375 m VIIRS channels. A 375-m active fire product was used in our analysis. The location (i.e., latitude and longitude) and date (acquisition date) on which the fire was detected were used in our research. To make the temporal comparison, data from the Fire Information for Resources Management System between March 4 and May 17 for the years 2019 and 2020 (FIRMS) was considered.

Impact of multiple lockowns on levels of atmospheric pollutants

Approach

Sentinel 5P and MODIS pollutant concentration data were utilised to perform a spatiotemporal comparison.
of major pollutants such as nitrogen dioxide (NO$_2$), carbon monoxide (CO) and aerosol optical depth (AOD). The time of data capture was aligned with the duration of before and each Lockdown 1.0, 2.0 and 3.0. Figure 2 shows the series of data processing steps followed during data analysis. The study considers 2019 as a reference year for comparison of key air pollutants in India during the lockdown. Composite rasters were generated using median statistics for each scenario and observations obtained during the same period in the years 2019 and 2020. The four different scenarios are (A) before lockdown period (4 March to 23 March), (B) Lockdown 1.0 (24 March to 14 April), (C) Lockdown 2.0 (15 April to 3 May) and (D) Lockdown 3.0 (4 May–17 May 2020). The per cent reduction in NO$_2$ and CO concentrations was computed by comparing data from 2019 to 2020 for four distinct scenarios (refer to Eqs. 1 and 2). However, for AOD analysis, data from MODIS AOD was used for the period of 2016 to 2020. The percentage decrease in AOD was calculated by comparing the temporal mean of AOD from 2016 to 2019 with the AOD data from 2020 (refer to Eq. 3). Furthermore, rule-based classification and detailed causal analysis was performed on the output raster map.

\[
\text{PercentageDecrease(NO}_2) = \frac{(\text{NO}_2\text{of2019} - \text{NO}_2\text{of2020})}{\text{NO}_2\text{of2019}}
\]

(1)

\[
\text{PercentageDecrease(CO)} = \frac{(\text{CO}\text{of2019} - \text{CO}\text{of2020})}{\text{CO}\text{of2019}}
\]

(2)

\[
\text{PercentageDecrease(AOD)} = \frac{(\text{MeanAOD of (2016 to 2019)} - \text{AOD of 2020})}{\text{MeanAOD of (2016 to 2019)}}
\]

(3)

Figures 3, 4 and 5 depict maps for lockdown scenarios (A–D) and median NO$_2$, CO and AOD observations, respectively. In India, nitrogen oxides are mostly produced through the combustion of fossil fuels and crop stubble burning (primarily wheat, rice and sugarcane). Figure 3A depicts the situation before the lockdown. A rise in NO$_2$ levels in India’s north-western area was observed. The states of Punjab and Haryana have 11.86% and 8.55% of area under wheat cultivation (MoAFW, 2018). Wheat harvesting takes place every year from mid-April to mid-May (Singh, 2018). After that, the wheat stubble is burned to clear the land for the next farming season. The increase in NO$_2$ levels in the region is due to increased automobile emissions. The western region (i.e., the states

![Flowchart for temporal classification of pollution levels](image-url)
of Gujarat and Maharashtra) has a higher concentration of NO$_2$ than the coastal region of Gujarat, owing to its proximity to the sea. However, Goa state has shown a significant decrease in NO$_2$ levels in spite of its proximity to the sea during the pre-lockdown period in 2020 compared to 2019. The levels of NO$_2$ in Maharashtra’s rural areas are decreasing. However, sugarcane stubble burning and closeness to the Arabian Sea have also contributed to an increase. The southern region showed a significant decrease in the NO$_2$ levels. Within the southern region, Karnataka and Kerala states have the highest decrease in NO$_2$ levels during the pre-lockdown period in 2020 compared to 2019. Moreover, Chennai and its surrounding areas in Tamil Nadu have shown an increase in NO$_2$ levels. This is attributed to an increase in urban and industrial emissions in 2020 compared to 2019. The central region has shown a mixed trend with a moderate decrease. Madhya-Pradesh has mostly shown a moderate decrease; however, Chattishgarh has shown a purely mixed trend with north part of the state having a significant decrease. The increase in central part of the state is mainly due to urban emissions of NO$_2$, and the southern part of the state has shown a moderate decrease. The east region of India showed a low to moderate decrease. In the eastern region, staggered areas show an increase in NO$_2$ levels. The increase in NO$_2$ levels has been observed mainly in the urban and industrial areas due to more emissions from automobiles and industries. The northeast region has a slight decrease in the NO$_2$ levels before lockdown. Further, Fig. 3B shows the scenario during Lockdown 1.0 (25 March to 14 April). High to significant amount of decrease in the NO$_2$ levels was observed. However, Jammu and Kashmir region showed a moderate decrease mainly due to the mountainous Himalayan region. Overall moderate to significant decrease across the nation is mainly caused due to heavy restrictions on the movement of vehicles as well as the shutdown of urban and industrial activities. Punjab, Haryana and Delhi from the northern region have shown a significant decrease in NO$_2$ levels. This is mainly due to a decrease in urban and rural emissions. Due to strict restrictions on the movement of vehicles and the shutdown of industries, there was a sharp drop in the urban emissions of NO$_2$. 

Fig. 3 Change in NO$_2$ levels during various lockdowns compared to 2019. Legend shows the change in NO$_2$ levels in percentage in five categories.
Moreover, there was a delay in the harvesting of the wheat crop and consequent stubble burning which resulted in a decrease in the NO$_2$ emissions from agricultural areas. The western region has shown a moderate to significant decrease except for the coastal areas of Gujarat. Within the southern region, Karnataka, Andhra Pradesh has shown a maximum decrease than other southern states. This might be due to the strict adherence to lockdown norms by these states. In the eastern and northeastern region, increase in NO$_2$ levels in few areas was noted. This is mainly attributed to urban emissions. Another possible reason is the number of COVID-19 infections was very less in the east and northeastern states during the Lockdown 1.0, and people in those areas might not have followed the guidelines of the lockdown. The change in NO$_2$ levels during Lockdown 2.0 is depicted in Fig. 3C. (15 April to 3 May). The government has relaxed the rules for industries with a small workforce, as well as essential travel with the necessary precautions and approvals. Mixed pattern was observed in the northern region, with a minor to moderate decrease in NO$_2$ levels and a slight increase in some parts of Punjab. This is strongly attributed to the wheat crop stubble burning. However, Delhi has shown a significant decrease during Lockdown 2.0. This is a combined effect of strict restrictions, and shutdown of industries as well as the impact of stubble burning from Punjab and Haryana was less as compared to 2019. Moderate to significant decrease was observed in the southern region of India. The coastal region of Tamil Nadu has shown an increase in NO$_2$ levels owing to its proximity to the sea. The eastern and northeast regions observed a slight increase in the NO$_2$ levels. This is attributed to relaxation in terms of travel and industries due to a very less number of COVID-19 cases. Figure 3D depicts the Lockdown 3.0 (4 to 17 May) scenario. Maharashtra, as the most industrialized state in the western region, has seen a modest rise in NO$_2$ levels. On the other hand, the southern region experiences an increase in NO$_2$ levels as a result of the relaxation in terms of travel and industry due to the lower number of COVID-19 cases in the southern region mainly in Kerala and Karnataka. Other
southern states, such as Tamil Nadu, Andhra Pradesh and Telengana, have shown a moderate to large fall in NO$_2$ levels, owing to the restriction, as cases continue to rise in these states. The NO$_2$ levels have decreased moderately in the central and eastern regions of India. Table 3 summarises the region-wise change in NO$_2$ across various scenarios.

Carbon monoxide is a major pollutant in the atmosphere. CO levels rise as a result of emissions from automobiles and numerous businesses, primarily in urban areas (Data Products-Carbon Monoxide, 2020). Crop stubble and fossil fuel burning, on the other hand, contribute to high CO levels in rural regions. Figure 4 depicts the change in CO levels in India under several scenarios before and after the lockdown. Figure 4A represents the pre-lockdown scenario, which depicts a small to moderate increase in CO levels in most regions. The northern region showed small to moderate increase in CO across the entire region. A similar trend has been observed in the southern region. Tamil Nadu has shown a moderate increase in CO levels; however, other southern states have shown a small increase in CO levels. The only exception to this trend was observed in some of

Fig. 5 Change in AOD levels during various lockdowns of year 2020 compared to 2019. Legend shows the change in AOD levels in percentage in five categories

Table 3 Summary of change in NO$_2$ levels in 2020 compared to 2019

| SN | Region    | Pre-lockdown | Lockdown 1.0 | Lockdown 2.0 | Lockdown 3.0 |
|----|-----------|--------------|--------------|--------------|--------------|
| 1  | North     | 1            | −3 to −4     | −1 to −2     | −1 to −3     |
| 2  | South     | −3 to −4     | −4           | −3 to −4     | Mixed        |
| 3  | East      | −3           | −3 to −4     | Mixed        | −3 to −4     |
| 4  | West      | −1 to −3     | −3           | −2 to −3     | Mixed        |
| 5  | Central   | −3 to −4     | −3 to −4     | Mixed        | −3 to −4     |
| 6  | Northeast | −2 to −4     | −3 to −4     | 1 to −2      | 1 to −3      |

1: Increase, − 1: slight decrease, −2: moderate decrease, −3: high decrease, −4: significant decrease
the eastern and western regions of India where a significant decrease in CO levels was observed. This can be attributed to less urban, rural and industrial emissions of CO from those regions. The maps for Lockdown 1.0 are shown in Fig. 4B. CO concentrations have decreased significantly in the northern, southern and eastern regions. There is also a large reduction in CO over India’s capital, Delhi. This is owing to the effective implementation of numerous lockdown strategies, such as the cessation of urban and industrial operations. In contrast, there was a moderate increase over western, central and northeastern regions. Even after effective implementation of lockdown, there was a surprising trend observed in this region. During Lockdown 2.0 (Fig. 4C), except the northeast region, a slight to moderate increase in CO levels was observed across the entire India. This is attributed mainly to rural and agricultural emissions across most of the region. Significant decrease of CO was observed over the eastern coastal region, northeast and the major portion of the northern region. During Lockdown 3.0 (Fig. 4D), overall, there is a slight to moderate decrease in CO level during the lockdown period. Table 4 shows the region-wise summary of the change in CO across various scenarios.

Aerosols are particles in the atmosphere that interfere with solar light scattering and absorption. Dust storms outbreaks, smoke from crop stubble burning, fossil fuel burning, etc. are responsible for aerosols (Allen, 1996). Figure 5 shows the spatial difference between pre- and post-lockdown AOD over India. Maps from the pre-lockdown period (Fig. 5A) show a modest increase in AOD in the northern, central and western regions. This is mainly attributed to dust outbreaks from the deserted region and vehicular and industry emissions. The dominance of westerly wind from arid and semi-arid regions and lower temperature along the Indo-Gangetic plains in March causes the AOD levels to be high compared to other regions. AOD levels have dropped significantly in all of the remaining regions. It should be noted that satellite data was unavailable in various parts of the northern states of India (Jammu and Kashmir). The AOD change in Lockdown 1.0 is depicted in Fig. 5B. A minor rise in AOD was noted in the western and central regions, owing to the deserted areas and proximity to the sea. A significant decline in AOD levels has been observed in the southern and northern regions, particularly in the capital city of Delhi and its surroundings. This is attributed to restrictions in industrial and urban activities as well as the movement of vehicles and travel ban. Moreover, delay in the wheat crop harvesting from Punjab, Haryana, led to delay in crop residue burning; hence, emissions from crop residue burning were also significantly low. The impact of the same has been observed over Delhi and the surrounding region. In terms of AOD change, a distinct trend was seen during Lockdown 2.0 (Fig. 5C) and 3.0 (Fig. 5D). Only a few regions, such as Delhi and its surroundings, experienced a continuous and large drop. However, in comparison to 2019, AOD increased in the central and western regions. During the various lockdowns, no apparent increasing or declining AOD trends can be seen in any of the other regions. Table 5 summarises the change in AOD by region for various scenarios.

Since the onset of COVID-19, various researchers have attempted to analyse the impact of COVID-19 on air, water quality across the globe including India. Muhammad et al. (2020) focused on studying the impact of COVID-19 on air quality across the globe. The study region spanned across the globe, and limited insights were derived for the Indian geography with very little consideration on issue of crop stubble burning. In this study, we covered detailed spatiotemporal comparative assessment of key pollutants during lockdowns within India. Research studies by Lokhandwala and Gautam (2020), Gautam (2020),

### Table 4  Summary of change in CO levels in 2020 compared to 2019

| SN | Region      | Pre-lockdown | Lockdown 1.0 | Lockdown 2.0 | Lockdown 3.0 |
|----|-------------|--------------|--------------|--------------|--------------|
| 1  | North       | Mixed        | −2 to −3     | Mixed        | Mixed        |
| 2  | South       | 1 to 2       | −2 to −3     | 1 to 2       | Mixed        |
| 3  | East        | Mixed        | −3           | Mixed        | Mixed        |
| 4  | West        | 1 to 2       | 2            | 1 to 2       | 1 to 2       |
| 5  | Central     | 1 to −3      | 1 to 2       | 1 to 2       | 1 to 2       |
| 6  | Northeast   | Mixed        | 1 to 2       | −3           | −3           |

2: moderate increase, 1: slight increase, −1: slight decrease, −2: moderate decrease, −3: high decrease
Singh and Chauhan (2020) have considered impact of lockdown on air quality of India. Lokhandwala and Gautam (2020) have studied changes in AOD derived from MODIS, NO\textsubscript{2} derived from Sentinel-5 P on individual dates over India. However, no detailed spatiotemporal comparative assessment was performed for temporal windows of lockdown and limited regional coverage of India. Gautam (2020) described the impact only on the AOD during COVID-19 lockdown, without consideration for other pollutants and issue of stubble burning. The research studies have mainly considered changes in air pollution levels on major cities, country or the globe and considered the impact due to urban and industrial emissions. Detailed regional level comparative analysis will be very useful to categorize the areas from future monitoring and mitigation perspective.

Summary

Analysis of percentage change in various pollutants during the lockdown period provided us with interesting insights. There was a moderate to a significant decrease in NO\textsubscript{2} levels during all lockdowns. However, the western region and south region showed an increase during the Lockdown 3.0. The northern and the eastern coastal region show slight decrease whereas all the other regions have shown a slight increase in CO levels. Analysis of AOD level shows a mixed and varied trend. Only a couple of regions such as Delhi and the surrounding region show a consistent and significant decrease in AOD level.

Insights gained from spatiotemporal analysis of key pollutants triggered a curious question about quantification of contribution of stubble burning. The subsequent section covers a case study on the impact of crop stubble burning on air quality of major wheat producing region of India during COVID-19 lockdown.

| SN | Region       | Pre-lockdown | Lockdown 1.0 | Lockdown 2.0 | Lockdown 3.0 |
|----|--------------|--------------|--------------|--------------|--------------|
| 1  | North        | 1            | −3 to −4     | −4           | −4           |
| 2  | South        | Mixed        | −4           | Mixed        | −3 to −4     |
| 3  | East         | Mixed        | −3 to −4     | 1            | Mixed        |
| 4  | West         | Mixed        | 1            | 1            | Mixed        |
| 5  | Central      | 1            | 1            | 1            | Mixed        |
| 6  | Northeast    | −3 to −4     | −4           | Mixed        | −4           |

Future implications of the research Scope

The COVID-19-related implementation of lockdown resulted in a considerable reduction in NO\textsubscript{2}, a slight reduction in CO, and a moderate reduction in AOD. Low levels of pollution are beneficial to keeping the environment clean and reducing the effects of climate change. COVID-19 has shown us how to adapt to the new normal during the lockdown. Even when the COVID-19 lockdowns are lifted, there are a few potential solutions that could be effective in reducing the effects of urban and industrial pollution.

1. Work from home strategy: In the IT and services sector, India has a significant workforce. Even if only a tiny percentage of this workforce works from home daily, this will contribute to the lower vehicle and industrial emissions.

2. Green and eco-friendly workplaces: One of the most effective ways to keep emissions low is to maintain green and eco-friendly workplaces.

Case study on the impact of crop stubble burning on air quality of major wheat producing regions of India during COVID-19 lockdown

Approach

To investigate the pollutant contribution, the major wheat-growing regions of Punjab and Haryana were chosen. Figure 6 depicts the flowchart of data analysis steps used to investigate the impact of wheat stubble burning on pollutant emissions during the lockdown period.

Punjab and Haryana are two states in the northern region where the rice–wheat farming technique is widely followed by farmers. Burning of agricultural stubble left on the field after harvesting rice
and wheat is a widespread practice in the region. COVID-19 occurrence overlapped with the wheat harvesting period, which is followed by stubble burning. While numerous lockdowns implemented in India have resulted in a major reduction in pollution emissions, wheat stubble burning may have increased atmospheric gases such as NO₂, CO and AOD. For the period of 4 March to 17 May 2020, column NO₂, CO estimations from Sentinel-5P and AOD data from MODIS were used in the analysis. For each scenario, median composites of column NO₂, CO and AOD was generated and compared them over time. Also,

Fig. 6 Overall framework for stubble burning vs. pollutants analysis

Fig. 7 Temporal maps of NO₂ column number density across various scenarios. Legend shows the NO₂ column number density in mol/m²
data from FIRMS on VIIRS fire occurrences was considered in the analysis. As an indicator of stubble burning, data on the total number of fire occurrences for each scenario was considered. Figures 7, 8, and 9 depict the changes in NO$_2$, CO and AOD before and after the lockdown. The numbers next to each district represent the total number of fire events that have occurred in that district.

The NO$_2$ column number density (mol/m$^2$) before the lockdown (4 to 23 March 2020) is shown in Fig. 7A. Although there were few stubble burning incidents at this time, functioning industries and urban activities resulted in moderate NO$_2$ emissions. Punjab region has shown low to moderate NO$_2$ levels in spite of a couple of stubble burning events in certain districts. Haryana has shown moderate levels of NO$_2$ levels during the pre-lockdown period. Due to heavy anthropogenic activities, extremely high levels of NO$_2$ were reported over Delhi and the surrounding region of Haryana. The NO$_2$ levels during the Lockdown 1.0 are shown in Fig. 7B. Vehicle mobility restrictions, industry shutdowns and very low stubble burning activities have all resulted in lower NO$_2$ levels than the pre-lockdown period (i.e., Fig. 7A). This clearly shows the significant impact of strict lockdowns on the levels of NO$_2$. Although the NO$_2$ levels in the districts of Haryana closer to Delhi were moderate, there was a reduction as compared to the pre-lockdown period. NO$_2$ emissions during Delhi were moderate, there was a reduction as compared to the pre-lockdown period. NO$_2$ levels during Lockdown 2.0 are depicted in Fig. 7C. NO$_2$ levels have dramatically increased as a result of the increased number of stubble-burning incidents. Moreover, certain restrictions have been eased during the lockdown period during Lockdown 2.0; this has caused the increase in the overall NO$_2$ levels in the Haryana districts closer to Delhi. NO$_2$ emissions during lockdown 3.0 are depicted in Fig. 7D. A considerable increase in NO$_2$ levels was induced by a large increase in post-harvest crop stubble burning. In spite of the very minimum movement of vehicles and minimal industrial activities during this period, the NO$_2$ levels have increased; this shows the impact of stubble burning on the rise of NO$_2$ levels. During Lockdown 1.0, very few stubble-burning events were noted, but

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**Fig. 8** Temporal maps of CO across various scenarios. Legend shows the CO levels in mol/m$^2$.
there were a lot of them recorded in Lockdown 3.0. Furthermore, percentage rise in the NO₂ levels was calculated to estimate impact of agricultural stubble burning. The study found that during the Lockdown 3.0, NO₂ levels rose from 22 to 80%, this has a causal relationship with stubble burning (Fig. 10A). Also, percentage median rise in NO₂ levels vs. the increase in agricultural stubble burning incidents at the district level from Lockdown 1.0 to Lockdown 3.0 was plotted for visual comparison (Fig. 11). The
strong positive linear relationship ($R^2 = 0.68$) between changes in burning events and an increase in NO$_2$ levels are shown in Fig. 11A. This has aided in the quantification of NO$_2$ levels resulting from crop stubble burning.

Figure 8A–D show the different scenarios in terms of CO levels. Figure 8A depicts the pre-lockdown period, which shows moderate to high CO levels. This is mainly due to the urban and industrial operations as the number of occurrences of wheat stubble burning was quite low during this period. The region of Haryana close to Delhi has shown very high levels of CO mainly due to the anthropogenic activities. This clearly shows the impact of vehicular and industrial emissions on the rise in CO levels. Figure 8B depicts CO levels during Lockdown 1.0. Due to lockdown limitations and a small number of wheat stubble burning activities, a slight drop has been seen, primarily in Punjab. Although, the CO levels in Harayan were slightly higher than in Punjab, they were reduced during the Lockdown 1.0 as compared to the pre-lockdown period due to the restrictions in vehicle mobility and industrial emissions. CO levels during Lockdown 2.0 and 3.0 are shown in Fig. 8C, D, respectively. During this time, there has been a moderate and large increase in CO levels. This is certainly due to the increase in the number of burning events. A clear increasing trend in CO levels due to stubble burning events has been observed during the Lockdown 2.0 and 3.0. A comparison of CO levels between Lockdown 1.0 and 3.0 reveals a 7 and 25% increase in CO levels, which can be linked to the burning of wheat stubble (Fig. 10B). Figure 11B illustrates the percentage increase in CO levels vs. the increase in burning events at the district level. The research reveals a substantial logarithmic association between burning events and CO levels ($R^2 = 0.38$)

AOD levels in various pre and post-lockdown scenarios are shown in Fig. 9A–D. Human and industrial activity are primarily to blame for high AOD levels (Fig. 9A) before the lockdown. The dominance of westerly wind from the arid and semi-arid region and lower temperature along the Indo-Gangetic plains in march causes the AOD levels to be high. During Lockdown 1.0, AOD levels were slightly reduced due to the adoption of strict lockdown (Fig. 9B). During Lockdown 2.0 (Fig. 9C) and 3.0 (Fig. 9D), a considerable number of stubble burning incidents led the AOD levels to rise. Also, westerly disturbances resulted in dust and thunderstorms in the northwest and Delhi regions (Express News Service, 2020), causing AOD levels to significantly increase. The patterns of change between Lockdown 1.0 and Lockdown 3.0 are mixed and fairly variable. This mixed and variable pattern is the combined effect of stubble burning events as well as dust/thunderstorms that occurred in the region during that period. The majority of the districts showed an increase in AOD levels ranging from 1 to 426% (Fig. 10C). Four districts, on the other hand, indicate a decline in AOD levels of 2–15%. The increase in AOD levels vs. the change in burning occurrences from lockdown 1.0 to 3.0 were plotted; results showed no evidence of a substantial linear/non-linear relationship (Fig. 11C). Dust out-breaks in the northwest region due to westerly disturbances may have contributed to the rise in AOD levels. As stubble burning cannot be the only cause of AOD levels, this rise could be the cause of an inconsequential association.

Moreover, to the best of our knowledge, no research has considered linkage between COVID-19, stubble burning and air quality. We strongly believe that findings of the study specifically on stubble-burning and air pollution during the COVID-19
period would be highly useful to monitor and predict the rise in NO2 and CO levels due to stubble burning.

Summary

Studies on quantification of the impact of stubble burning on the emission of various pollutants have shown quite encouraging results. Due to stubble burning, NO2 levels have increased by 22 to 80%. In addition, there was a clear positive association between the change in burning events and the percentage increase in NO2. Furthermore, stubble burning was found to cause a 2 to 15% increase in CO levels. A moderately positive and exponential relationship was observed between crop stubble burning and an increase in CO levels. AOD increased by 1 to 426% as a result of stubble burning. Dust storms during Lockdown 3.0 may have caused AOD levels to rise, explaining the wide range of AOD increase.

Future implications of the research

The findings of this investigation revealed a clear and quantitative influence of stubble burning on the increase in pollutant emissions. The findings of this study will be beneficial to:

1. Future NO2 and CO monitoring: Every year, the majority of farmers grow rice–wheat crops. Data on fire events is provided by FIRMS daily. The rise in NO2 and CO levels as and when stubble burning events occur can be estimated using the proposed approach. This information will assist the government in taking proactive steps and motivate farmers towards alternative ways of stubble management.

2. Season-wise prediction on the rise in NO2 and CO: Time series satellite data can be used to estimate crop area and crop growth stages such as the start and end of the growing season in a given location (Mohite et al., 2019). When the end-of-season data is merged with the crop map, it will be possible to anticipate the likely harvesting zones (e.g., every week). Given that farmers will begin burning immediately after harvesting, it is possible to estimate the amount of stubble that will be burned in a given week. When paired with the findings of this study, this weekly data might be used to forecast the weekly spike in NO2 and CO near the end of the harvest cycle. The government and non-governmental organizations could use the advanced knowledge on NO2 and CO projections to prioritize regions for conducting awareness initiatives among farmers to minimize stubble burning.

3. Prioritization of regions for stubble collection: Stubble leftovers are a good source of fuel. Weekly NO2 and CO projections can aid in detecting hotspot locations ahead of time, which may suggest areas that will be burned. This information about hotspots could be used to prioritise regions for collecting stubble from farmers so that they do not burn it.

4. Reduce NO2 and CO emissions from other sources: Given the quantified increase in NO2 and CO that occurs after wheat harvesting, which occurs in April and May each year, the government and policymakers can focus on reducing NO2 and CO emissions from other sources, such as industry and urban emissions, so that overall levels of NO2 and CO do not exceed the limits.

Conclusions

The effect of lockdown on CO and NO2 emissions, as well as spatiotemporal fluctuations in AOD, was investigated in this study. Results showed considerable reduction in NO2 levels in 2020 compared to 2019 observations across India during the various periods of lockdown. On the Indian subcontinent, we discovered a general reduction in CO concentration. The CO levels have increased only in places close to the coast and in deserted areas. Also, we noticed a slight drop in AOD levels with a wholly contrasting pattern, particularly in the western and central regions. The impact of lockdown and effective implementation of the shutdown of urban and industrial activities has helped in a decrease in various pollutants compared to 2019. During the lockdown harvesting of post-monsoon (i.e., Rabi), wheat crop was allowed. The results showed link between changes in pollution levels and crop stubble burning. During the post-harvest period, the levels of the number of pollutants have increased. While NO2, CO and AOD levels were much lower during Lockdown 1.0, there was a large increase during Lockdown 2.0 and 3.0, which was linked to crop stubble burning activities.
Lockdowns imposed to curb spread of COVID-19 have facilitated in the reduction of various contaminants. Furthermore, actions implemented during the lockdown, including the work-from-home policy, the use of shared vehicles for transport or restricted movement of vehicles only for emergency purposes and the avoidance of unnecessary travel, have a significant influence on India’s air quality. The findings of this study demonstrated that stubble burning has a clear and quantitative impact on the increase in pollutant emissions. The significant link that has been established between the number of burning events and the levels of various pollutants will aid in the prediction of increase in NO$_2$ and CO concentration. The government and other agencies can use such predictions to prioritise regions for stubble collection. Moreover, findings from this study will help in identification of policy decisions and strategies to avoid or minimize the NO$_2$, CO emissions from other sources. Therefore, overall levels of NO$_2$ and CO shall be maintained within limits that are not harmful to the environment, humans and other ecosystems.

**Future work**

In this study, we were able to quantify the impact of crop stubble burning on level of NO$_2$, CO and AOD. The two major crop harvest seasons, i.e., September–October (monsoon season) and March–April (post-monsoon season), followed by crop stubble burning have major impact on regional pollutant levels. In addition to atmospheric remote sensing, we are planning to use spatiotemporal meteorological parameters such as wind speed and wind direction to understand the impact of crop stubble burning on neighbouring cities. An attempt is being made to identify the key environmental indicators and establish operational approach to predict the crop harvest areas. Finally, to assist various stakeholders like farmers, public and private sector agencies for crop stubble management.

**Abbreviations**

AOD: Aerosol optical depth; CO: Carbon monoxide; DNB: Day-and-night band; ESA: European Space Agency; FIRMS: Fire Information for Resources Management System; GEE: Google Earth Engine; MAIAC: Multi-angle implementation of atmospheric correction; MODIS: Moderate resolution imaging spectroradiometer; MoHFW: Ministry of Health and Family Welfare; NE: Northeast; NO$_2$: Nitrogen dioxide; PHEIC: Public Health Emergency of International Concern; S. N.: Serial number; Sentinel-5P: Sentinel-5 Precursor; Suomi NPP: Suomi National Polar-Orbiting Partnership; SWIR: Shortwave infrared; TROPOMI: TROPospheric Monitoring Instrument; VIIRS: Visible Infrared Imaging Radiometer Suite; WHO: World Health Organization

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**Availability of data and material**

Openly available Sentinel-5P and FIRMS datasets are used in this study which can be accessed from 1. Sentinel-5P: https://s5phub.copernicus.eu/dhus/ 2. FIRMS Data: https://firms.modaps.eosdis.nasa.gov/map/.

**Code availability**

The authors belong to the private organization and are not allowed to share any code as per the organizational policy.

**Declarations**

**Competing interests**

The authors declare no competing interests.

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