Exploring short term spatio-temporal pattern of $PM_{2.5}$ and PM_{10} and their relationship with meteorological parameters during COVID-19 in Delhi

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ABSTRACT

Present study aims to examine the impact of lockdown on spatio-temporal concentration of $PM_{2.5}$ and PM_{10} - categorized and recorded based on its levels during pre-lockdown, lockdown and unlock phases while noting the relationship of these levels with meteorological parameters (temperature, wind speed, relative humidity, rainfall, pressure, sun hour and cloud cover) in Delhi. To aid the study, a comparison was made with the last two years (2018 to 2019), covering the same periods of pre-lockdown, lockdown and unlock phases of 2020. Correlation analysis, linear regression (LR) was used to examine the impact of meteorological parameters on particulate matter (PM) concentrations in Delhi, India. The findings showed that (i) substantial decline of PM concentration in Delhi during lockdown period, (ii) there were substantial seasonal variation of particulate matter concentration in city and (iii) meteorological parameters have close associations with PM concentrations. The findings will help planners and policy makers to understand the impact of air pollutants and meteorological parameters on infectious disease and to adopt effective strategies for future.

1. Introduction

Clean and fresh air is one of the basic requirements of good human health as well as well-being of people. However, air pollution has recently become a significant health hazard across the world due to a rapid growth in urbanization, economic development, energy consumption, transportation and motorization. Air pollution is not only one of the biggest issues in developing countries, but an urgent problem negatively affecting developed countries as well. The cities of developing countries are more polluted than the cities of developed countries. Exposure to air pollution was treated as the biggest environmental health risk of the world (Anenberg et al., 2010; Krewski et al., 2009; Pedersen et al., 2013; Pope Iii et al., 2002; Smith et al., 2014; Sun et al., 2019; Weinmayr et al., 2015) that causes approximate 7 million deaths per year (WHO World Health Organization, 2014). The concentration of particulate matter (PM)

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including PM$_{2.5}$ has hence become a major cause of concern when it comes to global environmental health. The concern reigns supreme everywhere, including the capital city of India - Delhi, which is the prime focus of the present study. Air quality assessment, particularly of PM$_{2.5}$ concentrations over Indian cities has become a core public concern due to the serious health risks that accompany their rising levels. In India, premature deaths due to PM$_{2.5}$ exposure have increased significantly since 1990 (as per a recent estimate (2016), approximately 1.0 million premature deaths can be attributed to PM$_{2.5}$ exposure (https://vizhub.healthdata.org/gbd-compare/india). Most of the polluted cities of India are concentrated in and around the National Capital Territory of Delhi (NCTD), making this region a leading hub of pollution in the world (Guttikunda and Calori, 2013; Tiwari et al., 2012; Pandey et al., 2016). The cities of NCTD including Delhi, Gurugram, Faridabad (Haryana) and several other cities located in Uttar Pradesh and Bihar are the most vulnerable to PM$_{2.5}$exposures. In previous research studies, it has been well documented that the concentration of PM$_{2.5}$ in the IGP, particularly the NCT of Delhi exceed the National Ambient Air Quality Standard (annual NAAQS) of 40 μg/m^3 (it is four times higher than the WHO's standard limit) (Chowdhury et al., 2019; Chowdhury and Dey, 2016; Dey et al., 2012; Tiwari et al., 2013). A number of policies were thus consequently implemented to reduce pollution levels across the cities of India. For instance, in the NCT of Delhi, measures covered the shutting down of factories, revamping of the public transport system, use of compressed natural gas (CNG) and reduction in the use of sulphur content diesel (Chowdhury et al., 2019; Goel and Pant, 2016; Narain and Krupnick, 2007). In addition to this, National Green Tribunal act was imposed in 2015 for banning diesel vehicles older than 15 years to reduce pollution levels within the city. All these improved levels. No measure, however, proved especially effective for Delhi NCR, a region equally polluted as Gurugram, Faridabad, Agra, Panipat, Budh nagar etc. The concentrations of PM$_{2.5}$ remained higher than the NAAQ standards even after the implementation of a number of measures (some as listed above) over this region along with the IGP (Chowdhury et al., 2019). From the above analysis, it was easy to realize that the mere implementation of policies and regulations could not be enough to reduce pollution levels over cities. Short term lockdowns (3 to 7 days), in addition, may prove to be an alternative measure to effectively combat extreme pollution levels ailing the most polluted cities of India. This will, most of all, be of urgent help to the city of Delhi (The most recent World Air Quality report (2018) published by IQ Air Visual on the basis of PM$_{2.5}$ level declares India's capital city as the most polluted capital city in the world, with an average annual PM$_{2.5}$ measuring 113.5 μg/m^3).

In previous research studies, it was recognized that there is a strong association between particulate matter and the outbreak of various diseases such as respiratory infection, asthma, lung cancer etc. (Raaschou-Nielsen et al., 2013; Beelen et al., 2014; Pedersen et al., 2013; Cesaroni et al., 2014; Adams et al., 2015). These studies helped to establish an evident relationship between air pollution and respiratory diseases. Most of them, however, were performed in Europe and North America, with very few studies being conducted in and focusing upon Asian cities (Maji et al., 2018a, 2018b). The COVID-19 pandemic has brought change in this scenario. During this period, studies have been initiated with renewed vigour in Asia, with several being performed to examine the impact of lockdown on air quality in India (Mahato et al., 2020; Sharma et al., 2020; Singh et al., 2020). All the same, the association of air pollutants with meteorological parameters and COVID-19 at city scale remains limited and unexplored in the context of Indian megacities.

It is widely known that the capital city of India i.e. Delhi is considered as one of the most polluted megacities of the entire world (Gurjar et al., 2010). Most of the year, Delhi violates the standard limits of the NAAQS (Guttikunda and Goel, 2013). Previously, a few research studies have been performed which focus on the relationship of air quality with respiratory diseases (Kumar et al., 2010; Balakrishnan et al., 2011; Rajarathnam et al., 2011; Dholakia et al., 2014; Maji et al., 2017; Chhabra et al., 2001; Pande et al., 2002; Agarwal et al., 2006; Jayaraman, 2008). In recent times, however, to the best of our knowledge, no studies have been performed to examine the relationship of particulate matters with COVID-19 in Delhi during the lockdown situation. Air pollutants, especially particulate matters, can play a crucial role in COVID-19 transmissions and infection in two ways. Firstly, the spreading of airborne viruses is greatly affected by fine particles (Andree, 2020). COVID-19, being a respiratory disease, can linger in aerosols for hours (van Doremalen et al., 2020; Zhu et al., 2020a; Zhu et al., 2020b). Secondly, it has been recognized that air pollution has tremendous impact on lung surfactant composition as well as lung damage (Pastva et al., 2007). Thus, air pollution makes the human body more vulnerable to respiratory infections, asthma and other chronic diseases (Fattorini and Regoli, 2020; Kim et al., 2018; Korber, 2020). The lungs are the main targets of corona-virus (Ali and Alharbi, 2020), thus the chances of infection may rise if one is exposed to severe air pollution (Zhang et al., 2020). It was mentioned in previous literatures and WHO's report (2018) that Delhi is the most polluted capital city. Higher levels of air pollution within the city may hence have a significant impact on COVID-19 transmissions as well as mortalities in Delhi.

COVID-19 has already been declared a 'global pandemic' by the World Health Organization on 11 March 2020. The outbreak of COVID-19 has brought to the fore an unprecedented threat to human health (Das et al., 2021a; Das et al., 2021b). To combat the new disease, a number of countries adopted restrictions in order to fight its highly communicable nature. It was stated in previous studies that the spreads of COVID-19 cannot be examined through geographic distance, population density, age composition and epidemic models (Becchetti et al., 2020; Setti et al., 2020; Travaglio et al., 2020; Wu et al., 2020a; Wu et al., 2020b). Instead, COVID-19 transmissions and infections are greatly affected by atmospheric conditions (Bashir et al., 2020a; Bashir et al., 2020b; Becchetti et al., 2020; Fattorini and Regoli, 2020; Qi et al., 2020; Xie and Zhu, 2020; Wang et al., 2020a). COVID-19 spreads via respiratory droplets, close contact as well as through air via aerosols (Wang et al., 2020b; Paules et al., 2020; van Doremalen et al., 2020). Now the basic question that needs to be addressed in this context is how these atmospheric conditions affect COVID-19 transmissions. To understand this, it is important to find out the relationship of COVID-19 transmissions and mortalities with meteorological parameters (such as temperature, humidity, wind speed etc). Recent studies are available to observe the same, studies which have documented that meteorological parameters have a crucial impact on COVID-19 transmissions as well as mortalities (Bashir et al., 2020a; Becchetti et al., 2020; Fattorini and Regoli, 2020; Qi et al., 2020; Xie and Zhu, 2020; Wang et al., 2020b).

Recently, several studies have been performed across the cities of the world to examine the immediate impact of lockdown on air pollution levels (Otmani et al., 2020; Tobías et al., 2020; Xu et al., 2020). In China, the concentration of primary air pollutants (such as

PM$_{2.5}$, PM$_{10}$, SO$_2$, CO and NO$_2$) in three major cities have declined by 30.1%, 40.5%,33.4%, 27.7% and 14.9%, respectively due to lockdown (Xu et al., 2020). Other studies have, in addition to this, recorded similar results in the major cities of Spain, Brazil and Morocco (Dantas et al., 2020; Otmani et al., 2020; Tobías et al., 2020; Xu et al., 2020). In India as well, a number of studies have been performed to assess the impact of lockdown on air quality (Jain and Sharma, 2020; Mahato et al., 2020; Mahato and Ghosh, 2020; Singh and Chauhan, 2020; Sharma et al., 2020). These vital studies performed in India primarily take into account large megacities and other most polluted regions. After a quick review of the previously published studies on the assessment of air pollution level, few notable research gaps have been identified. **First**, the previous research studies on the assessment of air quality have focused on particular megacities such as Delhi (Mahato et al., 2020; Khan, 2020; Sikarwar et al., 2020) and Kolkata (Sarkar et al., 2021), but very few studies were performed on the relationship between particulate matter concentration and meteorological parameters (Dhaka et al., 2020). **Second,** although many recent studies have been performed to assess air pollution levels in India during lockdown phases (Mahato and Ghosh, 2020; Sharma et al., 2020), very few studies have been carried out during the progression of the unlock phases of lockdown in India (Ravindra et al., 2021). **Third,** to the best of our knowledge, seasonal variations of particulate matter concentration were studied for the first time during lockdown periods. Delhi, being one of the most polluted cities in the world, it is very essential to model spatial concentration of air pollutants and to find out its relationship with meteorology. Thus, the findings of the study will study assist (a) to understand that how restricted emissions from various sources can improve the air quality (b) during unlock down periods the air quality improved in comparison to pre-lockdown periods even after relaxation of guidelines. Thus, short terms lockdown may be an effective measure to improve the air quality of the city and to enhance the quality of life of the urban citizens.

2. Materials and method

2.1. About study area: Delhi megacity

The air quality in Delhi, the capital of India, according to a WHO survey world cities, is the worst of any major city in the world. Pollution in Delhi, which spikes during winter, had hit almost 30 times the WHO's safe limits in the second week of November 2016. Air pollution in India is estimated to have killed 1.5 million people in 2012, giving it the position of the fifth most frequent cause of death in India. India has the world's highest death rate from chronic respiratory diseases and asthma, according to WHO reports (2018). Two prominent features pertaining to the geography of Delhi are the Yamuna flood plains and the Delhi ridge. The Yamuna River was once the historical boundary between Punjab and UP, and its flood plains provide fertile alluvial soil suitable for agriculture, although being prone to recurrent floods. Delhi has been continuously inhabited since the sixth century BCE (Asher, 2000). Through
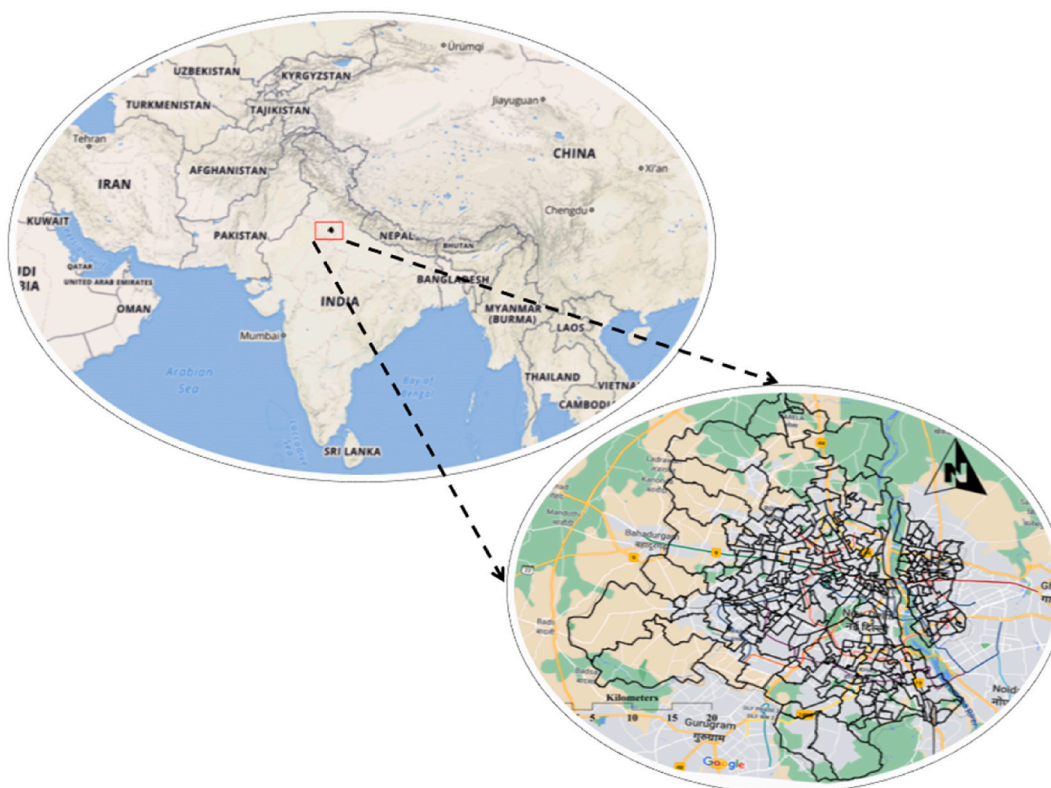

Fig. 1. Location map of NCT-Delhi.

most of its history, Delhi has served as a capital of various kingdoms and empires. It has been captured, ransacked and rebuilt several times, particularly during the medieval period, and modern Delhi is a cluster of many cities spread across the metropolitan region (Sikarwar et al., 2020). The city extends between 28°24′30″N to 28°53′4″N and 76°49′58″S to 77°20′15″S, respectively (Fig. 1). The state of Delhi is characterized by weather extremes. Both summer and winter are severe with June being the hottest month and January the coldest. The annual rainfall is around 700 mm. Maximum rain occurs during July to August. The city is 216 m above the mean sea level (MSL) (Table 1). The city is surrounded by other major growth centers of adjoining states such as Haryana and Uttar Pradesh, and the geographical location of this city influences the weather conditions of Delhi. Thus, the significant variations in climate in the specified geographical region may influence the $PM_{2.5}$ concentrations. The population in Delhi was more than 16 million in 2011 as per Census of India (2011). The population density of National Capital Territory (NCT) of Delhi grew substantially from 1176 to 11,297 people per square kilometer of land area between 1951 and 2011 as per Census of India.

2.2. Collection of air quality data ($PM_{2.5}$ and PM_{10})

In Delhi air pollution level is monitored by Central Pollution Control Board (CPCB) (also known as National Air Quality Monitoring Programs- NAMP), Government of India. For the assessment of particulate matter concentrations in Delhi, data has been collected from the CPCB online portal from 2018 to 2020. CPCB monitors across about 793 monitoring stations extending 344 cities of India (over 29 states and 7 Union Territories). CPCB provides data on major air pollutants such as Suspended Particulate Matter (SPM), Carbon Monoxide (CO), Sulphur Dioxide (SO_2), Nitrogen Dioxide (NO_2), Ozone (O_3), respectively. Daily data of particulate matter concentration has been collected from 31 air quality monitoring stations in Delhi from five zones (North, South, East, West and Central). These air quality monitoring stations are operated by CPCB and Delhi Pollution Control Board (DPCB). The details of the air quality monitoring stations are presented in Table 2.

The COVID-19 pandemic has already faced three monsoonal seasons i.e. pre-monsoon (March to May), monsoon (June to September) and winter (December to February), respectively. Most interestingly, these three monsoonal seasons are well-matched with pre-lockdown (winter-January to February), during lockdown (pre-monsoon-April to May) and unlock phases (June onwards). Thus, seasonal variation of particulate matter can easily assist to understand any variation over different phases of lockdown.

2.3. Collection of meteorological data

In this study, the relationship between particulate matter concentration and meteorological parameters has been assessed from 2018 to 2020 during the same periods of time which have, in 2020, fallen under lockdown and unlock phases. In previous research studies, it was recognized that there was a strong relationship between air pollutants and meteorological parameters (Zhang et al., 2015a; Zhang et al., 2015b; Dholakia et al., 2014; Banerjee et al., 2011). Thus it is essential to consider meteorological parameters while discussing temporal concentrations of particulate matters. In addition to this, there was a substantial decrease in air pollutant concentrations across many cities of the world due to COVID-19 induced lockdown. In this context, solely assessing the impact of lockdown on spatio-temporal concentration is not enough. It is rather crucial to consider the meteorological parameters during the different lockdown and unlock phases and compare it with previous meteorological conditions during the same periods. This study considers seven meteorological parameters from 2018 to 2020 during periods same as that of the lockdown and unlock phases to understand the relationship between particulate matter concentrations and metrological parameters. The data related to meteorological parameters has been collected from world weather on line portal (https://www.worldweatheronline.com/).

Table 1
City profile- Delhi NCR.

Basic information	
Official name	**The National Capital Territory of Delhi (NCTD)**
Formation	1985
Local bodies	(i) New Delhi Municipal Council (NDMC) (ii) Delhi Cantonment Board (DCB) (iii) North Delhi Municipal Corporation (iv) South Delhi Municipal Corporation (v) East Delhi Municipal Corporation
Administrative units	9 districts and 27 sub-districts
Demographic profile (Census of India, 2011)	
Total population	16.3 million
Population density (person/ km^2)	11,297
Literacy rate (%)	86.2
Urban population (%)	97.5
Climatic features	
Climate type	Semi-arid
Season	(i) Summer-March to May (ii) Monsoon-June to September (iii) Post monsoon- October to November (iv) Winter- December to February and (v) Pre-monsoon-March to May
Temperature (°C) in winter	4 to 10
Temperature (°C) in summer	42 to 48
Precipitation (mm)	762

Table 2
Details of the air quality monitoring stations (considered in this study) in Delhi Megacity (Author's own classifications).

Zones in Delhi	Number of stations	Name of the station
West	4	Najafgarh; NSIT-Dwarka; Dwarka Sector 8; Mundka
East	9	Anand Vihar; CRRI - Mathura Road; Patparganj; Sonia Vihar; Vivek Vihar; IHBAS-Dilshad Garden; ITO - Delhi; IP Extension; Gazipur.
South	7	IGI Airport; Sri Arobindo Marg; Ayanagar; Dr. Karni Singh Shooting Range; Siri Fort; Nehru Nagar; Jawaharlal Nehru Stadium
North	5	BawanaIndustrial Area; Narela; Pooth Khurd; DTU-Rohini; Alipur
Central	6	DPCC – Pusa Road; Shadipur; Mandir Marg; Wazirpur, Ashok Vihar; Major Dhyan Chand National Stadium

2.4. Statistical analysis

There is a strong relationship between meteorological parameters and air pollutants. In many previous research studies, correlation analysis was performed to examine the relationship between air pollutants and meteorological parameters (Lin et al., 2015; Grinn-Gofroń et al., 2011; Kliengchuay et al., 2018; Owoade et al., 2012; Trivedi et al., 2014). But till now no study has been performed to examine the relationship between meteorological parameters and particles matter concentrations on severely affected cities in India during COVID-19 pandemic. In this study, correlation coefficient (r) has been performed to examine the relationship between particulate matter concentration and meteorological parameters during periods same as that of lockdown and unlock phases from 2018 to 2020. This assessment of correlation will not only assist to understand the relationship between particulate matter concentrations and meteorological parameters during lockdown and unlock phases, but also help to understand the degree of relationship in previous years during the same periods.

The concentrations of particulate matters are largely affected by meteorological conditions. In previous research studies it was well recognized that there were significant impact of meteorological parameters on the concentration of particulate matter (Lin et al., 2015; Wang et al., 2015). In this study, simple linear regression (LR) model was used to examine the impact of meteorological parameters on particulate matter concentration. The concentration of particulate matters ($PM_{2.5}$ and PM_{10}) have been considered as dependent variables and meteorological parameters (such as temperature. Wind speed, relative humidity, rainfall, pressure, sun hour and cloud cover) have been considered as independent variables. LR model can be expressed as shown in Eq. (1):

$$Y_i = \beta 0 + \beta 1 X1 + \varepsilon 1 \tag{1}$$

where, Y_i is the dependent variables; β_0 is the estimate of regression intercept; β_1 is the estimate of regression slope; X_i is the independent variables and ϵ_i random error term.

All the statistical analysis has been performed using SPSS (version 22) software (Fig. 2).
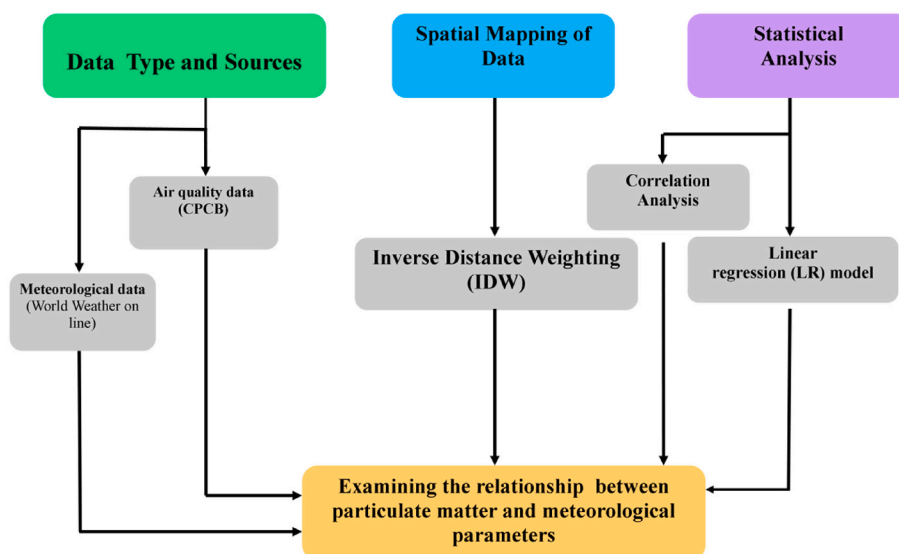

Fig. 2. Methodological framework of the study.

3. Result

3.1. Comparison pattern of particulate matters concentration in last two years

In case of $PM_{2.5}$ (μg/m^3), average concentration from April to August (2018) was 137 μg/m^3 (during periods of lockdown and unlock phases in 2020) that declined to 87 μg/m^3 in 2020 during the corresponding time periods (decreased by 36.36%). During full lockdown periods (from 1st April to 31st May, 2020), average concentration was 175 μg/m^3 in 2018 that found to be 124 μg/m^3 in 2020 (declined by 30%). Again during unlock phases (up to phase III in 2020), the average concentration of $PM_{2.5}$ was 112 μg/m^3 and 82 μg/m^3 in 2018 and 2019, respectively, that declined to 62 μg/m^3 in 2020 (Figs. 3 and 4).

Similar pattern of PM_{10} (μg/m^3) has also been recorded over the eight selected stations in Delhi. Results recorded that average concentration from April to August (2018) was 154 μg/m^3 (during periods of lockdown and unlock phases in 2020), which declined to 93 μg/m^3 during corresponding time periods of 2020 (decreased by 40%). During full lockdown periods (from 1st April to 31st May of 2020), average concentration of $PM_{2.5}$ was 216 μg/m^3 in 2018 that reached to 118 μg/m^3 in 2020 (declined by 46%). Similarly, during unlock phases (up to phase III), the average concentration of $PM_{2.5}$ was 113 μg/m^3 in 2018 that found to be 76 μg/m^3 in 2020 (decreased by 32%). Thus from the overall analysis it was clear that the concentrations of particulate matters ($PM_{2.5}$ and PM_{10}) in Delhi substantially decreased during lockdown and unlock phases. Thus, as per results, it has been documented that the concentrations of particulate matter have substantially declined after the implementation of lockdown (since 25th March to 31st May 2020) and unlock phases (since 1st June onwards, 2020) (Tables 3 and 4).

3.2. Pattern of particulate matter concentrations in different phases

3.2.1. Before lockdown period (from January to March, 2020)

Just before three months of lockdown, the concentrations of particulate matters were relatively high in Delhi. During the month of January, average concentrations of $PM_{2.5}$ (μg/m^3) and PM_{10} (μg/m^3) were above 400 μg/m^3 and 350 μg/m^3 that reached to 300 μg/m^3 and 250 μg/m^3, respectively during February (Fig. 5).

3.2.2. During full lockdown period (from last week of March to 31st May, 2020)

In India, lockdown started from 25th March to 31st May, 2020 in four phases (i.e. phase I from 25th March to 14th April; phase II from 15th April to 3rd May; phase III from 4th May to 17th May and phase IV from 18th May to 31st May, 2020). During lockdown period, there was substantial decrease of particulate matter concentration in Delhi NCT in comparison to the pre-lockdown period. As per results, it was also recorded that the concentration of particulate matters slightly increased in successive lockdown phases due to relaxation of guidelines (such as allowing private vehicles to ply, reopening of markets, shopping malls etc). During phase I, the average concentration of $PM_{2.5}$ (μg/m^3) and PM_{10} (μg/m^3) were 70.61 μg/m^3 and 76.58 μg/m^3 which increased to 84.11 μg/m^3 and 86.38 μg/m^3 during phase II, 94.16 μg/m^3 and 98.62 μg/m^3 during phase III and 111.42 and 135.35 during phase IV of lockdown, respectively (Fig. 6).
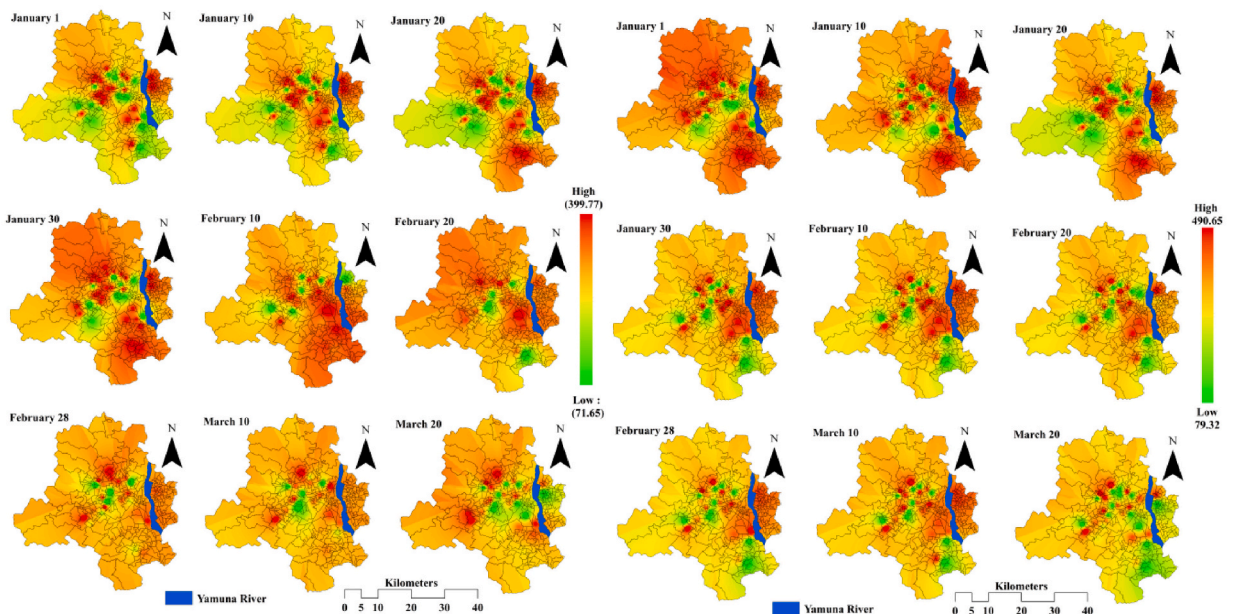

Fig. 3. Concentration of $PM_{2.5}$ (left) and PM_{10} (right) (μg/m^3) before lockdown in 2018 during same periods.
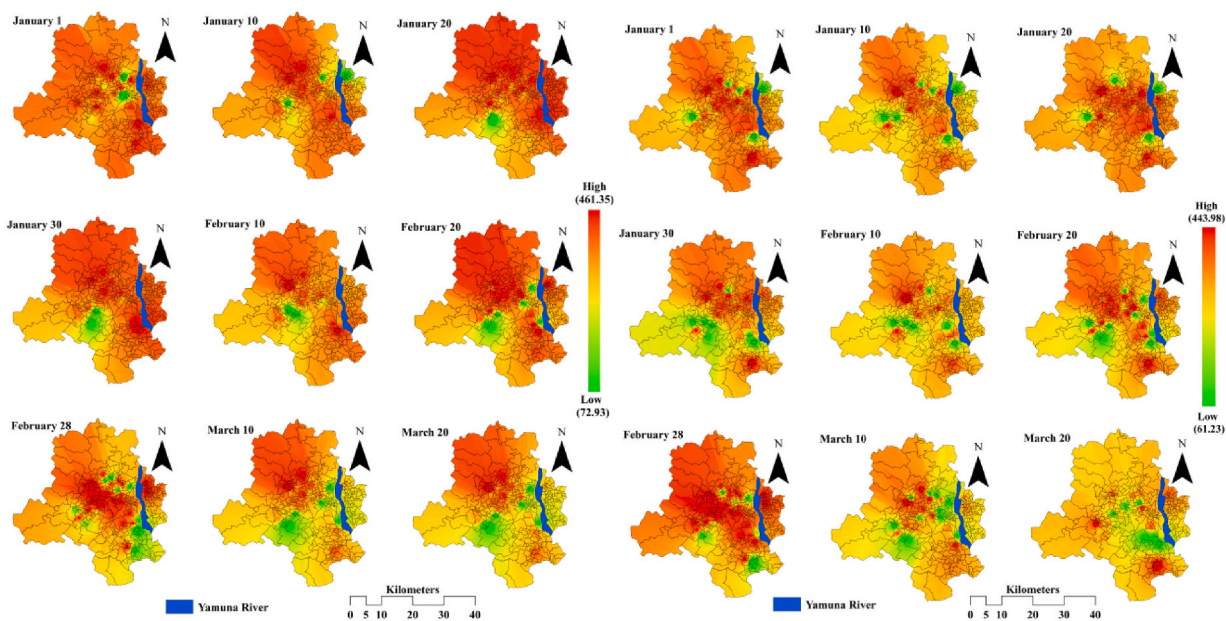
Fig. 4. Concentration of PM$_{2.5}$ (left) and PM$_{10}$ (right) (μg/m^3) before lockdown in 2019 during same period.

3.2.3. During unlock periods (from 1st June to 31st August, 2020)

In India, unlock has been started from 1st June 2020 and it continues. In this study concentration of particulate matters has been assessed up to unlock III. Unlock I was started from 1st June to 30th June 2020 (30 days), unlock II was started from 1st July to 31st July, 2020 (31 days) and unlock III was started from 1st August to 31st August, 2020(31 days) (Fig. 7).

As per results, it was documented that the concentrations of particulate matter substantially decreased in unlock I (except unlock III for PM$_{10}$) (Fig. 8). During unlock I, average concentrations of PM$_{2.5}$ (μg/m^3) was108 that declined by more than 30% (average) during unlock II and III. On the other hand, during unlock I, average concentrations of PM$_{10}$ (μg/m^3) was 75 μg/m^3 that reached to 45 μg/m^3(declined by 45%) and 54 μg/m^3(decreased by 20%) during unlock I and unlock II, respectively. During unlock phases, concentration of particulate matter increased in many parts of the city due to relaxations of guidelines such as economic activities, transportations etc.

3.3. Seasonal pattern of particulate matters concentration

As per results of the study, it was noted that there was considerable decrease of particulate matter concentrations in 2020 due to lockdown in different monsoonal seasons (Tables 5 and 6). For example, in 2018 average concentrations of PM$_{2.5}$ (μg/m^3) and PM$_{10}$(μg/m^3) across 8 stations were 340 μg/m^3 and 280 μg/m^3 that declined to 246 μg/m^3(decreased by 28%) and 178 μg/m^3(decreased by 36%) in 2020 during winter (pre-lockdown phases). During pre-monsoon (lockdown phases), average concentrations of these two particulate matter were 176 μg/m^{3}and 218 μg/m^{3}in 2018 that reached to 123 μg/m^3(decreased by 30%) and 115 μg/m^3(decreased by 47%) in 2020, respectively. Similar kind of result has been recorded during monsoon season (unlock phases). Thus from the overall analysis, it is clear that the concentration of particulate matters decreased notably in different monsoonal seasons in 2020 as compared to the last two years (2018–2019) in Delhi (Fig. 9).

3.4. Relationship between meteorological parameters and particulate matter concentrations

Correlation coefficient (r) between particulate matters and meteorological parameters recorded presence of statistically significant negative correlation between particulate matters and temperature in 2020 ($r = -0.77$ for PM$_{2.5}$ and -0.66 for PM$_{10}$) as well as in 2018 ($r = -0.73$ for PM$_{2.5}$ and -0.65 for PM$_{10}$) and 2019 ($r = -0.74$ for PM$_{2.5}$ and r $= -0.74$ for PM$_{10}$), respectively. Wind speed had also negative relationship with particulate matter concentration in 2020 ($r = -0.39$ for PM$_{2.5}$ and -0.279 for PM$_{10}$), in 2018 ($r = -0.34$ for PM$_{2.5}$ and -0.33 for PM$_{10}$) and 2019 ($r = -0.61$ for PM$_{2.5}$ and -0.27 for PM$_{10}$), respectively. There was no further significant relationship of particulate matters with any other meteorological parameters (such as relative humidity and rainfall). It can be factually observed that there is a negative correlation between concentration of particulate matter and temperature (i.e. concentration of particulate matter decreases with increasing temperature). In this study, the correlation between concentration of particulate matters and meteorological parameters revealed that majority correlation coefficients (r) are similar with the previous research studies, albeit with minor difference in case of relative humidity (Fig. 10 and Table 7). From the result, it was observed that the average concentration of PM$_{2.5}$ and PM$_{10}$ during winter (January and February) was 246 (μg/m^3) and 178 (μg/m^3) with average temperature

Table 3
Concentrations of particulate matter PM$_{2.5}$ (μg/m^3) in last two years and 2020 during same lockdown and unlock phases.

Stations	2018					2019					2020				
	April	May	June	July	August	April	May	June	July	August	Full Lockdown		Unlock I	Unlock II	Unlock III
											April	May	June	July	August
Shadirpur	163	233	233	90	63	74	114	152	73	46	24	156	43	71	35
RK Puram	148	210	210	84	65	77	68	123	74	35	29	124	30	47	34
IHBAS	233	186	213	95	74	81	340	210	130	34	18	189	61	51	38
DTU	125	195	195	78	46	63	80	146	91	26	38	233	56	86	59
Dwarka	176	148	190	68	47	45	66	130	48	14	37	186	49	78	48
Sirifort	181	179	179	48	39	43	73	121	51	13	38	159	66	84	52
Punjab Bagh	137	198	182	95	55	42	70	142	47	13	56	292	69	96	56
ITO	95	191	191	90	53	67	67	163	66	30	211	190	86	130	83

Table 4
Concentrations of particulate matters PM_{10} ($\mu g/m^3$) in last two years and 2020 during same lockdown and unlock phases.

| Stations	2018					2019					2020				
	April	May	June	July	August	April	May	June	July	August	Full Lockdown		Unlock I	Unlock II	Unlock III
											April	May	June	July	August
Shadirpur	160	210	113	59	63	74	114	88	69	46	60	140	43	78	35
RK Puram	206	253	152	102	75	60	98	85	72	40	64	124	69	87	38
IHBAS	222	210	170	68	75	81	340	169	130	34	16	130	71	101	38
DTU	230	238	159	97	69	76	226	99	68	56	94	227	95	91	72
Dwarka	267	231	163	156	116	86	139	135	109	13	78	161	106	100	60
Sirifort	286	262	172	116	88	118	123	110	75	18	70	145	143	100	59
Punjab Bagh	178	196	153	135	78	69	120	84	63	18	69	270	80	96	61
ITO	144	174	149	104	80	63	111	72	74	21	85	150	69	73	81
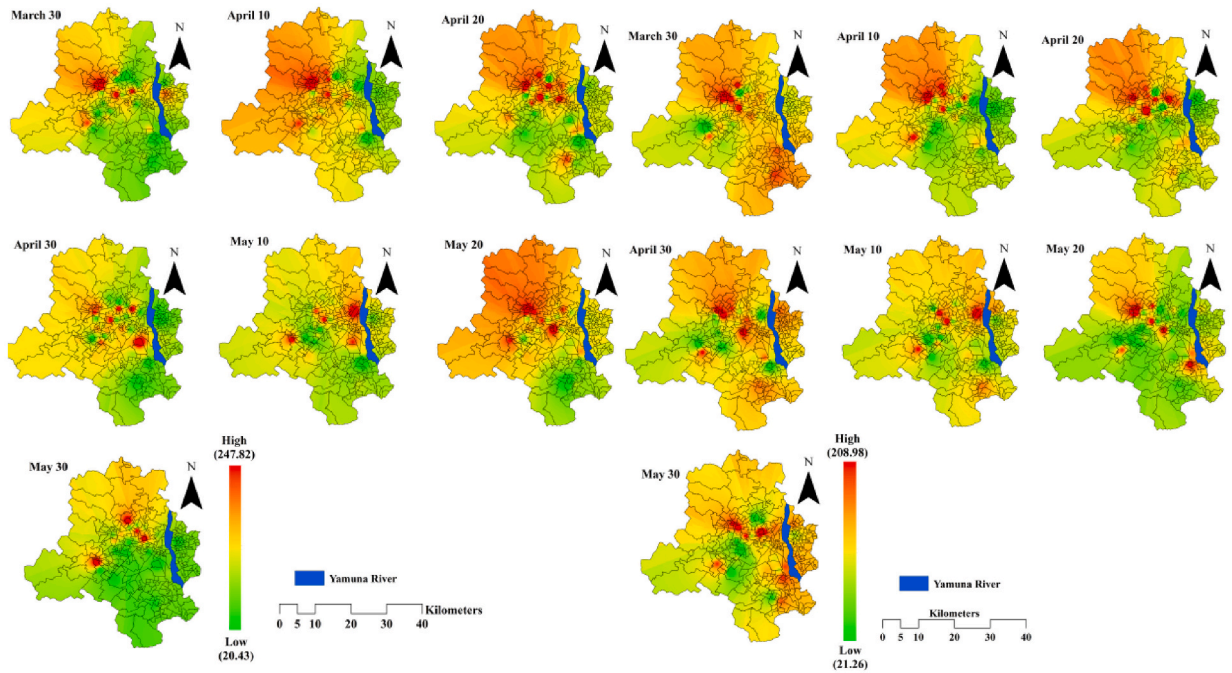
Fig. 5. Concentrations of particulate matterPM$_{2.5}$in last two years and 2020 during same lockdown and unlock phase.

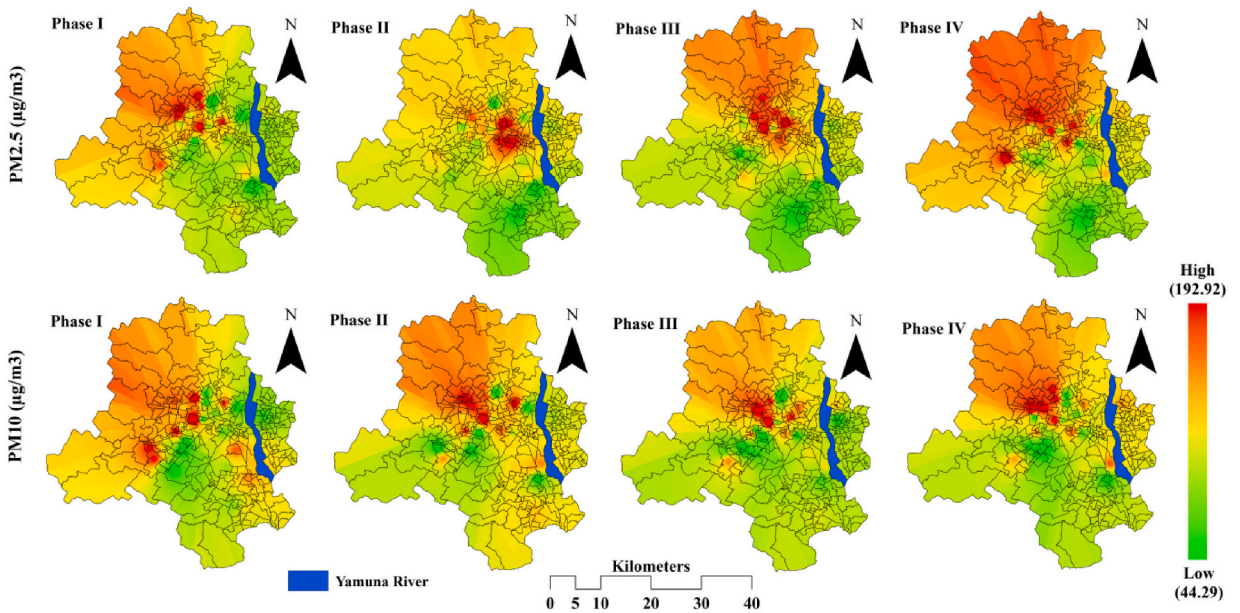**Fig. 6.** Average concentration of PM$_{2.5}$ and PM$_{10}$ (μg/m^3) in Delhi during lockdown phases.

of 19 °C. On the other hand, during the month of pre-monsoon (March, April and May), average concentration of PM$_{2.5}$ and PM$_{10}$ were 138 (μg/m^3) and 124 (μg/m^3) with average temperature of 32.7 °C. Thus, it clearly denotes that there were negative relationship between particulate matter concentration and temperature. Similarly wind speed also showed negative correlation with particulate matter concentration as during the season of winter and pre-monsoon, the average wind speed was 9.5 (kmph) and 11.0 (kmph), respectively. The seasonal variations of particulate matter with reference to meteorological parameters are shown in Fig. 11.

The average relative humidity remains high during winter and monsoon season and that result in the lack of a strong relationship between particulate matters and relative humidity. Therefore, a very weak correlation (both negative and positive) has been observed between relative humidity and particulate matters concentrations ($r = -0.24$ for PM$_{2.5}$ and -0.44 for PM$_{10}$ in 2018, $r = -0.26$ for
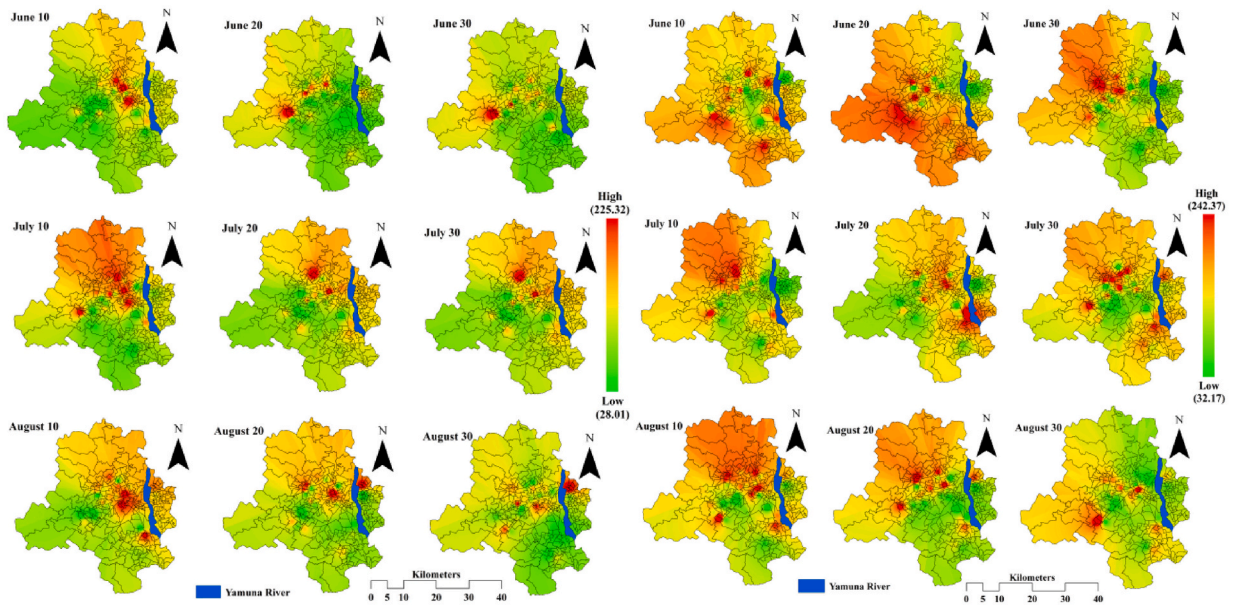
Fig. 7. Concentration of PM$_{2.5}$ (left) and PM$_{10}$ (right) (μg/m^3) in Delhi megacity during unlock phases.
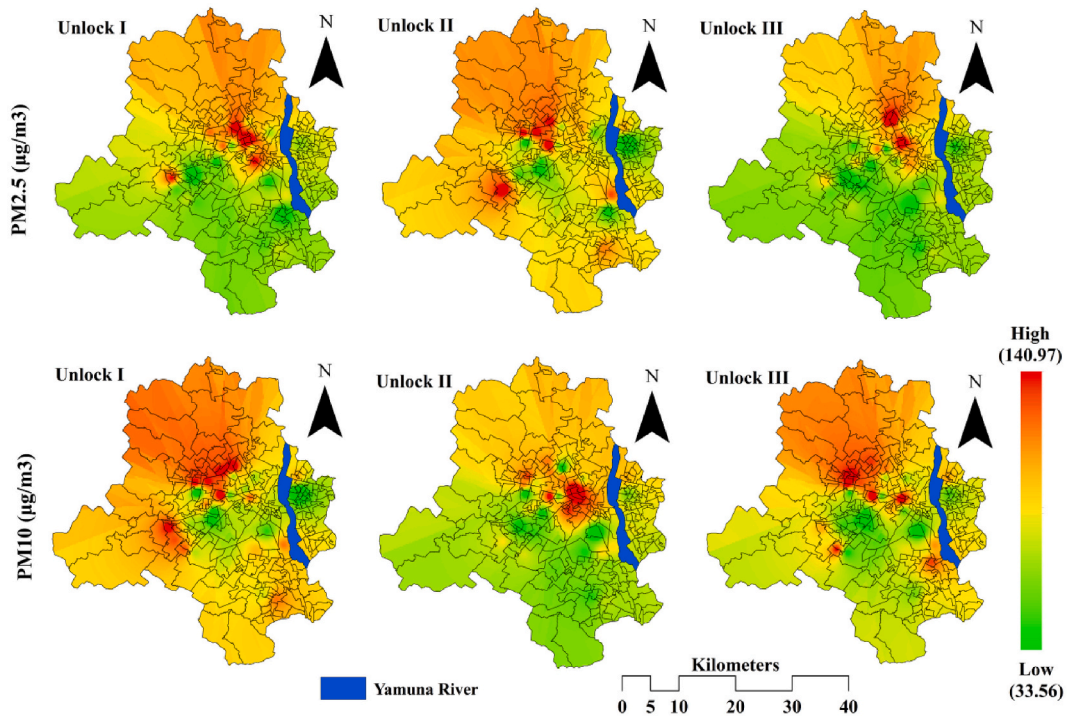

Fig. 8. Concentration of PM$_{2.5}$ and PM$_{10}$ (μg/m^3) in Delhi megacity during unlock phases.

PM$_{2.5}$ and $r = -0.07$ for PM$_{10}$ in 2019 and $r = 0.27$ for PM$_{2.5}$ and $r = 0.14$ for PM$_{10}$ in 2020, respectively). From previous findings, it was observed that the correlation between particulate matters and meteorological parameters somewhat differ. This variation may be due to locations and different climatic conditions such as temperature, rainfall, relative humidity patterns etc.

As per linear regression (LR) model, it was recognized that the concentrations of particulate matter (particularly PM$_{2.5}$) was largely influenced by meteorological parameters and showed positive associations with atmospheric pressure (R^2 = 0.61), relative humidity (R^2 = 0.60), temperature (R^2 = 0.59), sun hour (R^2 = 0.25), cloud cover (R^2 = 0.24), wind speed (R^2 = 0.15) and rainfall (R^2 = 0.53), respectively (Table 8).

Table 5
seasonal variations of PM$_{2.5}$ (μg/m^3) concentrations in last two years (2018–2019) and during lockdown and unlock phase (2020).

Stations	2018			2019			2020		
	Winter	Pre-monsoon	Monsoon	Winter	Pre-monsoon	Monsoon	Winter	Pre-monsoon	Monsoon
Shadirpur	329.00	198.00	128.67	308.50	94.00	89.67	269.50	90.00	49.67
RK Puram	349.00	179.00	119.67	327.00	72.50	103.00	213.00	76.50	37.00
IHBAS	254.50	206.50	119.67	325.50	210.50	124.67	201.50	103.50	50.00
DTU	376.00	160.00	106.33	322.00	71.50	87.67	271.50	135.50	67.00
Dwarka	357.50	183.00	98.33	260.00	55.50	64.00	285.00	111.50	58.33
Sirifort	360.00	180.00	88.67	284.50	58.00	61.67	246.50	98.50	67.33
Punjab Bagh	351.50	158.50	110.00	316.50	56.00	67.33	245.00	166.00	65.33
ITO	346.00	143.00	113.67	321.50	67.00	83.00	236.50	205.50	99.67

Table 6
seasonal variations of PM$_{10}$ (μg/m^3) concentrations in last two years (2018–2019) and during lockdown and unlock phase (2020) in selected stations.

| Stations	2018			2019			2020		
	Winter	Pre-monsoon	Monsoon	Winter	Pre-monsoon	Monsoon	Winter	Pre-monsoon	Monsoon
Shadirpur	218.50	185.00	78.33	308.50	94.00	75.33	183.00	94.00	52.00
RK Puram	299.00	228.00	99.00	306.50	79.00	65.67	176.00	94.00	66.00
IHBAS	217.00	231.00	104.33	325.50	210.50	111.00	142.50	68.00	73.00
DTU	289.00	234.00	108.33	273.00	151.00	74.33	212.50	160.50	86.00
Dwarka	311.50	256.00	140.67	305.00	112.50	85.67	251.00	119.50	88.67
Sirifort	310.00	274.00	125.33	335.50	120.50	67.67	168.00	107.50	100.67
Punjab Bagh	317.50	179.00	121.00	268.00	94.50	55.00	162.50	167.50	80.67
ITO	284.50	159.00	111.00	237.50	87.00	55.67	133.00	113.50	74.33
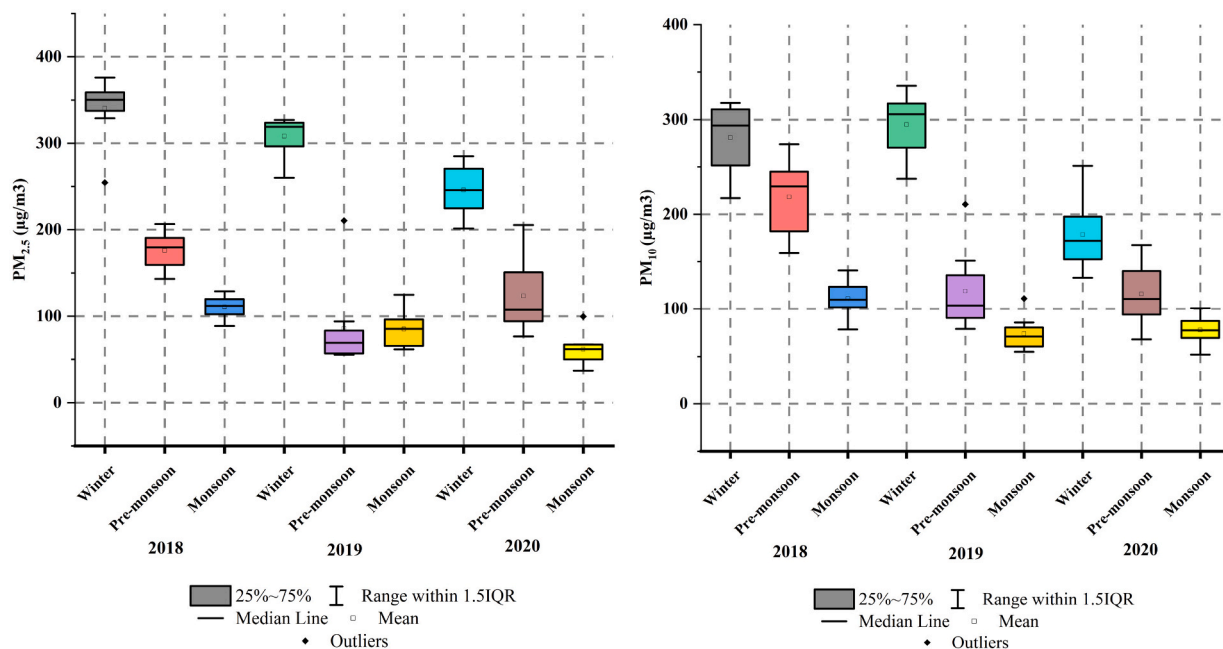
Fig. 9. Seasonal variations of PM$_{2.5}$ and PM$_{10}$ in some selected stations on Delhi.

4. Discussion

In this present study, the concentrations of particulate matters (PM$_{2.5}$ and PM$_{10}$) in megacity- Delhi has been assessed in pre-lockdown, during lockdown and unlock phases (up to phase III). The concentration of particulate matters in Delhi has also been compared with previous years during same periods of lockdown in order to aid better understanding of the impact of lockdown during different phases in last two years (2018 to 2019). From the results of the study, it was recognized that the concentration of particulate matter substantially decreased during lockdown and unlock phases in Delhi. Thus, the outbreak of COVID-19 provided an opportunity
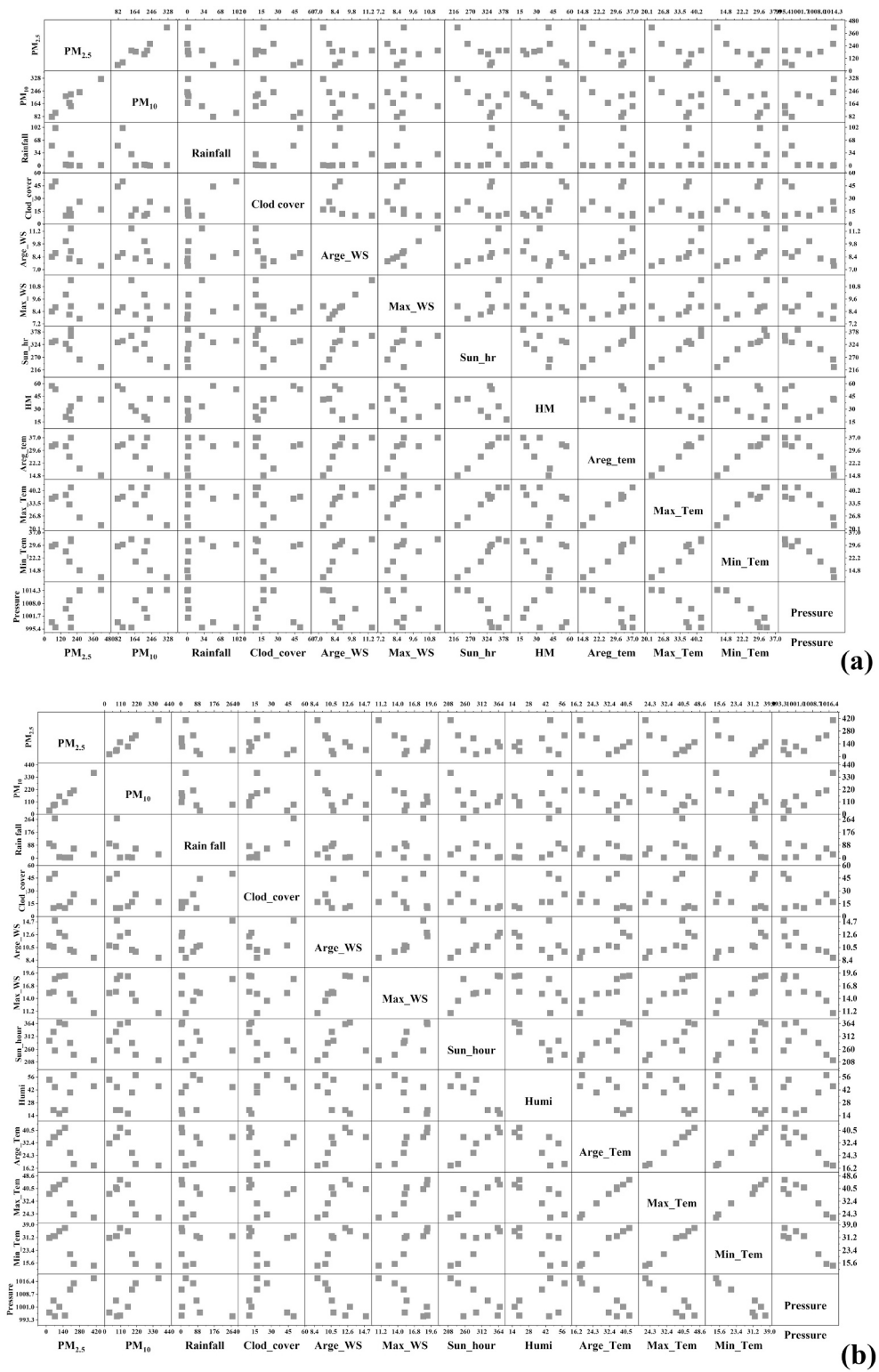
Fig. 10. Scatter plots showing the relationship between particulate matters and meteorological parameters.
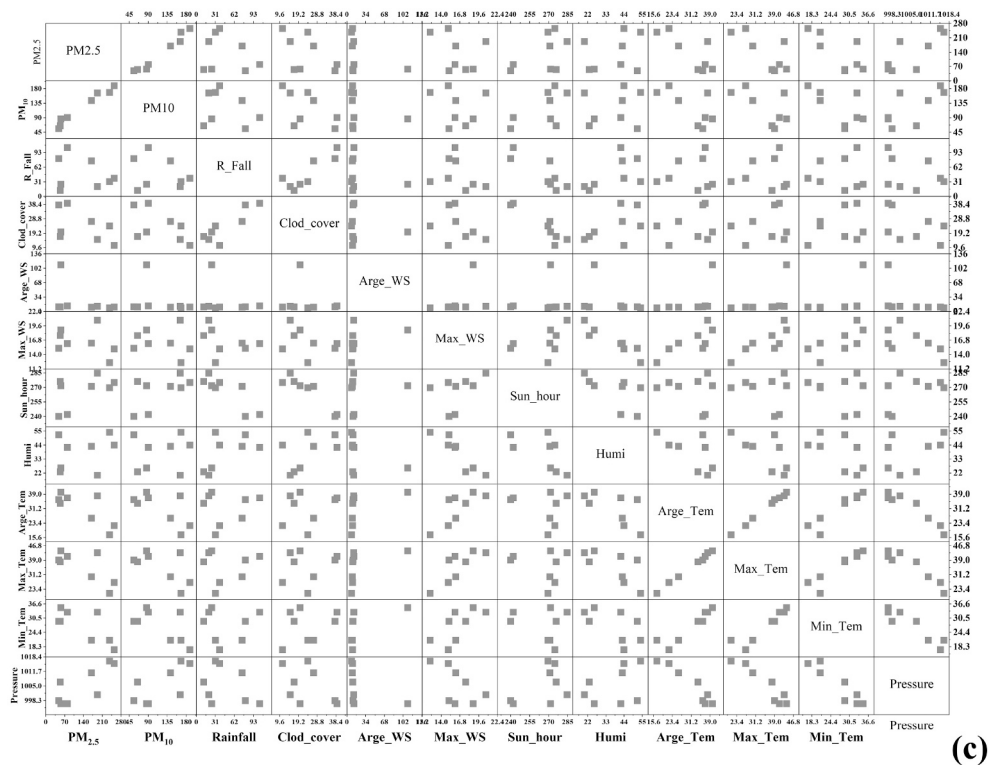
Fig. 10. (*continued*).

Table 7
Comparison correlation coefficient (r) of suspended particulate matters (SPM) with meteorological parameters.

Contents			Meteorological parameters				
			Average temperature	Wind speed	Relative humidity	Rainfall	References
Previous studies			−0.762	−0.109	0.249	−0.561	Banerjee et al., (2011)
			−0.303	−0.431	0.09		Ilten and Selici (2008)
			−0.622	0.047	0.47	−0.141	İçağa and Sabah (2009)
			−0.795	−0.64	0.13	−0.075	Turalıoğlu et al. (2005)
			0.05 to (−0.65)	0.15 to (−0.35)	−0.08 to (+0.058)		Monn et al. (1995)
In this study	PM $_{2.5}$	2018	−0.737	−0.343	−0.24	−0.64	–
		2019	−0.741	−0.611	0.266	−0.437	
		2020	−0.779	−0.392	0.277	−0.23	
	PM $_{10}$	2018	−0.657	−0.344	−0.44	−0.743	–
		2019	−0.745	−0.577	−0.071	−0.419	
		2020	−0.668	−0.279	0.143	−0.254	

to understand the impact of lockdown on environmental pollution level. Recently, a number of studies were performed observing the assessment of air quality after the outbreak of COVID-19 across the world (He et al., 2020; Liu et al., 2020b; Watts and Kommenda, 2020; Cadotte, 2020; Ogen, 2020; Coccia, 2020). In these studies, it was documented that the air pollution levels substantially declined due to outbreak of COVID-19, particularly because of lockdown. In India a number of studies were performed to find out the impact of lockdown on air quality (Dhaka et al., 2020; Maji et al., 2021; Manchanda et al., 2021; Navinya et al., 2020; Roy and Balling Jr, 2021; Singh and Chauhan, 2020). More particularly, a study was conducted by Mahato et al. (2020) in Delhi, India, with results showing that the concentration of PM$_{2.5}$ level has declined after the implementation of lockdown.

Rapid rate of urbanization is taking place in India due to excessive migration to cities (Rai, 2012). As a result of this, the percentage of urban population is likely to reach 50% by 2050. This Urbanization is being promoted by consumption of energy and fuel, primarily in transport and industrial sectors leading to high pollution levels (Gambhir et al., 2017). Purohit et al. (2010) estimated that the concentration of PM$_{2.5}$ will increase by 25% in 2030 in India. Even the concentrations of other air pollutants such as sulphur dioxide (SO$_2$) and nitrogen oxide (NO$_2$) also likely to increase by 3 to 5 times. The annual average concentration of PM$_{2.5}$ is expected to reach 150 µg/m^3 in most Indian cites by 2050 (TO OEO. 2050). In this context, it is essential to carry out continuous assessment of air pollutants to build environmental sustainability and sustainable urban health.
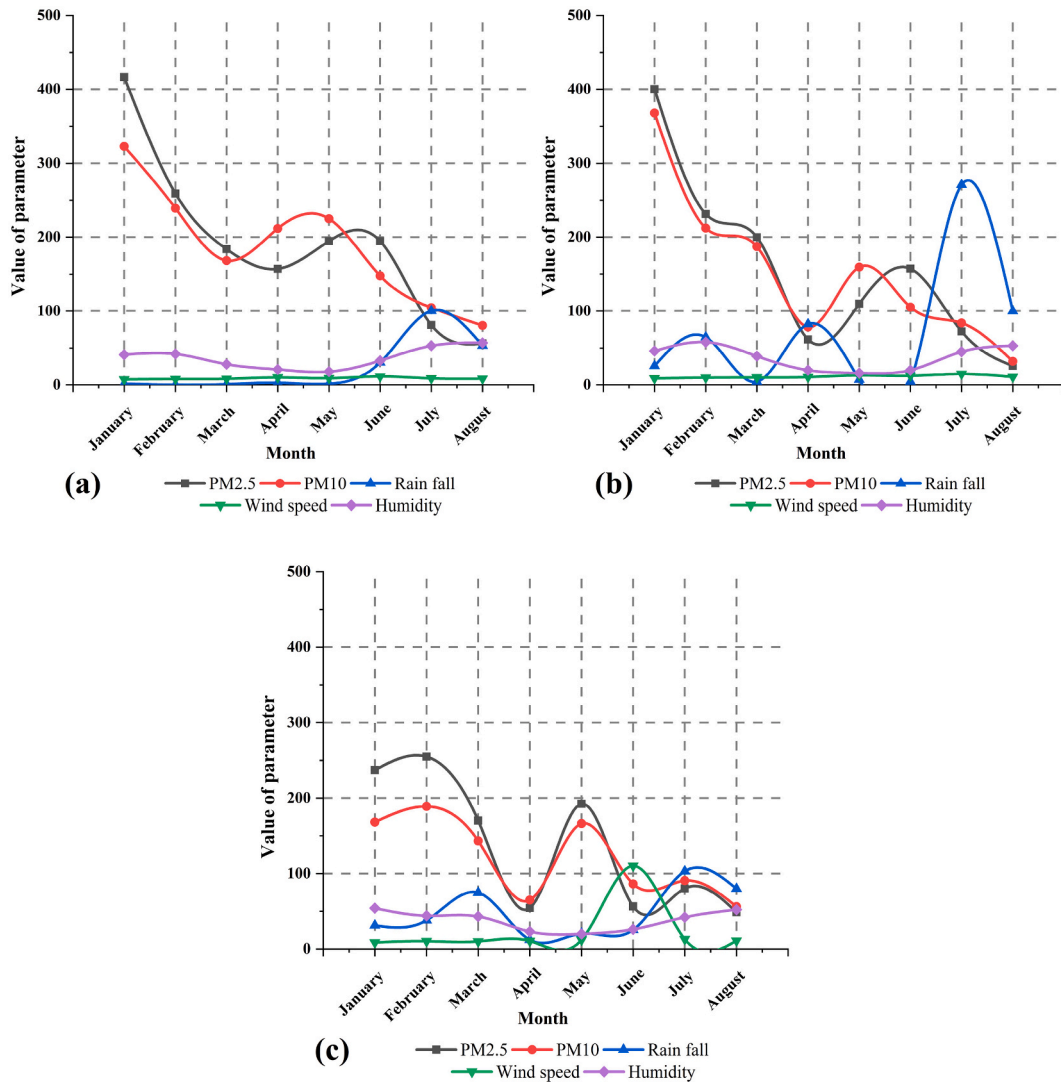
Fig. 11. Seasonal variation of particulate matter with reference to meteorological parameters since 2018 to 2020.

Table 8
Severely COVID-19 affected cities in India (by 12th June 2020).

City	States/UTs	In percentage to the state	In percentage to the country	Temperature (°C)		Relative humidity (%)		Wind speed (kmph)	
				During full lockdown	During unlock periods	During full lockdown	During unlock periods	During full lockdown	During unlock periods
Mumbai	Maharastra	55	18	31	28.66	68	79.66	13.95	22.5
Delhi	Delhi	60	11	36.5	37.7	18.5	41.66	11.45	11.03
Chennai	Tamil Nadu	70	9	31	30.66	71	67.66	17.75	17.63
Thane	Maharastra	29	5.22	33	29.33	58	75.33	11.45	18.53
Ahmedabad	Gujarat	70	5.21	35.5	32.33	29.5	64	15.9	15.73

In previous literature, it was recognized that climatic conditions were one of the significant predictors of corona-virus illnesses because meteorological conditions (such as wind speed, temperature, humidity) play a vital role in transmitting infectious disease (Dalziel et al., 2018; Yuan et al., 2006). Recent studies were performed to find out the relationship between meteorological parameters (such as air temperature, relative humidity, and wind speed) and COVID-19 across the world (Xie and Zhu, 2020; Yongjian et al., 2020; Liu et al., 2020b; Wang et al., 2020a; Auler et al., 2020; Ma et al., 2020; Gupta et al., 2020; Wu et al., 2020a; Wu et al., 2020b; Jiang and

Xu, 2020). Most of these studies have reported that there was a significant association between meteorological parameters and COVID-19. For example, Zhu et al. (2020c) performed a study encompassing 122 cities in China and the result of the study recorded that there was a positive liner association between average temperature and COVID-19 cases. A study was also performed by Kumar and Goyal (2011) in India to examine the impact of meteorological parameters on COVID-19. The findings of the study recorded that there was a positive relationship between temperature and COVID-19 cases, along with a mixed association with humidity. Recent literatures revealed that temperature had a surprising impact on COVID-19 transmission in Brazil, China and other countries (Prata et al., 2020; Qi et al., 2020; Wang et al., 2020b; Wang et al., 2020a; Wang et al., 2020b). Humidity was considered as one of the significant meteorological factors with respect to COVID-19 transmission (Ali and Alharbi, 2020; Auler et al., 2020; Bashir et al., 2020a; Bashir et al., 2020b), pertaining to how it is partially suppressed with increasing humidity (Ahmadi et al., 2020; Wu et al., 2020a; Wu et al., 2020b). Wind speed acts as a significant meteorological factor in spreading respiratory infectious diseases and it affects corona-virus infection by influencing air quality (Ellwanger and Chies, 2018; Frontera et al., 2020; Wang et al., 2020a; Zhu et al., 2020a; Zhu et al., 2020b), It was consequently observed that the impact of wind speed on COVID-19 transmissions was controversial i.e. it ranges from negative (Ahmadi et al., 2020) to positive (Şahin, 2020), to insignificant (Bashir et al., 2020a).

In many previous research studies, it was documented that urban ambient air pollution was closely associated with deaths due to respiratory causes (Schwartz, 2005; Bell et al., 2006; Wilson, 2014; Pekkanen et al., 2002; Brooks et al., 2010). In addition to this, the link between particulate matter concentration and risk of respiratory morbidity was widely studied (Ostro et al., 1995; Schwartz and Morris, 1995; Agarwal et al., 2006; Maji et al., 2018a, 2018b). There was significant positive as well as statistical association of respiratory disease with air pollutants (Wong et al., 2002; Wai et al., 2012; Cropper et al., 1997). Rajarathnam et al. (2011) conducted research in Delhi to find out the relationship between air quality and adverse human health, and their results recorded that there was a positive relationship between air quality and cause of mortalities. Thus from previous research studies, it was clear that concentrations of particulate matter increase the risk of respiratory mortalities. COVID-19 being a respiratory disease, it is natural to infer that the concentration of air pollutants largely influences COVID -19 mortalities. Recently, studies have examined how the concentration of air pollutants was an important risk factor contributing to COVID-19 mortalities (Martelletti and Martelletti, 2020; Ogen, 2020; Zhu et al., 2020a; Zhu et al., 2020b; Fattorini and Regoli, 2020). Thus, it is obvious that the cities with higher concentration of air pollutants are highly vulnerable when it comes to COVID-19 mortalities. As per WHO's report (2018), Delhi was the most polluted capital city of the world with an annual average $PM_{2.5}$ concentrations 113.5 μg/m^3. Thus higher concentration of $PM_{2.5}$ in Delhi may have a significant impact on COVID mortalities. As of 16th June 2020, about 1327 people have died in Delhi owing to the disease (2nd highest COVID mortalities after Mumbai where 2182 people died due to COVID-19) according to the Economic Times. On the other hand, total COVID-19 confirmed cases in Delhi were 1,74,748, with deaths at about 4444 people as of 30th August (Government of Delhi, 2020). Among the ten most severely affected cities in India, Delhi was the second severely affected megacity. Nearly 11% of the total COVID-19 cases of India were recorded in Delhi. Thus, from the results of previous studies and present study, it can be stated that higher concentrations of particulate matter have had a significant impact on COVID-19 mortalities in Delhi.

A slew of effective steps has been adopted by the Government of Delhi to control the air pollution level in the capital over the last ten years. This includes but is not limited to restricting emissions from vehicles, implementation of odd and even motor vehicles, switching to cleaner fuels, relocation of polluted industries etc. As a result of this, the concentration of SO_2 and lead has gradually declined. Concentration of particulate matters, on the other hand, have still remained relatively high and above acceptable levels (CSE, 2012; Rizwan et al., 2013; Maji et al., 2018a, 2018b). In addition to this, government needs to be focused towards effective policies to reduce air pollution level and to combat with the infectious diseases (like COVID-19) in future. During lockdown periods, various measures were adopted to reduce the spreading of COVID-19 over Delhi such as restricted emissions from factories, industries, transportations and other economic activities. In Delhi, there are three thermal plants namely Indraprasta Power Station and Rajghat Power House in east, Badarpur Power Station in north-western parts of Delhi. Thus, restricted emission due to lockdown resulted reduction particulate matter concentrations over Delhi. In previous studies, it was well documented that industrial activities, constructions (road side), transportations, emission from the regional sources were the main source of air pollution (Saxena et al., 2017; Sen et al., 2016; Sharma et al., 2016). Thus, complete shutdown on transportation, industrial activities and other anthropogenic activities caused substantial reduction of particulate matter concentration over Delhi during lockdown periods. The concentrations of particulate matter also varied during different phases of lockdown and unlock phases in 2020 as well as in 2018 and 2019. The main cause of this spatial variation was due to difference of land use types and anthropogenic activities. For example, it can be stated that Badarpur Thermal Station is located in north-western parts of Delhi and northern and western parts of Delhi also dominated by residential areas (Roy and Balling Jr, 2021).

4.1. Limitations of the study

Though this study has immense potentiality to understand the relationship between particulate matter concentration and meteorological parameters during pre-lockdown, during lockdown and unlock down periods, respectively. The findings of the study may be very helpful to understand how in Delhi as most polluted capital city of the world, air quality drastically improved due to restricted emissions from different sources and restricted anthropogenic activities. In spite of this, this study has some limitations. Firstly, the $PM_{2.5}$ and PM_{10} data were collected from Central Pollution Control Broad (CPCB) and many times data were not available for a specific data. In this case, the data of next and last few days were considered. Secondly, the meteorological data were not available for each CPCB locations, so average meteorological data of the city was collected. Thirdly, unlock phases of lockdown were considered till August (2020), not all the phases of unlock were taken into consideration and seasons were considered till monsoon (August, 2020)

5. Conclusion

The study tried to examine the spatio-temporal patterns of particulate matter during pre-lockdown, lockdown and unlock phases; as well as the relationship of particulate matter concentrations with meteorological parameters in Delhi. The study compared the spatio-temporal concentrations with that of previous years (2018 and 2019) during same periods of time (April to August) to aid an understanding of the impact of lockdown and unlock phases upon particulate matter concentrations. Correlation analyses, linear regression (LR) model was used examine the relationship as well as association between particulate matter concentrationsand meteorological parameters. The findings of the study recorded that (i) there was substantial decrease of particulate matter concentrations in Delhi after implementation of lockdown and during unlock phases. Over 2018–2020 during full lockdown periods, (April and March 2020). The concentrations of particulate matters (both $PM_{2.5}$ and PM_{10}) decreased by about 40%. On the other hand, over 2018–2020 during unlock periods (up to phases III from June to August 2020), particulate matter concentrations decreased by about 35%. (ii) As per results, it was documented that there was an association between particulate matter concentrations and meteorological parameters in Delhi and the outcomes observed were similar to that seen in previous studies. During periods of lockdown and unlock phases (up to phases III), there were no significant changes of meteorological conditions in comparison to the last three years (from 2017 to 2019). For example, for all the years, particulate matters had a negative correlation with temperature (r value ranges from −0.657 to −0.797) and wind speed, respectively. Temperature, in particular, may have tremendous impact on COVID-19 cases as well as COVID-19 mortalities in Delhi.

The study tried to examine the relationship of particulate matter ($PM_{2.5}$ and PM_{10}) with meteorological parameters in Delhi rather than other air pollutants. This may be treated as one of the limitations of the study. But this study focuses on $PM_{2.5}$ and PM_{10} as representative measures because both have a wide range of chemical makeup as well as sources. Particulate matters, especially $PM_{2.5}$ are regarded as air pollutants which have the most negative impact on human health in relation to other pollutants. $PM_{2.5}$ can penetrate deep into the human respiratory system and throughout the entire human body due to its small size. This naturally leads to many short-term and long term health effects. In addition to this, particulate matter is the primary air pollutant which affects most of the globe. Secondly, there was a lack of data related to COVID-19 cases and COVID-19 mortalities at district and sub-district level across the city of Delhi. There is, therefore, scope for future research to examine the relationship of particulate matter with meteorological parameters, COVID-19 cases and COVID-19 mortalities at regional level as meteorological conditions, COVID-19 cases and COVID-19 mortalities may vary across regions.

In spite of the limitations mentioned above, the study undoubtedly makes an important scientific contribution as it may assist in developing an understanding of how strongly air pollutants are linked with meteorological conditions and how closely it is associated with infectious disease. The findings of the study will not only help in the future adoption of effective policies and planning for Delhi, they may also be helpful for other large cities of India as well as the many pollutions affected cities of developing countries.

Author statement

On behalf of all authors, I declare that all authors read and approve the manuscript titled "Exploring short term spatio-temporal pattern of $PM_{2.5}$ and PM_{10} and their relationship with meteorological parameters during COVID-19 in Delhi" and there is no conflict of interest. The contributions of all authors are equal.

Data availability statement

The datasets used to support the findings of this study are available from the corresponding author on reasonable request.

Authors contribution statement

Conceptualization, Data curation, Formal analysis: MD, AD, SS, SG; Investigation, Methodology, Project administration: MD, AD, RS, SS; Resources, Software: MD; Supervision, Validation, Visualization: AD, RS, SG; Writing - original draft, Writing - review & editing: MD, RS, PP.

Declaration of Competing Interest

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

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