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Spatio-temporal variation in fine particulate matter and effect on air quality during the COVID-19 in New Delhi, India

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ABSTRACT

Novel Coronavirus disease has affected almost all the countries; which leads to the pandemic, impacting adversely on environment. The impact on environment during pre-and during lockdowns needs an attention to correlate the pollutants from industrial emissions and other factors. Therefore, the current study demonstrates the changes in fine particulate matter PM$_{2.5}$, PM$_{10}$ and effect on air quality during lockdown. The highest reduction was observed in lockdown I (25 March - 14 April) as compared to others lockdowns (between 15 April and 31st May 2020) due to the complete shutdown of industrial, transport, and construction activities. A significant reduction in PM$_{2.5}$ and PM$_{10}$ from 114.27 $\mu$g/m$^3$ and 194.48 $\mu$g/m$^3$ for pre-lockdown period to 41.41 $\mu$g/m$^3$ and 86.81 $\mu$g/m$^3$ for lockdown I was observed. The levels of air quality index fall under satisfactory category for lockdown I whereas satisfactory to moderate category for other lockdowns. The present study revealed a strong correlation between PM$_{2.5}$ and PM$_{10}$ levels during the pre-lockdown period (0.71) and through lockdown IV (0.76), which indicate that change in the PM$_{10}$ level influences the PM$_{2.5}$ level greatly. The findings of the present study could be scaled up nationwide and might be useful in formulating air pollution reduction policies in the future.

1. Introduction

In December 2019, a novel coronavirus disease 2019 (COVID-19) outbreak occurred due to human respiratory virus that originated from the city of Wuhan, China, (Li et al., 2020a, 2020b; Wu et al., 2020) and the disease was officially declared pandemic on March 11, 2020 by the World Health Organization (WHO) (Rothan and Byrareddy, 2020; WHO, 2020). A Chinese study revealed that the associated symptoms in patients include fever (98.6%), fatigue (69.6%), and dry cough (59.4%) (Zhou et al., 2020). Several studies have reported the global mortality rate of coronavirus in the range 2%-5% across 186 affected countries, since 2019 (Wang et al., 2020a, 2020b, 2020c). New scientific evidence indicates that the spread of the virus may be through droplet nuclei (aerosols) in the absence of aerosol-generating procedures, particularly in a close environment with poor ventilation, (Asadi et al., 2020; Morawska and Cao, 2020; WHO, 2020) with a higher predilection in the old age population of more than 60 years (Bontempi, 2020) and having comorbidities such as hypertension and heart disease. Additionally, several studies have suggested that airborne transmission is a probable pathway for the coronavirus disease transmission (Buonanno et al., 2020; Harapan et al., 2020; Neeltje van Doremalen et al., 2020; Setti et al., 2020; Stadnytskyi et al., 2020). The transmission of coronavirus diseases such as Middle East respiratory syndrome-associated coronavirus (MERS-CoV) and severe acute respiratory syndrome-associated CoV (SARS-CoV-1) is influenced by various
transport, commercial, and industrial activities (except for the essential activities) that resulted due to lockdown improved the air
the epidemic curve, which was escalated further to a city-scale lockdown from March 24, 2020 (Gettleman, 2020). Reduction in
Karnataka (David et al., 2020). On March 22, 2020, an emergency called ‘Janata Curfew’ was imposed in the whole country to flatten
meteorological parameters, such as ambient temperature (Bi et al., 2007; Casanova et al., 2010; Chen et al., 2020; Pani et al., 2020; Tan
et al., 2005; van Doremalen et al., 2013).

Reports of WHO and other agencies, as of September 20, 2020, indicate that more than 31 million people have been infected by
COVID-19 and more than 964 thousand people have died across countries (including India) (World Health Organization, 2020). India
was the second most affected country in the world following United States of America (USA), as of September 20, 2020, with more than
5.4 million infected cases and more than 87,000 deaths (One Word Data, 2020). In India, the first case was reported on January 30,
2020, in Kerala, which was directly linked to Wuhan, (Ghosh et al., 2020) and the first death was reported on March 12, 2020, in
Karnataka (David et al., 2020). On March 22, 2020, an emergency called ‘Janata Curfew’ was imposed in the whole country to flatten
the epidemic curve, which was escalated further to a city-scale lockdown from March 24, 2020 (Gettleman, 2020). Reduction in
transport, commercial, and industrial activities (except for the essential activities) that resulted due to lockdown improved the air

Table 1
Several recent studies across the world during the lockdown period.

| The study area (city, country) | Pollutants types | Key findings for PM<sub>2.5</sub> and PM<sub>10</sub> | Author (year) |
|------------------------------|------------------|---------------------------------|---------------|
| Present Study (Delhi, India) | PM<sub>2.5</sub> and PM<sub>10</sub> | Average concentrations for PM<sub>2.5</sub> and PM<sub>10</sub> were 41.14, 49.84, 54.92, 60.56 µg/m<sup>3</sup> and 86.81, 116.31, 123.01, 169.32 for lockdown I, II, III, IV respectively. | Present Study |
| India (Delhi, Mumbai, Kolkata, and Bangalore) | PM<sub>2.5</sub> and PM<sub>10</sub> | Concentration declined in PM<sub>2.5</sub> (~ 41%) and PM<sub>10</sub> (52%). | JAIN & Sharma et al. (2020) |
| Delhi (India) | PM<sub>2.5</sub> and PM<sub>10</sub> | Pollutant concentrations decreased during lockdown compared to before lockdown except for O<sub>3</sub> at all stations. Due to prevailing high-speed winds, PM<sub>2.5</sub> and PM<sub>10</sub> remained either close to or higher than the National Ambient Air Quality Standards (NAAQS). | Chaudhary et al. (2021) |
| Mumbai, Delhi, and Kolkata (India) | PM<sub>2.5</sub> and PM<sub>10</sub> | The concentrations of PM<sub>2.5</sub> and PM<sub>10</sub> are the major air pollutants in India that reduced by 47%, 41%, in Mumbai; 52%, 39%, in Delhi; and 49%, 37%, in Kolkata, respectively, in the lockdown phase. In addition, PM<sub>2.5</sub> and PM<sub>10</sub> exhibited significant correlations across the three megacities. | Mandal & Pal (2020) |
| Uttar Pradesh (India) | PM<sub>2.5</sub> and PM<sub>10</sub> | A significant reduction in the ground-level pollution load of PM<sub>2.5</sub> and PM<sub>10</sub> has been observed during the lockdown period in Uttar Pradesh. | Kumar et al. (2020) |
| Delhi (India) | PM<sub>2.5</sub> and PM<sub>10</sub> | A similar study conducted in Delhi, the result showed that PM<sub>2.5</sub> and PM<sub>10</sub> levels declined upto 55-65% during the lockdown period | (Garg et al., 2021) |
| Delhi (India) | PM<sub>2.5</sub> and PM<sub>10</sub> | The average concentrations of atmospheric air pollutants PM<sub>2.5</sub> and PM<sub>10</sub> were reduced to 42.15 µg m<sup>-3</sup>, and 128.68 µg m<sup>-3</sup> and where 73.85%, and 46.48% lower than pre-COVID-19 level. | Dutta and Jinsart (2020) |
| Chennai (India) | PM<sub>2.5</sub> | overall PM<sub>2.5</sub> values decreased for the lockdown (ranging from –32–187%), weekly analysis shows the variation in reduction/increase. | Singh and Tyagi (2020) |
| Indo-Gangetic Plains, western, southern, and eastern (India) | PM<sub>2.5</sub> | The five megacities observed a sharp decline in the daily mean concentration of PM<sub>2.5</sub> (32% in Delhi to 59.62% in Bengaluru) during the lockdown 2020 as compared to the analogous period of lockdown in 2019 | Lal et al. (2020) |
| Delhi, Mumbai, Kolkata, Chennai, and Hyderabad (India) | PM<sub>2.5</sub> and PM<sub>10</sub> | The average concentration levels of PM<sub>2.5</sub>, and PM<sub>10</sub> have decreased nationwide by 33%, and 34% respectively during the nationwide lockdown compared to their concentration levels before the lockdown. | Verma and Kamotra (2020) |
| Uttar Pradesh and the Delhi-National Capital Region (India) | PM<sub>2.5</sub> | The PM<sub>2.5</sub> concentrations during lockdown Phase 1 were approximately 44.6% lower for cities in Uttar Pradesh and approximately 58.5% lower for the Delhi-NCR. | Goel et al. (2019) |
| Ahmedabad, Delhi, Bangalore, Nagpur (India) | PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, and CO | The highest decline is observed over Ahmedabad (68%), Delhi (71%), Bangalore (87%), and Nagpur (63%) for PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, and CO, respectively. The Northern region shows the highest decline for all the pollutants with most days below NAAQS during lockdown—86%, 68%, and 100% compared to 18%, 0%, and 38% in 2019 for PM<sub>2.5</sub>, PM<sub>10</sub>, and NO<sub>2</sub>, respectively. | Navinya et al. (2020) |
| Delhi, Mumbai, Kolkata, and Chennai (India) | PM<sub>2.5</sub> and PM<sub>10</sub> | The findings conclude a significant improvement in air quality with respect to a reduction of 49-73%, 17-63%, in the mean concentration of PM<sub>2.5</sub> and PM<sub>10</sub>, respectively. | Pant et al. (2020) |
| Malaysia and Southeast Asia | PM<sub>2.5</sub> and PM<sub>10</sub> | Reduced concentration in PM10 for (industrial: 28–39%, urban: 26–31%), and PM2.5 (industrial: 20–42%, urban: 23–32%) respectively. | Kanniah et al. (2020) |
| Southern European cities (Nice, Rome, Valencia and Turin) and Wuhan (China) | PM<sub>2.5</sub> and PM<sub>10</sub> | Declined in PM2.5 and PM10 (~8% in Europe and ~42% in Wuhan) at urban stations respectively. | Sicard et al. (2020) |
| Yangtze River Delta Region (China) | PM<sub>2.5</sub> and PM<sub>10</sub> | Reductions in PM2.5 (27–46%) in China. | Li et al. (2020a, 2020b) |
| 44 cities in northern China | PM<sub>2.5</sub> and PM<sub>10</sub> | The AQI for PM<sub>2.5</sub>, and PM10, decreased by 6.76%, and 5.93%, respectively. | Bao and Zhang (2020) |
| Almaty (Kazakhstan) | PM<sub>2.5</sub> and PM<sub>10</sub> | Reduction in PM2.5 (21%, spatial variations: 6–34%). | Kerimray et al. (2020) |
| Northern China | PM<sub>2.5</sub> and PM<sub>10</sub> | Reduction in PM2.5 (29 ± 22%), and (31 ± 6%), in Northern China and Wuhan respectively. | Shi and Brasseur (2020) |
| Salé City (Morocco) | PM<sub>2.5</sub> and PM<sub>10</sub> | PM10 was reduced by 75% in Sale City. | Otmani et al. (2020) |
quality as confirmed through several studies (Bherwani et al., 2020; Gautam, 2020a, 2020b; Ghosh et al., 2020; Nakada and Urban, 2020; Pani et al., 2020; Zhu et al., 2020; Zoran et al., 2020). Particulate matter (PM_{2.5} and PM_{10}) is considered one of the major air pollutants that is associated directly with the short-term adverse health effects (Levy et al., 2012; Pun et al., 2014; Yang et al., 2018). Several scientists have investigated the relationship between particulate matter and COVID-19 (Zhu et al., 2020). A study reported that the long-term exposure to PM_{2.5} leads to an increased mortality risk rate associated with COVID-19 (Contini and Costabile, 2020; Liu et al., 2020; Wu et al., 2020). Although the association of COVID-19 spread and associated mortalities due to air pollution is under investigation by various scientific communities, a study indicates that high levels of air pollutants may be associated with increased mortality rates (Conticini et al., 2020; Yao et al., 2020; Wang et al., 2020a, 2020b, 2020c). A correlation study in China also suggested a positive correlation between particulate matters (PM_{2.5} and PM_{10}) and mortality rates of COVID-19 (Bashir et al., 2020). Similar studies conducted throughout the world have shown an association between prolonged exposure to particulate matters (PM_{2.5} and PM_{10}) and COVID-19 infection outbreak in Northern Italy (Bashir et al., 2020; Report et al., 2020), in the case of China (Mehmood et al., 2020; Wang et al., 2020a, 2020b, 2020c), and a similar result for the United (Wu et al., 2020).

According to the environmental performance index, Delhi is one of the most polluted megacities in the world (World Health Organization, 2016). A report on environmental monitoring database calculated during 2011 and 2016 placed Delhi at the top in the list of 100 leading megacities in the world that emits large amount of particulate matter (Singh et al., 2021a). As per the National Ambient Air Quality Standards (NAAQS), the PM_{2.5} concentration has been high in Delhi (Singh et al., 2014, 2021a,b). Several studies have reported a strong link between prolonged exposure to air pollutants and coronavirus (Gautam et al., 2021; Gautam, 2020b; Babu et al., 2020; Coccia, 2020; Babu et al., 2020). Table 1 presents a comparative analysis of studies from various countries during lockdown.

Sharma et al. (2020) reported the concentration of PM_{2.5} decline of 43% during the lockdown of March 2020, when compared with similar months in previous years. A study conducted in Delhi investigated reduction in PM_{2.5} (43%) and PM_{10} (60%) as compared to 2019 (Mahato et al., 2020). Kumar et al. (2020) investigated substantial reductions in PM_{2.5} concentration from 19 to 43% (Chennai), 41–53% (Delhi), 26–54% (Hyderabad), 24–36% (Kolkata), and 10–39% (Mumbai) during the lockdown period in India. Several researchers reported that significant reduction in air quality in short term in different parts of Indian cities (Gautam et al., 2020a, 2020b; Gautam et al., 2020a; Kumar et al., 2020).

Although various studies have been reported for early phases of lockdown in countries such as China, Italy, USA (Duthieil et al., 2020; Tobias et al., 2020; Xu et al., 2020), and a few studies on metropolitan cities of India such as Delhi and Mumbai (Jain and Sharma, 2020; Mahato et al., 2020; Chauhan and Singh, 2020; Sharma et al., 2020; Sahoo et al., 2021); while some of studies have been reported in India measuring the impact of covid-19 lockdown on air quality but for very short term period (Chauhan and Singh, 2020 (Dec 2019–March 2020); Jain and Sharma, 2020 (10th March–6th April 2019–2020); Kotnala et al., 2020 (January–March 2020); Kumar et al., 2020 (March–May 2020); Kumar et al., 2020 (March–April 2015–2020); Mahato et al., 2020 (3rd March–14th April 2020); Navinva et al., 2020 (1st February–3rd May 2019–2020); Sharma et al., 2020 (16th March–14th April 2017–2020); Shehzad et al., 2020 (1st January–20th April 2019–2020); Singh and Chauhan, 2020 (March 2019–2020); Srivastava et al., 2020 (1st–20th February and 24th March–14th April 2020). However, a detailed analysis on phases wise lockdown is lacking. None of the previous studies have focused on detailed analysis involving various phase wise lockdown in India. This study allowed developing a critical understanding of particulate matter for an extended period (phase-wise). Moreover, permitting the phase-wise relaxation in lockdown explored potential factors that influence differences between divergent variations in different monitoring stations in Delhi.

Hence, the present study aims to evaluate the levels of particulate matter (PM_{2.5} and PM_{10}) in different phases of lockdown for pre and during the lockdown period (1st January to 31th May 2020). Furthermore, compared the concentration of particulate matter for pre-and during the lockdown period and also explored the potential factors that could influence differences between divergent variations in different monitoring stations. In present study the monitoring of air quality index was studied in relation to pre and during lockdowns. The present study reveals a strong correlation between PM_{2.5} and PM_{10} levels during the lockdown period.

2. Materials and methods

Delhi, being the capital, is a chief metropolitan city of India. It is situated between the latitude of 28°34’ N and the longitude of 77°12’ E at an elevation of around 213.3 to 305.4 m above sea level. The atmosphere of Delhi is subtropical and is characterized by a semiarid climate with summer (April–June), moderate rainfall (July–September), post–monsoon (October–November) and winter (December–February). Temperature of Delhi is characterized by a maximum of ~45–48 °C in June during the summer season and minimum of ~1–2 °C in January during the winter season and the average rainfall is around 611 mm (Sindhwani and Goyal, 2014). Air quality data were procured from Delhi-based air quality monitoring stations to assess the air quality status of Delhi during COVID-19 pandemic and lockdown period. Hourly data of the particulate matter were collected regularly from January 1, 2020 to May 31, 2020 from 21 monitoring stations in Delhi. The distribution of monitoring stations in various zones of Delhi has been presented in supplementary Table 1.

2.1. Data and sources

Hourly and daily data of air pollutants were obtained from the online portal of Central Pollution Control Board (CPCB), particularly the data for PM_{10} (particulate matter less than ten microns in size), PM_{2.5} (particulate matter less than 2.5 μm in size), sulfur dioxide
(SO\textsubscript{2}), nitrogen dioxide (NO\textsubscript{2}), carbon monoxide (CO), toluene, ammonia (NH\textsubscript{3}), ozone (O\textsubscript{3}), and meteorological parameters. We collected data from January 1, 2020 to May 31, 2020 to determine the relative changes (in %) in air quality (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing). CPCB provides data quality assurance or quality control (QA/QC) programs by defining rigorous protocols for the sampling, analysis, and calibration (Mahato et al., 2020). Beside this some of limitations that monitoring stations in Delhi can be classified according to the type of environment in which they are located, in order to permit more meaningful evaluation of data. The site description will generally reflect the influence of a particular pollutant source or of overall land use. Typical monitoring location types, as used in urban areas rather than in rural and remote areas. Few of the discontinuous data from the few of the stations were procured.

The Air Quality Index (AQI) India provides the data of air pollution with real-time Air Quality Index for various air pollutants. The National Ambient Air Quality Standard (NAAQS) revised AQI by considering eight parameters, namely, PM\textsubscript{10}, PM\textsubscript{2.5}, NO\textsubscript{2}, SO\textsubscript{2}, CO, O\textsubscript{3}, NH\textsubscript{3}, and Pb for a short term (up to 24 hourly average) period (CPCB, 2016). An AQI is used to provide information about the quality of air in terms of pollution level which are directly associated with public health. The public health risk increases with an increase in the AQI level. Six AQI categories have been defined for health risk, namely, “Good”, “Satisfactory”, “Moderately polluted”, “Poor”, “Very Poor”, and “Severe”. Further, this index provides information to the public who are sensitive to air pollution. To identify the overall improvement in air quality over Delhi, AQI was calculated (Sharma et al., 2020). The AQI is divided into five categories: good (0–50), satisfactory (51–100), moderate (101–200), poor (201–300), and severe (401–500) respectively. AQI method that provides sub-index approach using six criteria pollutants (i.e., PM\textsubscript{10}, PM\textsubscript{2.5}, SO\textsubscript{2}, NO\textsubscript{2}, CO and O\textsubscript{3}) were converted into AQI standard value. The AQI for each pollutant was calculated by the following formula given by (Sahu and Kota, 2017).

\[ \text{AQI}_i = \frac{\text{HI}_i - \text{ILO}_i}{\text{BreakHI}_i - \text{BreakLO}_i} \times (\text{Ci} - \text{BreakLO}) + \text{ILO}_i \]

where \( \text{Ci} \) is the observed concentration of the pollutant “i”; \( \text{BreakHI}_i \) and \( \text{BreakLO}_i \) are breakpoint concentrations, greater and smaller to Ci; and \( \text{IHI}_i \) and \( \text{ILO}_i \) are corresponding AQI ranges.

The pandemic situation has been classified into two categories - before and during the lockdown period. Before the announcement of lockdown, the ‘pre-lockdown’ situation refers to the period between 1 January and 24 March 2020, whereas the period between 25 March to 31 May 2020 is the ‘lockdown’ situation for Delhi.

For the final calculation of AQI for individual pollutants, at least a minimum of three pollutants for the AQI value is required. In this study, we have considered the daily average values of other pollutants (NO\textsubscript{2} and O\textsubscript{3}) to calculate AQI values. The formula for the calculation of the AQI value was presented in the supplementary file. The AQI values for particulate matter (PM\textsubscript{2.5} and PM\textsubscript{10}) before and during the lockdown period were calculated corresponding to the other pollutants.

2.2. Measures

The pandemic situation was classified into two periods, before lockdown and during lockdown. The time before lockdown (between January 1, 2020, and March 24, 2020) was termed as ‘pre-lockdown’ period, and the time between 25 March and 31 May 2020 was termed as ‘during-lockdown’ period. Lockdown was extended four phases until May 30, 2020, with the first, second, third, and fourth phases ending on 14 April, May 3, May 17, and May 30, 2020, respectively. The pre-lockdown and during-lockdown data for PM\textsubscript{2.5} (\( n = 3070 \)) and PM\textsubscript{10} (\( n = 3071 \)) were obtained to determine the air quality status. The missing data for PM\textsubscript{2.5} and PM\textsubscript{10} which accounted for 0.97% and 0.98%, respectively, were omitted from this study.

All 21 air quality monitoring stations in Delhi were selected in this study and classified into a different district (https://ceodelhi.gov.in/OnlineErms/Reports/PS_LocationListOn15thOctDistrictwise.aspx) (Table S1). These are namely Ashok Vihar, Jawaharlal Nehru Stadium (JLN Stadium), Arya Nagar, Karni Singh, Delhi Technical University (DTU), Income Tax Office (ITO), Jahangirpuri, Lodhi road, Najafgarh, Neral, North Campus University, Ramakrishna Puram (RK Puram), Rohini, Vivek Vihar, Sirifort, Okhla, Patparganj, Bawana, Sri Aurobindo Marg, Alipur, and Wazirpur.

2.3. Data analysis and procedure

The present study analyzed the total data (\( n = 2955 \)) collected from the 21 monitoring stations located in different sites in New Delhi during the pandemic period. Time series plotting techniques were used to determine variable changes over time during the pre-lockdown and during-lockdown periods. Statistical analyses were performed using Statistical Package for the Social Science (SPSS) version 26.0 (SPSS Inc., Chicago, IL, USA). Pearson correlation analysis was performed to identify correlated variables. The AQI map was generated using Arc GIS (ArcMap 10.4; 10.4.1, New York Street, USA) to investigate the variable color changes in the during-lockdown period (Desktop et al., 2016). A geo-referenced shapefile for Delhi city was prepared to associate with physical space in Arc GIS. Air quality concentration data for PM\textsubscript{2.5} and PM\textsubscript{10} were attributed to the respective point shapefile for the time scales for every month.
3. Results and discussion

3.1. PM$_{2.5}$ and PM$_{10}$ levels in the pre-lockdown and during-lockdown periods

The present study focused on determining drastic changes in the concentrations of air pollutants, especially particulate matter PM$_{2.5}$ and PM$_{10}$ concentrations, during the pandemic situation in India, including Delhi. The PM$_{2.5}$ and PM$_{10}$ concentrations significantly declined from January 2020 to May 2020 during the pandemic situation in Delhi. A constant decline in the PM$_{2.5}$ and PM$_{10}$ concentrations was observed in subsequent months due to complete lockdown, during which international and domestic flights, trains, traffic activities, markets, and industrial activities were suspended. The average PM$_{2.5}$ and PM$_{10}$ concentrations across all the stations were 90.43 $\mu$g/m$^3$ and 168.36 $\mu$g/m$^3$, respectively. The average concentration levels varied from 67.92 $\mu$g/m$^3$ (Arya Nagar) to 114.01 $\mu$g/m$^3$ (Bawana) for PM$_{2.5}$ and from 112.30 $\mu$g/m$^3$ (Sri Aurobindo Marg) to 206.22 $\mu$g/m$^3$ (Jahangirpuri) for PM$_{10}$ across all the stations during the pandemic situation. The concentration of pollutants in the ambient atmosphere is governed by prevailing meteorological variables such as wind velocity, temperature, relative humidity, and the planetary boundary layer (PBL). Usually, low relative humidity and high wind speed support the dispersal of pollutants compared to a calm atmosphere. Furthermore, an increase in PBL height leads to decreased concentrations due to the dispersion of pollutants in a larger volume in the ambient atmosphere in Delhi during the lockdown periods (Chaudhary et al., 2021). Thus, it can be concluded that both lockdown and the prevailing meteorological variables like increase in PBL and high wind speed were responsible for lower pollution levels in Delhi.

The present PM$_{2.5}$ and PM$_{10}$ values were observed lower as compared to the previous year’s values mentioned by many research scholars (Maji et al., 2021; Gautam, 2020a, 2020b; Zhang et al., 2021; Sharma et al., 2020; Shukla and Kumar, 2020) due to the complete closure of non-essential services. The average PM$_{2.5}$ and PM$_{10}$ concentrations for all the stations were as follows: 114.27 $\mu$g/m$^3$ and 194.48 $\mu$g/m$^3$, respectively, for the pre-lockdown period; 41.41 $\mu$g/m$^3$ and 86.81 $\mu$g/m$^3$, respectively, for lockdown I; 49.84 $\mu$g/m$^3$ and 116.31 $\mu$g/m$^3$, respectively, for lockdown II; 54.92 $\mu$g/m$^3$ and 124.49 $\mu$g/m$^3$, respectively, for lockdown III; and 60.56 $\mu$g/m$^3$ and 169.32 $\mu$g/m$^3$, respectively, for lockdown IV (Fig. 1). The average value reported during lockdown I was minimum due to complete restriction in transport and industrial activities, which are considered major sources of primary PM$_{2.5}$ and PM$_{10}$ emissions. The present concentrations of particulate matter were observed lowest in lockdown I but remained higher than prescribed limits by NAAQS due to many factors such as meteorological parameters (wind speed, relative humidity, rainfall) that might be responsible for the lowering of particulate matter in Delhi. In addition, meteorological factor-like rainfall witnessed further lowering the particulate matter through the washout during the month of March in Delhi. The values of the particulate matter remain higher than the standard value due to measure of essential services such as the functioning of the Inter-state- bus services movement for migrant people to their native states during the lockdown periods, an operative of the local factories (in industrial areas only), and running of agricultural activates. In addition, the meteorological wind played a significant role in the emission and transportation of dust particles from the neighbouring state due to geographic location (landlocked). Furthermore, due to complete lockdown I, domestic cooking and coal-fired power plant in Delhi could be considered one of the anthropogenic sources.

![Fig. 1. Mean, maximum, and minimum concentrations of PM$_{2.5}$ and PM$_{10}$ at Delhi.](image-url)
The maximum PM$_{2.5}$ and PM$_{10}$ concentrations were 475.22 $\mu$g/m$^3$ and 591.96 $\mu$g/m$^3$, respectively, at Okhla, whereas the minimum concentrations were 11.33 $\mu$g/m$^3$ and 17.52 $\mu$g/m$^3$, respectively, at Patparganj and Najafgarh (Figs. 2 and 3). The concentrations at Okhla were observed higher than the values found at any other monitoring stations because the Okhla site is considered an industrial zone (waste to energy plant). Furthermore, that waste to energy plants used municipal solid waste (which was generated from the household) as fuel, so during the lockdown periods also it was in processing mode. Therefore, the waste burning was attributed to the
release of particulate matter and other gases in this station. Higher concentrations of PM$_{2.5}$ and PM$_{10}$ could be attributed to construction activities around this station, and wind blow dust or local resuspension of particles have also been reported in previous studies (Chowdhury et al., 2007; Srivastava et al., 2008; Nagar et al., 2017; Kumar et al., 2018). The concentrations were found to be minimum at Patparganj and Najafgarh because these two sites connected with the Northern National highway (Uttar Pradesh and Haryana), where transport was the major source of particulate matter. The Northern National highway was closed entirely with restrictions on emission sources and precautions taken by the general public to restrict unnecessary movement before and during the lockdown period. In addition to meteorological parameters, such wind and rainfall might be played a significant role in lowering the values of particulate matter (Kumar et al., 2018). In addition, the absence of non-essential vehicles and combustion activities in industrial and commercial sites during the period is attributable to the decline.

Supplementary Figs. 1-14 present the time series analyses of PM$_{2.5}$ and PM$_{10}$ concentrations for all the stations between January 2020 and May 2020. The peak PM$_{2.5}$ values for most of the time for all the stations (except for the ITO) station were less than the standard value (40 μg/m$^3$) prescribed by the CPCB during lockdown I, II, and III. The average PM$_{2.5}$ concentration ranged from 67.92 μg/m$^3$ (Arya Nagar) to 114.01 μg/m$^3$ (Bawana) for the pre-lockdown period, which was lower than that reported in a study conducted in Delhi between November 2016 and October 2017 (Gorai et al., 2018). The PM$_{2.5}$ and PM$_{10}$ concentrations for all the stations were increased during the IIIrd and IVth lockdown period because permission was granted for the operation of several non-essential activities to boost the economic growth, including the inter-State movement of passenger vehicles and buses, with the mutual consent of the States/UT(s). In addition, Government has given particular directions to ensure the movement of all types of goods/cargo, including empty trucks during the same period (https://www.mha.gov.in/sites/default/files/MHAOrderextension_1752020.pdf). Furthermore, all government offices engaged in essential services were permitted to work with full strength, whereas private offices were permitted to work with 33% strength, which increased the transport activities, such as public transport (excluding metro) and private transport, 2- and 4-wheelers.

The PM$_{2.5}$ and PM$_{10}$ concentration levels during lockdown III and IV were higher than those during lockdown I and II. The maximum reduction in PM$_{2.5}$ and PM$_{10}$ concentrations was observed in South Delhi (−73%, Karni Singh) and North East Delhi (−67%, Sirifort) during lockdown I, whereas the minimum reduction was observed in East Delhi (−7%, Arya Nagar) during lockdown III and in North East Delhi (38%, ITO) during lockdown IV. According to Kerimra, 2020, spatial reduction in the PM$_{2.5}$ values varied between 6% and 34% during the lockdown period in Almaty, Kazakhstan. A study conducted in Zaragoza, Spain, also reported a decline in the PM$_{2.5}$ concentration by 58% during March 2020 as compared with February 2020. Similar changes were also observed in Beijing and other Chinese cities during the lockdown period (Chauhan and Singh, 2020). Another study observed a 27.8% and 31% reduction in the PM$_{10}$ concentration in urban background and traffic areas, respectively, in Barcelona (Spain), during the lockdown periods (Tobías et al., 2020). A significant reduction in the PM$_{2.5}$ and PM$_{10}$ concentrations during the lockdown period can be attributed to a low frequency of temperature inversions, low atmospheric temperature, high wind speed, and changes in wind direction. The average, maximum, and minimum concentrations of PM$_{2.5}$ and PM$_{10}$ have been presented for pre-lockdown, lockdown I, lockdown II, lockdown II, and lockdown IV (Sfigure 15 and 16).

### 3.2. Particulate matter concentration during lockdown I

The nationwide “Janta curfew” (people’s curfew) was imposed on March 22, 2020 and was further extended to “total lockdown” from March 24 for 21 days (until April 14, 2020) to curb the spread of the infectious coronavirus pandemic. This period was referred to as lockdown I due to the complete closure of all activities including those of transport (public and private), industry, and market. Moreover, the lowest concentrations resulted due to complete shutdown of the industrial monitoring site during the lockdown I compared to other phases. Furthermore, concentrations increased phase-wise due to relaxation in industrial activities with a limited workforce and permission for essential services. For example, in the first phase of lockdown, Mahato, Pal, and Ghosh et al. (2020) reported a 60%, and 39% reduction of PM$_{10}$ and PM$_{2.5}$, respectively, compared to 2019 in Delhi. Further, the concentration of PM$_{2.5}$ and PM$_{10}$ were observed higher after 2, 3 weeks (lockdown II and III) due to partial relaxation on necessary transportation and controlled industrial activity outside the COVID-19 infected zone or containment zone declared by the government for Delhi (Mahato et al., 2020; Srivastava et al., 2020; Kumar et al., 2020).

The results indicate a drastic and sudden decline in concentrations of air pollutants, particularly the particulate matters, during lockdown I. Because of a considerable reduction in PM$_{2.5}$ and PM$_{10}$ concentrations, a huge reduction in air pollution level was witnessed within 2 weeks of the initial 21-day lockdown. The maximum PM$_{2.5}$ and PM$_{10}$ average concentrations were 55.62 μg/m$^3$ and 111.19 μg/m$^3$ in ITO and Jahangirpuri, respectively, whereas the minimum concentrations were 24.85 μg/m$^3$ and 64.12 μg/m$^3$ in North Campus and Arya Nagar, respectively, during lockdown I. A study in China also reported a reduction in the PM$_{2.5}$ concentration from 65 μg/m$^3$ to 51.4 μg/m$^3$ (Wang et al., 2020a, 2020b, 2020c). The PM$_{2.5}$ and PM$_{10}$ concentrations were significantly reduced during lockdown I, compared with those observed during the pre-lockdown period, mainly due to complete closure of the industrial and construction activities and decreased on-road traffic movements. The maximum reduction in the average PM$_{2.5}$ and PM$_{10}$ values was witnessed in Karni Singh and North Campus by −73%, whereas the least reduction was observed in ITO and Arya Nagar by −56%, respectively. Drastic changes in PM$_{2.5}$ and PM$_{10}$ levels during lockdown I was due to reduction in private vehicle and other non-essential transportation, complete closure of the market, construction, and industrial activities. Another study reported that one of the major factors responsible for reduction in particulate matter concentration is the lower overall traffic (97%) and the number of trucks and commercial vehicles (91%) entering the capital during lockdown I (April), compared with those in the pre-lockdown months (January–February).
### Table 2
National AQI classes, range, health impacts and health breakpoints for the seven pollutants (Scale: 0–500).

| AQI category (Range) | Associated health impacts | PM2.5 | PM10 | Pre- lockdown | During lockdown I | During lockdown II | During lockdown III | During lockdown IV |
|----------------------|---------------------------|-------|------|--------------|------------------|------------------|-------------------|-------------------|
| Good (0–50)          | Minimal Impact            | 0–50  | 0–50 | 41.14        | 49.84            |                  |                   |                   |
| Satisfactory (51–100)| Minor breathing discomfort to sensitive people | 31–60 | 51–100 | 86.81 | 54.92 |                  |                   |                   |
| Moderately Polluted (101–200) | Breathing discomfort to the people with lung disease | 61–90 | 101–250 | 194.48 | 116.31 | 123.01 | 60.56 | 169.3 |
| Poor (201–300)       | Breathing discomfort to the people with prolonged exposure | 91–120 | 251–350 | 114.27 |                  |                  |                   |                   |
| Very Poor (301–400)  | Breathing illness to the people with prolonged exposure | 121–250 | 351–430 |                  |                  |                  |                   |                   |
| Sever (401–500)      | Respiratory effects even on healthy people | 250+  | 430+ |                  |                  |                  |                   |                   |
3.3. Particulate matter concentration during lockdown II

The period between April 15, 2020 and May 3, 2020 was referred to as lockdown II. To reduce the economic burden, selected additional activities were permitted during lockdown II. According to the Ministry of Home Affairs (MHA), all preparatory arrangements concerning social distancing in offices, workplaces, factories, and establishments, and other sectoral requirements were ensured to be in place before granting relaxation. Lockdown II relaxation measures included the permission for activities of all private vehicles to transport essential commodities, which resulted in slightly increased particulate matter levels. The range of average PM$_{2.5}$ and PM$_{10}$ concentrations was 30.44 $\mu$g/m$^3$ (Karni Singh) and 84.41 $\mu$g/m$^3$ (Arya Nagar) to 111.19 $\mu$g/m$^3$ (ITO) and 212.10 $\mu$g/m$^3$ (North Campus) during lockdown II, which was slightly higher than that observed during lockdown I. The highest PM$_{2.5}$ and PM$_{10}$ concentrations were observed in ITO and Bawana (211.10 $\mu$g/m$^3$ and 275.04 $\mu$g/m$^3$, respectively) because the supply of essential goods

![Air quality index of PM$_{2.5}$ for pre- and during lockdown period.](image)

Fig. 4. Air quality index of PM$_{2.5}$ for pre- and during lockdown period.
from the manufacturing sector, wholesale sector, retail sector, and shops was permitted. The minimum changes in PM$_{2.5}$ concentration were noticed in ITO (−11%) and Lodhi Road (−23%) during the same period. Similar findings were reported in China and Kazakhstan by Zambrano-Monserrate et al. (2020) and Kerimray et al. (2020), respectively. The maximum reduction in PM$_{2.5}$ and PM$_{10}$ levels was observed in Karni Singh (−73%) and both Sirifort and Wazirpur regions (−57%), whereas the minimum reduction in PM$_{2.5}$ and PM$_{10}$ levels was observed in ITO (−11%) and Alipur (−19%), respectively, during lockdown II. A similar result was reported in India, with reduction of 43% and 31% in PM$_{2.5}$ and PM$_{10}$ levels, respectively (Sharma et al., 2020). ITO and Sirifort were considered as urban and semi-urban sites that attributed highly variable and affected by traffic flow patterns (Gokhale and Khare, 2007).

3.4. Particulate matter concentration during lockdown III

In the wake of rising coronavirus cases in India, the Ministry of Home Affaire (MHA) announced its decision to extend the lockdown
until May 17, 2020, which was referred to as lockdown III. New guidelines were issued for the regulation of different activities. Based on risk profiling, districts of the country were divided into red (hotspot), green, and orange zones. The detailed guidelines permitted considerable relaxations in the districts categorized under the green and orange zones (MHF, 2020a). During lockdown III, the range of average PM$_{2.5}$ and PM$_{10}$ concentrations were 37.47 μg/m$^3$ and 85.79 μg/m$^3$, respectively, in RK Puram and 77.67 μg/m$^3$ and 170.83 μg/m$^3$, respectively, in Nerala. The maximum PM$_{2.5}$ and PM$_{10}$ values were 140.86 and 261.07 μg/m$^3$, respectively, in Bawana, whereas the minimum values were 19.33 μg/m$^3$ (Rohini) and 33.07 μg/m$^3$ (Sri Aurobindo Marg), respectively. The particulate matter concentrations were high in Bawana because it is a prime industrial area, where the industrial and construction activities were

![Graphs showing correlation between PM$_{2.5}$ and PM$_{10}$ concentrations during different lockdown phases.](image)

**Fig. 6.** Correlation between PM$_{2.5}$ and PM$_{10}$. 


permitted, which include the manufacturing of essential goods such as drugs, pharmaceuticals, medical devices, and their raw material and intermediates. The operation of production units requiring a continuous process and a supply chain were also permitted, which enhanced the level of air pollution. The maximum changes in PM$_{2.5}$ and PM$_{10}$ values were observed in JLN Stadium (-62%) and R. K. Puram (-58%), whereas the minimum changes were observed in Arya Nagar (-7%) and ITO (-38%), respectively, during the same period. These changes occurred because the market activities, including all standalone (single) shops, neighborhood (colony) shops, shops in residential complexes areas, were permitted without any distinction between essential and non-essential goods. Higher changes in levels of air pollutants were observed in South Delhi district (>60%), compared with the rest of the districts, because of more greenery and less industrial areas in the region.

### 3.5. Particulate matter concentration during the lockdown IV

Because of the increasing number of coronavirus cases in India, the MHA extended the COVID-19 lockdown period for 2 weeks until May 31, which was referred to as lockdown IV. Under the lockdown IV guidelines, rules to open the economy, such as the operation of all markets, offices, industries, and businesses, along with plying of buses in all zones, barring the containment zones, were completely relaxed (MHA, 2020b). The PM$_{2.5}$ and PM$_{10}$ levels had been increasing continually in most of the monitoring stations during lockdown IV, compared with the previous lockdowns. The maximum PM$_{2.5}$ and PM$_{10}$ concentrations were 147.39 mg/m$^3$ in Bawana and 327.52 mg/m$^3$ in Nerala, respectively. The average PM$_{2.5}$ and PM$_{10}$ concentrations were 46.85 mg/m$^3$ and 79.99 mg/m$^3$, respectively, in Sri Aurobindo Marg and 110.56 mg/m$^3$ and 232.66 mg/m$^3$, respectively, in Nerala. These results indicated a spike in the pollution level due to the removal of the restriction on various activities during lockdown IV. The System of Air Quality Weather Forecasting and Research reported that dust particles transported from Rajasthan were likely to be the dominant factor contribution to increased particulate matter concentration during lockdown IV. The present study reported a reduction in PM$_{2.5}$ level by 33% in Nerala and by 26% in Arya Nagar. Similar results were reported in Sao Paul state in Brazil (Nakada and Urban, 2020).

The range of average concentrations in different phases of lockdown I-IV for PM$_{2.5}$ (49.84-60.56 mg/m$^3$) for was found to be higher than standard prescribed various agencies such a WHO (25 mg/m$^3$), European Union (25 mg/m$^3$), but below permission limit for CPCB (60 mg/m$^3$), whereas for PM$_{10}$ (116.56–169.32 mg/m$^3$) was higher than WHO (25 mg/m$^3$), European Union (50 mg/m$^3$), and CPCB (100 mg/m$^3$) (Central Pollution Control Board, 2009; World Health Organisation, 2005; European Environment Agency, 2012). Delhi had witnessed high levels of particulate matter during the winter season before the lockdown period (1st January-24 March) due to the high density of traffic, thermal power plant, and biomass, including stubble burning from neighbouring states. A stable atmospheric condition in the winter season also favoured the level of PM$_{2.5}$ and PM$_{10}$. Additionally, inversion conditions, low humidity, scarce rainfall, and arid soil conditions were observed during the winter season. These conditions proved favourable for building up fine
aerosol from various activities leading to a higher concentration of PM$_{2.5}$ and PM$_{10}$ before lockdown (Singh et al., 2021a,b). During the lockdown period, all the anthropogenic activities were restricted movement except only essential activities, which were accountable for lowering PM$_{2.5}$ and PM$_{10}$. In addition, meteorological parameters such as rainfall, relative humidity, ambient temperature, wind speed, and direction played a crucial role in the dispersion, transformation, and removal of particulate matter from the lower atmosphere. Despite these restricted measures, the level of PM$_{2.5}$ and PM$_{10}$ were observed much higher than the standard prescribed by WHO and EU because Delhi witnesses and is influenced by natural and anthropogenic sources of pollution. Meteorological parameters such as prominent winds carrying dust from Rajasthan and sometimes Pakistan and Afghanistan. Furthermore, anthropogenic sources such as paddy stable, thermal power plant, high congestion of traffic witnessed to increase the level of particulate matter in Delhi.

### 3.5.1. Air Quality Index (AQI)

The AQI provides information about the air quality in terms of pollution level and is directly associated with the public health. The public health risk increases with increase in the AQI level. The standard ambient air quality in India is based on the concentration levels of 8 pollutants, namely, PM$_{10}$, PM$_{2.5}$, NO$_2$, SO$_2$, CO, O$_3$, NH$_3$, and Pb, which has been prescribed by the NAAQS and set by the CPCB. The AQI value is calculated every 24 h by taking into account all the eight pollutants. Government agencies have categorized the air pollution level into six AQI groups, namely, “Good”, “Satisfactory”, “Moderate”, “Poor”, “Very Poor”, and “Severe”. Overall, a remarkable improvement in average PM$_{2.5}$ and PM$_{10}$ concentrations was observed during the lockdown period in Delhi relative to previous years.

A report released by the automotive research association of India and the energy and resources institution was reported the sectorial share of Industries (28%), road dust (13%), residential (20%), and agricultural burning (17%) were the main contributors to PM$_{10}$ emissions in NCR. For PM$_{2.5}$, industries (24%), residential (25%), agricultural burning (19%), and transport (13%) were the significant contributors to NCR (The Automotive Research Association of India & The Energy and Resources Institute ARAI & TERI, 2018). The air quality level had improved drastically due to reduced air pollutant levels during the lockdown period. The average range of PM$_{2.5}$ and PM$_{10}$ concentrations for all the stations were 81.67–152.21 μg/m$^3$ and 140.62–260.16 μg/m$^3$, respectively, during the pre-lockdown period, which can be categorized as “poor-to-very-poor” and “moderate-to-poor”, respectively (Table 2). Deteriorating air quality during the pre-lockdown period was due to sources outside Delhi, such as residential cooking, agricultural waste burning, industries (tall stacks), and dust particles, which probably entered Delhi through the incoming winds. The air quality levels of PM$_{2.5}$ for all the stations were “satisfactory” (30.08–57.09 μg/m$^3$), except for North campus, which displayed “good” category (24.85 μg/m$^3$) during lockdown I and “satisfactory-to-moderate” category during lockdown II, III, and IV (Figs. 4 and 5). This result indicates a sharp decline in the air quality during the lockdown period. The PM$_{10}$ levels during the pre-lockdown period was categorized “moderate” for all the stations, except for DTU, Jahangirpuri, and Wazirpur, which exhibited a “poor” category because of the dispersal of pollutants from sources due to a high wind velocity and a crucial role of western disturbance in Delhi during the winter month.
sources of primary air pollutants, such as emissions from vehicles, industry, construction, and brick kilns, during the lockdown period.

3.5.2. Correlation between PM$_{2.5}$ (February) (Dimri et al., 2015). The air quality levels drastically improved for all the stations because of the complete absence of major sources of primary air pollutants, such as emissions from vehicles, industry, construction, and brick kilns, during the lockdown period.

The air quality level of PM$_{10}$ for all the stations was categorized “satisfactory” (30.08 to 57.09 µg/m$^3$), except for North campus, which displayed “good” category (24.85 µg/m$^3$) during lockdown I and “satisfactory-to-the-moderate” category during lockdown II.

### Table 4
Correlation for PM$_{10}$ at different stations.

|          | AshokVihar | J L N Stadium | Arya Nagar | Karni Singh | DTU | ITO | Jahangirpuri | Lodhi Road | Najafgarh | Nerala |
|----------|------------|---------------|------------|-------------|-----|-----|--------------|------------|-----------|--------|
| AshokVihar | 1.00       |               |            |             |     |     |              |            |           |        |
| J L N Stadium | 0.91**   | 1.00          |            |             |     |     |              |            |           |        |
| Arya Nagar   | 0.84**    | 0.94**        | 1.00       |             |     |     |              |            |           |        |
| Karni Singh  | 0.90**    | 0.97**        | 0.97**     | 1.00        |     |     |              |            |           |        |
| DTU         | 0.88**    | 0.92**        | 0.82**     | 0.90**      | 1.00|     |              |            |           |        |
| ITO         | 0.67**    | 0.66**        | 0.55**     | 0.63**      | 0.58**| 1.00|              |            |           |        |
| Jahangirpuri | 0.93**   | 0.94**        | 0.95**     | 0.98**      | 0.94**| 0.61**|              |            | 1.00      |
| Lodhi Road   | 0.95**    | 0.95**        | 0.92**     | 0.98**      | 0.89**| 0.82**| 0.91**       | 1.00      |
| Najafgarh    | 0.48**    | 0.57**        | 0.62**     | 0.57**      | 0.68**| 0.28**| 0.60**       | 0.49**    |
| Nerala       | 0.60**    | 0.55**        | 0.55**     | 0.59**      | 0.66**| 0.39**| 0.62**       | 0.58*     | 0.67**    |
| North Campus | 0.76**    | 0.73**        | 0.62**     | 0.79**      | 0.76**| 0.40**| 0.76**       | 0.75**    | 0.58**    |
| R.K.Puram    | 0.80**    | 0.71**        | 0.69**     | 0.78**      | 0.75**| 0.51**| 0.76**       | 0.73**    | 0.57**    |
| Rohini       | 0.87**    | 0.94**        | 0.95**     | 0.95**      | 0.60**| 0.94**| 0.91**       | 0.68**    | 0.62**    |
| VivekVihar   | 0.92**    | 0.95**        | 0.87**     | 0.93**      | 0.91**| 0.66**| 0.94**       | 0.92**    | 0.55**    |
| Sirifort     | 0.82**    | 0.88**        | 0.87**     | 0.80**      | 0.74**| 0.82**| 0.77**       | 0.87**    | 0.51**    |
| Okhla        | 0.90**    | 0.95**        | 0.85**     | 0.93**      | 0.89**| 0.65**| 0.91**       | 0.95**    | 0.54**    |
| Patparganj   | 0.93**    | 0.97**        | 0.93**     | 0.90**      | 0.90**| 0.67**| 0.94**       | 0.94**    | 0.53**    |
| Bawana       | 0.82**    | 0.91**        | 0.97**     | 0.90**      | 0.93**| 0.57**| 0.90**       | 0.88**    | 0.68**    |
| Sri Aurobindo | 0.90**   | 0.97**        | 0.90**     | 0.97**      | 0.89**| 0.66**| 0.92**       | 0.95**    | 0.54**    |
| Marg         |            |              |            |             |     |     |              |            |           |        |
| Alipur       | 0.77**    | 0.87**        | 0.84**     | 0.85**      | 0.88**| 0.56**| 0.864**      | 0.864**   | 0.672**   |
| Wazirpur     | 0.92**    | 0.94**        | 0.81**     | 0.91**      | 0.90**| 0.62**| 0.926**      | 0.921**   | 0.493**   | 0.488**|

**Correlation is significant at the 0.01 level (2-tailed).
III, and IV. The present study revealed significantly strong correlations between PM\(_{2.5}\) and PM\(_{10}\) levels during the pre-lockdown period (0.71) and lockdown IV (0.76), which indicate that change in the PM\(_{10}\) level influences the PM\(_{2.5}\) level greatly. The COVID-19 has provided a rare opportunity to countries including India to collect air pollution baseline data since, during the nationwide lockdown, air pollutants from transport, industries, and commercial activities were reduced significantly and relevant to air pollution reduction policies.

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- Ethics approval and consent to participate.
- Funding.

Author’s contributions

BPS acquired and analyzed the results and discussion and data interpretation section. PK contributed the scientific approach in the results and discussion section of the present manuscript.

Declaration of Competing Interest

The author declares that there 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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Appendix A. Supplementary data

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Singh, B.P., Kumar, K., Jain, V.K., 2021a. Source identification and health risk assessment associated with particulate- and gaseous-phase PAHs at residential sites in India. Aerosol Air Qual. Res. 21 (4), 1090–1098. https://doi.org/10.1007/s11356-020-11061-y.

Princeton, U., 2020. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. N. Engl. J. Med. 383 (24), 2386–2392. https://doi.org/10.1056/NEJMra2001922.

Kumar, P., Kumar, S., Yadav, S., 2018. Seasonal variations in size distribution, water-soluble ions, and carbon content of size-segregated aerosols over New Delhi. Environ. Sci. Pollut. Res. 25 (6), 6061–6076.

Lal, K., Patel, M., Patel, K., 2021. Fine particulate matter due to anthropogenic emissions switch-off during COVID-19 lockdown in Indian cities. Sustain. Cities Soc. May 2020, 102382. https://doi.org/10.1016/j.scs.2020.102382.

Kumar, D., Kumar, A., Kumar, V., Poyroja, R., Ghosh, A., 2020. COVID-19 driven changes in the air quality; a study of major cities in the Indian state of Uttar Pradesh. Environ. Pollut. 274, 116512. https://doi.org/10.1016/j.envpol.2021.116512.

Singh, R.P., Chauhan, A., 2020. Impact of lockdown on air quality during COVID-19 pandemic. Environ. Sci. Pollut. Res. 27 (9), 9211–9228. https://doi.org/10.1007/s11356-020-11054-9.

Mandal, I., Pal, S., 2020. Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. Sci. Total Environ. 730, 139086. https://doi.org/10.1016/j.scitotenv.2020.139086.

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Sharma, S., Mandal, T.K., Sharma, S.K., Kotnala, R.K., 2020. Emergence of blue sky over Delhi due to coronavirus disease (COVID-19) lockdown implications. Aerosol Sci. Eng. 4, 228–238. https://doi.org/10.4209/aaq.2020-00062-6.

Kumar, P., Hama, S., Omidvarborna, H., Sharma, A., Sahani, J., Abhijith, K.V., Debele, S.E., Zavala-reyes, J.C., Barwise, Y., Tiwari, A., 2020. Temporary reduction in fine particulate matter due to anthropogenic emissions switch-off during COVID-19 lockdown in Indian cities. Sustain. Cities Soc. May 22, 102381. https://doi.org/10.1016/j.scs.2020.102381.

Kumar, P., Mandal, T.K., Sharma, S.K., Kotnala, R.K., 2020. Emergence of blue sky over Delhi due to coronavirus disease (COVID-19) lockdown implications. Aerosol Sci. Eng. 4, 228–238. https://doi.org/10.4209/aaq.2020-00062-6.

Kumar, P., Mandal, T.K., Sharma, S.K., Kotnala, R.K., 2020. Emergence of blue sky over Delhi due to coronavirus disease (COVID-19) lockdown implications. Aerosol Sci. Eng. 4, 228-238. https://doi.org/10.4209/aaq.2020-00062-6.

Kumar, P., Mandal, T.K., Sharma, S.K., Kotnala, R.K., 2020. Emergence of blue sky over Delhi due to coronavirus disease (COVID-19) lockdown implications. Aerosol Sci. Eng. 4, 228-238. https://doi.org/10.4209/aaq.2020-00062-6.
Srivastava, A., Gupta, S., Jain, V.K., 2008. Source apportionment of total suspended particulate matter in coarse and fine ranges over Delhi. Aerosol Air Qual. Res. 8, 188–200.

Srivastava, S., Kumar, A., Baudh, K., Gautam, A.S., Kumar, S., 2020. 21-day lockdown in India dramatically reduced air pollution indices in Lucknow and New Delhi, India. In: Bulletin of Environmental Contamination and Toxicology. https://doi.org/10.1007/s00126-020-02895-w.

Stadnitskyi, V., Bax, C.E., Bax, A., Anfinrud, P., 2020. The airborne lifetime of small speech droplets and their potential importance in SARS-CoV-2 transmission. Proc. Natl. Acad. Sci. U. S. A. 117 (22), 3–5. https://doi.org/10.1073/pnas.2006874117.

Tan, J., Mu, L., Huang, J., Yu, S., Chen, B., Yin, J., 2005. An initial investigation of the association between the SARS outbreak and weather: with the view of the environmental temperature and its variation. J. Epidemiol. Community Health 59 (3), 186–192. https://doi.org/10.1136/jech.2004.020180.

The Automotive Research Association of India & The Energy and Resources Institute (ARAI & TERI). 2018. Source Apportionment of PM2.5 & PM10 of Delhi NCR for Identification of Major Sources. Report No. ARAI/16-17/DHI-SA-NCR/Final Report.

Tobias, A., Carnerero, C., Reche, C., Massagué, J., Via, M., Minguillón, M.C., Alastuey, A., Querol, X., 2020. Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. Sci. Total Environ. 726, 138540. https://doi.org/10.1016/j.scitotenv.2020.138540.

van Doremalen, N., Bushmaker, T., Munster, V.J., 2013. Stability of middle east respiratory syndrome coronavirus (MERS-CoV) under different environmental conditions. Eurosurveillance 18 (38), 1–4. https://doi.org/10.2807/1560-7917.ES2013.18.38.20509.

Wang, C., Horby, P., Hayden, F.G., Gao, G.F., 2020a. A novel coronavirus outbreak of global health concern. Lancet 395 (10223), 470–473. https://doi.org/10.1016/S0140-6736(20)30185-9.

Verma, R.L., Kamyotra, J.S., 2020. Impacts of COVID-19 on air quality in India. Aerosol Air Qual. Res. 21 (4) https://doi.org/10.4209/aaqr.200482.

Wu, F., Zhao, S., Yu, B., Chen, Y.M., Wang, W., Song, Z.G., Hu, Y., Tao, Z.W., Tian, J.H., Pei, Y.Y., Yuan, M.L., Zhang, Y.L., Dai, F.H., Liu, Y., Wang, Q.M., Zheng, J.J., Xu, L., Holmes, E.C., Zhang, Y.Z., 2020. A new coronavirus associated with human respiratory disease in China. Nature 579 (7798), 265–269. https://doi.org/10.1038/s41586-020-0008-3.

Yang, Y., Pun, V.C., Sun, S., Lin, H., Mason, T.G., Qiu, H., 2018. Particulate matter components and health: a literature review on exposure assessment. J. Public Health Emerg. 2, 14. https://doi.org/10.21037/jphe.2018.03.03.

Yao, M., Zhang, L., Ma, J., Zhou, L., 2018. On airborne transmission and control of SARS-Cov-2. Sci. Total Environ. 731, 139178. https://doi.org/10.1016/j.scitotenv.2020.139178.

Zambrano-Monserrate, M.A., Ruano, M.A., Sanchez-Alcalde, L., 2020. Indirect effects of COVID-19 on the environment. Sci. Total Environ. 728 https://doi.org/10.1016/j.scitotenv.2020.3633.

Zhang, J., Shi, L., Li, H., Lei, M., Zhang, L., 2021. The impact of the COVID-19 outbreaks on the air quality in China: evidence from a quasi-natural experiment. J. Clean. Prod. 269. https://doi.org/10.1016/j.jclepro.2020.126745.

Zhu, Y., Xie, J., Huang, F., Cao, L., 2020. Association between short-term exposure to air pollution and COVID-19 infection: evidence from China. Sci. Total Environ. 727, 138704. https://doi.org/10.1016/j.scitotenv.2020.138704.

Zoran, M.A., Savastri, R.S., Savasatri, D.M., Tautan, M.N., 2020. Science of the Total Environment Assessing the relationship between ground levels of ozone (O3) and nitrogen dioxide (NO2) with coronavirus (COVID-19) in Milan, Italy. Sci. Total Environ. 740, 140005. https://doi.org/10.1016/j.scitotenv.2020.140005.