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Article

Demographic Evaluation and Parametric Assessment of Air Pollutants over Delhi NCR

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Abstract: The impact of air pollution on people and the environment is a severe issue that has recently been the subject of extensive research. This study has looked at the factors that contribute to the seasonal and spatial variability of pollutant concentration over Delhi NCR from 2019 to 2021. Additionally, the causes of changes in air quality during the COVID-19's lockdown period in 2020 have been discussed, along with comparisons to the pre-lockdown year (2019) and the post-lockdown year (2021). Seven pollutant parameters, viz., (PM_{2.5}, PM₁₀, NO_x, CO, SO₂, NH₃, and O₃) were retrieved from the air quality monitoring stations spread over Delhi NCR. The results show a significant temporal (seasonal) and spatial variability in the air pollutants' concentration. The highest pollutant level was observed in winter and the lowest in summer seasons. The results suggest that the concentration of atmospheric pollutants was already lower (20–30%) before the implementation of the lockdown. Meteorology played an important role in emission reduction during the lockdown, in particular, and seasonal, in general. The results also suggest that Bhiwadi is not the most polluted city, as claimed in the World Air Quality Report 2022. The most polluted sites in terms of pollutant concentration were observed over Delhi in all the years considered.

Keywords: PM_{2.5}; PM₁₀; NO_x; CO; Delhi; air pollution

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1. Introduction

Air pollution (ambient/outdoor and household/indoor) caused by natural as well as anthropogenic activities is one of the most serious environmental health risks faced by mankind today [1]. The World Health Organization (WHO) claims that air pollution is the fourth-leading cause of mortality worldwide and is responsible for more than 7 million premature deaths annually caused by pulmonary, cardiovascular, and cancer diseases. Approximately 3 million deaths every year are completely attributable to outdoor air pollution. One out of every nine fatalities worldwide occur as a result of the poisonous air that more than 99% of the world's population breathes [2]. Air pollution is a threat to health in all countries, but it affects people in low- and middle-income countries the hardest. Countries can lessen the burden of diseases, long-term illnesses, and short-term illnesses by reducing air pollution levels. Air pollution causes 9% of deaths worldwide, with rates ranging from 2% in high-income nations to around 15% in several South and East Asian nations. India is one of the top five most polluted countries in the world, with Delhi being the most polluted capital city [3]. The lifespan in Delhi NCR is shortened by more than 10 years because of the poor air quality.

Particulate matter (PM) is a complex mixture of microscopic solid or liquid particles of organic and inorganic substances suspended in the atmosphere [4]. PM₁₀ with an

aerodynamic diameter of 10 micrometres (μm) or less are considered “thoracic” airborne particles that can enter the lower respiratory tract. The most dangerous pollutants for human health are $\text{PM}_{2.5}$, which has an aerodynamic diameter of 2.5 micrometres (μm) or less. These are referred to as “respirable” airborne particles and can penetrate deeply into the gas-exchange zone of the lungs [5,6]. In addition, nitrogen oxides, sulfur dioxide, volatile organic compounds (VOCs), dioxins, and polycyclic aromatic hydrocarbons (PAHs) are also considered air pollutants that are hazardous to humans. Ozone protects against ultraviolet light in the stratosphere, but its presence at ground level, where it is produced via photochemical reactions in the presence of sunlight and precursor pollutants (such as nitrogen oxides and volatile organic compounds) in high concentrations, is very harmful [7,8].

The Delhi National Capital Region (Delhi NCR) has been facing serious challenges linked to worrying levels of air pollution and the consequent health hazards. Delhi NCR is one of the world’s most polluted areas due to rapid industrialization and urbanization, rising vehicle density, the substantial use of coal in thermal power plants, and the burning of waste and crops. Numerous efforts were made by several Government and Private Organizations in Delhi NCR to curb or mitigate the pollution levels. Air pollution in Delhi and the adjacent regions is a complex phenomenon that depends on various factors. First and foremost is the input of pollutants (industries, power plants, fossil fuel combustion from motor vehicles, construction sites, landfills and agriculture, the domestic combustion of coal and biomass, wind-blown dust from open lands, roads, and deserts), followed by meteorological conditions [9–12]. In addition, the burning of crop residues and the use of firecrackers prior to the start of the winter season also contribute significantly to the deterioration of air quality in Delhi NCR [13,14]. The sectoral contribution from the above-mentioned sources varies significantly from season to season. The level of particulate matter over Delhi and NCR never reaches (except only a couple of days in the monsoon season) within the revised permissible limit set by the World Health Organization in 2021 ($\text{PM}_{2.5}$: $15 \mu\text{g}/\text{m}^3$ –24-h mean, $5 \mu\text{g}/\text{m}^3$ annual mean; PM_{10} : $45 \mu\text{g}/\text{m}^3$ –24-h mean, $15 \mu\text{g}/\text{m}^3$ annual mean) [15]. The average annual particulate matter and gaseous pollutants concentration is several times higher than the revised WHO limits ($\text{PM}_{2.5}$ ~18 times higher than the permissible limit).

Coronavirus (COVID-19) is a pandemic disease which was first reported from the Wuhan city of China [16]. To control the spread of the COVID-19 outbreak, a lockdown approach was followed in many nations worldwide including India. After four successive phases of the lockdown: I phase, 21 days from 25 March to 14 April 2020; II phase, 19 days from 15 April to 3 May 2020; III phase, 14 days from 4 May to 17 May 2020; and IV phase, 14 days from 18 May to 31 May 2020. With a gradual easing of restrictions, the lockdown was lifted in several phases. These lockdowns provided an opportunity window to study the behaviour and dynamics of air pollution in an artificial pristine environment. The lockdown, which was caused due to COVID-19, enforces restrictions and self-quarantine measures, which reduce anthropogenic activities (emissions especially from transportation, industries, and construction activities) not only in India but also worldwide, and it improved the air quality significantly.

Numerous studies suggested a decline in anthropogenic air pollution in nations responding to the COVID-19 pandemic. Satellite-based estimates by NASA (National Aeronautics and Space Administration) and ESA (European Space Agency) indicate that pollution in some nations responding to the COVID-19 pandemic (like Wuhan, Spain, Italy, and the USA etc.) has reduced up to 30% [17,18]. A global study over seven geographical regions of the world covering 25 countries coordinated by the World Meteorological Organization Global Atmospheric Watch (WMO/GAW) program suggested a decline of up to about 70% in mean NO_2 and between 30% and 40% in mean $\text{PM}_{2.5}$ concentrations during the 2020 lockdown time compared to the same period in 2015–2019 [19]. Several other regional or global studies also claimed a variable reduction in air pollutants during the lockdown due to COVID-19 in different countries like China,

Canada, Bangladesh, Iran, Brazil, Italy, USA, Kazakhstan, Poland, Korea, Spain, Japan, Russia, Morocco, Thailand, and several others ([20–38], and several others).

Like other nations, studies over Indian regions have also reported a variable but significant effect of the restriction on air quality during the COVID-19 pandemic. Sharma et al. [39] stated that during the pre- and first lockdown period in 2020 (16 March to 14 April 2020), PM_{2.5}, PM₁₀, CO, and NO₂ decreased by roughly 43, 31, 10, and 18% at 22 distinct places in India. The temporal and diurnal changes in the air pollutants' concentration across 134 locations in India during the lockdown period of 2020 were studied and compared with the same period in 2017–2019 by Singh et al. [40]. They reported a variable but considerable reduction in PM_{2.5}, PM₁₀, NO₂, and CO and a mixed behavior (increase/decrease) in SO₂ and O₃ concentration. Carbon monoxide (CO) emissions in Kolkata decreased by 24% to 45% during the lockdown as a result of a reduction in industrial pollutants and transport services [41]. There was an observed 40–50% drop in NO₂ levels during this time in major cities (Mumbai and New Delhi) [42]. Likewise, numerous other studies in several parts of India have reported a variable but considerable reduction in particulate matter and gaseous pollutants due to COVID-19 restrictions [43–54].

On the contrary, few recent studies (globally/regionally) claim that air quality was not improved significantly due to COVID restrictions, as previously thought. According to new and revised satellite-derived PM_{2.5} data, there was little change in global particulate pollution. Despite the well-known, rapid slowdown in the global economy, the global population weighted average PM_{2.5} level only decreased from 27.7 to 27.5 µg/m³ between 2019 and 2020 [55]. Pei et al. [56] also claimed that the atmospheric quality in urban areas of China has not improved overall despite the lockdown's restrictions. Most of the studies discussed above directly compared the pollutant levels during the lockdown periods of 2020 with the previous year (2019). However, there is little information in the literature about meteorological conditions and their effects on the variance of pollutant concentrations during the lockdown periods [23,39,53,54,57]. When comparing the decline to before the lockdown in the same year, the seasonal decline in pollution levels may also be taken into consideration [40]. In addition, the variability and comparison of air pollutant concentration during the closure period (2020) and the year after closure (2021) are sparse in the literature [58]. The aim of the present paper is to study the impact of the lockdown on the concentration of pollutants (particulate matter and gaseous pollutants) in 2020 and to compare the year before (2019) and the year after the lockdown (2021) over Delhi and the adjacent region.

2. Methodology and Study Area

To investigate the cause of variation in air pollution, the daily (24-h) concentrations of seven-pollutants, namely PM_{2.5}, PM₁₀, NO_x, CO, SO₂, NH₃, and O₃, were downloaded from the Central Pollution Control Board's (CPCB) online portal over Delhi NCR (<https://app.cpcbcr.com/ccr/#/caaqm-dashboard/caaqm-landing/data>, accessed on 1 April 2022). The data was collected from 65 air quality monitoring stations located across the Delhi NCR region during the years 2019, 2020, and 2021. These stations are spread across four states and are classified as follows based on their respective states:

- Delhi (36): Anand Vihar, Bawana, ITO, Vivek Vihar, Lodhi road, RK Puram, Nehru Nagar, Chandni Chowk, Jahangirpuri, Mandir Marg, Dilshad Garden, North Campus-DU, DTU, Alipur, Ashok Vihar, Aya Nagar, Dr. Karni Singh, Dwarka Sector-8, NSIT-Dwarka, IGI Airport, Major Dhyan Chand stadium, CRRI-Mathura Road, Narela, Patparganj, Okhla Vihar-Phase II, Punjabi Bagh, Pusa Road, Rohini, Sonia Vihar, Wazirpur, Shadipur, Najafgarh, Jawahar Lal Nehru Stadium, Mundka, Siri fort, and Sri-Aurobindo Marg

- Haryana (14): IMT-Manesar, Sector-51 Gurugram, Sonipat, Panipat, New Industrial town, Sector-16-A, and Sector-11 Faridabad, Palwal, Teri-Gram, Vikas Sadan, Bahadurgarh, Dharuhera, Jind, and Rohtak.
- Rajasthan (1): Bhiwadi
- Uttar Pradesh (14): Noida Sector 1, 62 and 125, Sanjay Nagar, Vasundhara, Indirapuram, Hapur, Bulandshahar, Meerut (Ganga Nagar-phase 2), Knowledge Park-Greater Noida, Loni, Baghpat, and Park-5 Greater Noida.

The locations of all the above-mentioned sites are shown in Figure 1. Before processing, the data was thoroughly reviewed several times. There were locations where the data was either not accessible or continuous for a few to several days in different years from 2019 to 2021. Such data sets were excluded after rigorous observation and analyses. The average value before and after the missing day was used, processed, and compared with the closest CPCB station data available if one day's worth of data was missing. Monitoring stations that had more than 60% valid data during the analysis period were taken into consideration. Additionally, we performed an outlier analysis on each pollutant data set to remove any odd data. We noted that Delhi's data on air quality monitoring stations is superior in terms of the number of parameter observations and the consistency of the data sets. To guarantee the accuracy of the measured data, the CPCB maintains a Quality Assurance/Quality Control program that comprises instrument calibration and maintenance, training, standards for monitoring ambient air quality, and the evaluation of monitoring stations (<https://cpcb.nic.in/quality-assurance-quality-control/>, accessed on 05 April 2022). Monthly average values from individual monitoring stations were used for map preparation. Maps were created using the Kriging interpolation method in Arc GIS software.

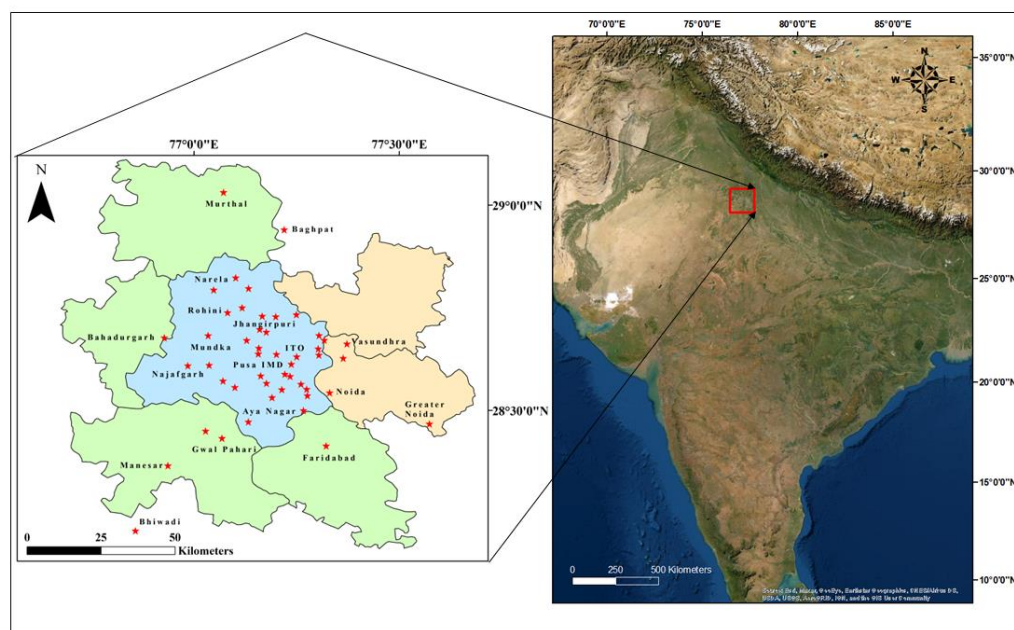


Figure 1. Map showing the location of the study area (Delhi NCR). Blue: Delhi, Green: studied regions of Haryana, and Pink: studied regions of Uttar Pradesh.

To study the effect of rainfall on air quality variability over Delhi NCR, satellite-retrieved daily average precipitation was used. The National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAEA) launched the Global Precipitation Measurement (GPM) satellite mission on 28 February 2014. The level 3 multi-satellite precipitation method of GPM is called IMERG (Integrated Multi-satellite Retrievals for GPM), and it combines monthly gauge precipitation data with

precipitation information acquired from the microwave sensor and infrared sensor onboard the GPM constellations [59,60]. In this study, we used GPM IMERG Final Precipitation 1 day $0.1^\circ \times 0.1^\circ$ V06 (GPM_3IMERGDF v06) as the daily satellite precipitation products.

The National Capital Region (NCR) is a region of dense population ($800/\text{km}^2$) that spans four states—National Capital Territory—Delhi, Haryana, Uttar Pradesh, and Rajasthan—with a total of twenty-three districts [61]. It is geographically located between the coordinates 27.60° N to 29.30° N and 76.20° E to 78.40° E. India's capital city, Delhi, has the highest registered motor vehicles in India. Delhi had roughly 6.93 million automobiles on the roads in 2011 and is projected to have 25.6 million by 2030 [62]. The study area experiences a semi-arid climate having four major seasons: Summer/pre-monsoon (March–June), Monsoon (July–Mid-September), Post-monsoon (Mid-September–November), and Winter (December–February). Temperature ranges between 4°C to 10°C in winter and 42°C to 48°C in summer [63]. In this location, December and January are the two coldest months of the year, and May and June are the two hottest. Despite slight spatial variability, Delhi and the adjacent regions receive the majority of rainfall (about 80 to 85%) during the southwest monsoon season [64]. Except during the monsoon season, the climate in the study area is characterized by low humidity, hot summer, and cold foggy winter [65]. Dust storms and thunderstorms are very common before or during the monsoon season. The studied sites also receive dust pollution via long-range transport processes from the Thar desert and from road dust. The influence of westerlies in the form of winter showers is also a common phenomenon in the studied regions.

3. Results and Discussion

3.1. Variability of Air Pollution

The time series of daily mean $\text{PM}_{2.5}$ and PM_{10} over Delhi and the adjacent regions during the years 2019, 2020, and 2021 are shown in Figures 2 and 3, respectively. Particulate matters showed great temporal variability with the highest concentration in the winter (highest in November, followed by January/December) and the relatively lower concentration in summer. The lowest annual particulate matter concentration was seen during monsoon seasons over all the studied regions (Figures 2a–d and 3a–d).

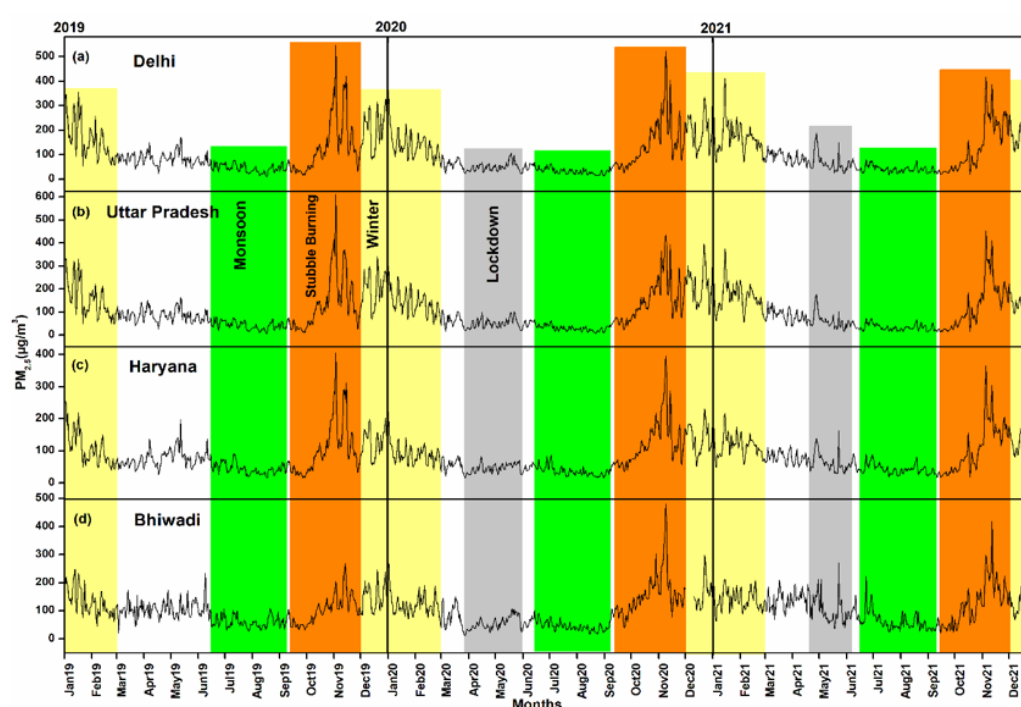


Figure 2. Graphs showing day to day variations of daily average PM_{2.5} mass concentration over (a) Delhi, (b) studied regions of Uttar Pradesh, (c) studied regions of Haryana, and (d) Bhiwadi from the year 2019 to 2021. The highlighted grey region represents lockdown periods (25 March to 31 May 2020 and 20 April to 7 June 2021), the green color represents monsoon seasons (July to September), the light yellow color represents winter seasons, and the orange color represents the stubble burning period over the study area.

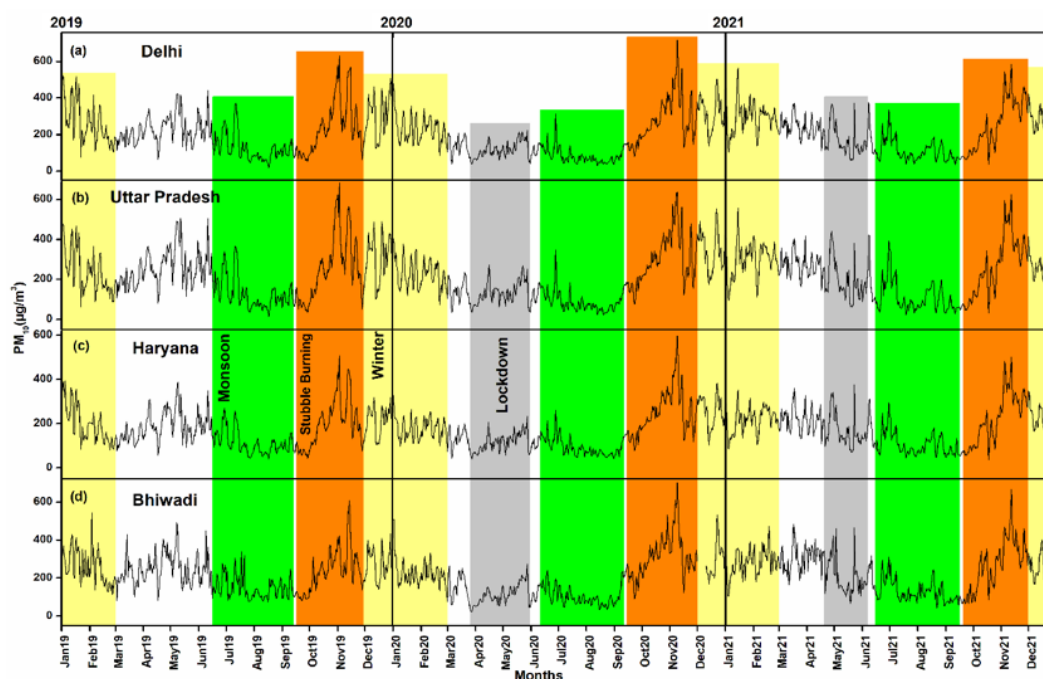


Figure 3. Graphs showing day to day variations of daily average PM₁₀ mass concentration over (a) Delhi, (b) studied regions of Uttar Pradesh, (c) studied regions of Haryana, and (d) Bhiwadi from the year 2019 to 2021. The highlighted grey region represents lockdown periods (25 March to 31 May 2020 and 20 April to 7 June 2021), the green color represents monsoon seasons (July to September), the light yellow color represents winter seasons, and the orange color represents the stubble burning period over the study area.

The annual average PM_{2.5} concentration was found to be $108.2 \pm 18.5 \mu\text{g}/\text{m}^3$ in 2019 (highest), $94.8 \pm 19.2 \mu\text{g}/\text{m}^3$ in 2020 (lowest), and $105.7 \pm 21.1 \mu\text{g}/\text{m}^3$ in 2021 over Delhi; $108.2 \pm 18.4 \mu\text{g}/\text{m}^3$ in 2019 (highest), $98.1 \pm 20.5 \mu\text{g}/\text{m}^3$ in 2020, and $97.4 \pm 19.7 \mu\text{g}/\text{m}^3$ in 2021 (lowest) over the studied regions of Uttar Pradesh; $84.1 \pm 11.2 \mu\text{g}/\text{m}^3$ in 2019, 77.3 ± 13.1 in 2020 (lowest), and $85.2 \pm 13.4 \mu\text{g}/\text{m}^3$ in 2021 (highest) over Haryana; and $101.9 \pm 10.0 \mu\text{g}/\text{m}^3$ in 2019, 97.7 ± 15.5 in 2020 (lowest), and $111.1 \pm 13.2 \mu\text{g}/\text{m}^3$ in 2021 (highest) at Bhiwadi (Table 1). In terms of PM₁₀, the annual average concentration was found to be $217.6 \pm 22.8 \mu\text{g}/\text{m}^3$ in 2019 (highest), $180.5 \pm 28.4 \mu\text{g}/\text{m}^3$ in 2020 (lowest), and $214.0 \pm 28.6 \mu\text{g}/\text{m}^3$ in 2021 over Delhi; $225.6 \pm 24.3 \mu\text{g}/\text{m}^3$ in 2019 (highest), $191.2 \pm 29.9 \mu\text{g}/\text{m}^3$ in 2020 (lowest), and $221.9 \pm 28.9 \mu\text{g}/\text{m}^3$ in 2021 over the studied regions of Uttar Pradesh; $167.5 \pm 16.5 \mu\text{g}/\text{m}^3$ in 2019, 162.9 ± 21.4 in 2020 (lowest), and $185.2 \pm 21.1 \mu\text{g}/\text{m}^3$ in 2021 (highest) over Haryana; and $224.3 \pm 17.5 \mu\text{g}/\text{m}^3$ in 2019, 191.9 ± 28.1 in 2020 (lowest), and $231.3 \pm 25.6 \mu\text{g}/\text{m}^3$ in 2021 (highest) at Bhiwadi. The monthly average PM_{2.5} and PM₁₀ values of the studied regions in all the years are compiled in Table 1.

Table 1. Compilation of monthly and annual average concentration of pollutants over Delhi, selected. The minimum and maximum in a year are marked with bold.

Location	PM _{2.5} (µg/m ³)			PM ₁₀ (µg/m ³)		
Delhi	2019	2020	2021	2019	2020	2021
January	203.6 ± 15.2	156.5 ± 12.4	196.3 ± 14.7	323.0 ± 21.5	239.9 ± 15.9	301.1 ± 20.6
February	122.3 ± 9.9	121.6 ± 6.8	152.2 ± 7.6	214.9 ± 14.2	223.1 ± 10.5	291.3 ± 11.8
March	84.6 ± 3.7	58.7 ± 3.9	95.5 ± 3.8	185.6 ± 7.1	126.7 ± 9.5	249.2 ± 10.0
April	82.3 ± 4.7	47.2 ± 2.2	85.9 ± 6.6	232.4 ± 11.2	106.5 ± 5.7	227.3 ± 13.3
May	89.7 ± 5.9	56.0 ± 4.0	54.4 ± 4.2	250.8 ± 16.2	138.5 ± 8.7	142.7 ± 12.0
June	63.5 ± 3.5	47.2 ± 2.1	52.5 ± 3.1	209.8 ± 13.2	122.2 ± 8.8	157.3 ± 14.5
July	47.0 ± 3.1	34.6 ± 2.1	39.4 ± 1.8	141.7 ± 15.8	77.6 ± 5.1	108.5 ± 10.7
August	34.9 ± 2.4	24.8 ± 1.5	40.3 ± 2.0	83.6 ± 5.6	56.2 ± 2.4	112.9 ± 7.0
September	40.4 ± 3.1	47.7 ± 2.7	32.3 ± 1.5	99.4 ± 5.5	122.6 ± 7.0	75.6 ± 3.4
October	123.3 ± 13.9	134.5 ± 9.7	75.1 ± 5.6	242.5 ± 19.0	283.2 ± 12.5	185.6 ± 12.0
November	204.0 ± 23.2	215.1 ± 20.7	240.6 ± 12.0	318.5 ± 27.8	352.1 ± 26.0	393.3 ± 13.7
December	202.8 ± 13.6	194.0 ± 11.8	203.5 ± 13.3	308.8 ± 19.5	316.8 ± 16.0	323.7 ± 18.3
Annual Average	108.2 ± 18.5	94.8 ± 19.2	105.7 ± 21.1	217.6 ± 22.8	180.5 ± 28.4	214 ± 28.6
Lockdown (I)	88.38	40.95	78.70	230.66	85.23	221.90
Lockdown (II)	77.44	46.80	90.04	230.46	113.84	231.63
Lockdown (III)	110.01	55.20	57.06	301.58	123.90	144.47
Lockdown (IV)	69.94	58.59	46.45	191.60	159.23	121.62

Location	NO _x (µg/m ³)			CO (g/m ³)		
Delhi	2019	2020	2021	2019	2020	2021
January	83.9 ± 7.0	67.1 ± 5.5	66.8 ± 5.4	1.9 ± 0.1	1.6 ± 0.1	1.8 ± 0.1
February	57.1 ± 4.9	61.5 ± 4.2	83.8 ± 5.0	1.4 ± 0.1	1.3 ± 0.0	1.8 ± 0.1
March	50.8 ± 2.8	38.0 ± 3.1	56.1 ± 3.7	1.2 ± 0.0	0.9 ± 0.0	1.2 ± 0.0
April	50.3 ± 3.0	22.3 ± 0.6	47.0 ± 3.0	1.3 ± 0.0	0.8 ± 0.0	1.2 ± 0.0
May	53.1 ± 3.5	24.1 ± 1.3	29.4 ± 1.5	1.4 ± 0.0	0.9 ± 0.0	1.0 ± 0.0
June	37.7 ± 2.7	20.6 ± 0.8	26.6 ± 1.0	1.2 ± 0.0	0.9 ± 0.0	1 ± 0.0
July	29.3 ± 1.2	20.6 ± 0.6	25.4 ± 0.8	1.1 ± 0.0	0.9 ± 0.0	1 ± 0.0
August	33.6 ± 1.3	23.7 ± 0.9	29.5 ± 0.9	1.1 ± 0.0	0.9 ± 0.0	1 ± 0.0
September	27.6 ± 0.7	31.7 ± 1.4	28.6 ± 1.1	1.0 ± 0.0	0.9 ± 0.0	1.1 ± 0.0
October	59.0 ± 4.2	79.5 ± 5.5	54.7 ± 3.1	1.5 ± 0.1	1.6 ± 0.1	1.3 ± 0.0
November	67.6 ± 4.6	95.5 ± 7.0	97.8 ± 4.9	1.7 ± 0.1	2.1 ± 0.1	2.3 ± 0.1
December	72.5 ± 5.5	82.0 ± 6.8	99.0 ± 7.0	1.8 ± 0.1	1.9 ± 0.1	2.1 ± 0.1
Annual Average	51.9 ± 5.1	47.2 ± 8.1	53.7 ± 8.2	1.4 ± 0.1	1.2 ± 0.1	1.4 ± 0.1
Lockdown (I)	54.07	18.90	53.19	1.33	0.68	1.15
Lockdown (II)	47.42	21.06	34.46	1.37	0.88	1.13
Lockdown (III)	56.23	20.79	30.10	1.46	0.87	1.06
Lockdown (IV)	51.72	25.02	29.84	1.31	1.03	0.92

Location	NH ₃ (µg/m ³)			SO ₂ (µg/m ³)		
Delhi	2019	2020	2021	2019	2020	2021
January	49.6 ± 1.7	43.3 ± 1.2	55.5 ± 1.7	17.2 ± 0.5	10.9 ± 0.5	12.9 ± 0.4
February	39.5 ± 1.4	38.3 ± 0.6	61.5 ± 1.5	16.5 ± 0.5	14.5 ± 0.6	15.8 ± 0.5
March	33.6 ± 0.7	31.7 ± 0.7	50.2 ± 1.1	18.8 ± 0.4	13.9 ± 0.4	18.7 ± 0.5
April	33.8 ± 1.0	29.1 ± 0.6	40.3 ± 1.1	22.3 ± 0.7	14.1 ± 0.4	20.2 ± 0.8
May	33.0 ± 0.9	29.5 ± 0.5	42.4 ± 0.9	20.7 ± 0.8	15.2 ± 0.7	11.2 ± 0.4
June	30.6 ± 0.9	32.2 ± 0.5	41.5 ± 0.7	15.1 ± 0.5	12.2 ± 0.3	9.7 ± 0.2
July	32.3 ± 0.9	29.1 ± 0.6	39.7 ± 0.9	10.4 ± 0.2	9.4 ± 0.2	8.2 ± 0.3
August	32.8 ± 0.8	25.2 ± 0.6	37.5 ± 1.0	9.3 ± 0.2	9.6 ± 0.2	7.7 ± 0.1
September	31.1 ± 0.9	27.8 ± 0.6	27.8 ± 0.5	10.2 ± 0.1	10.8 ± 0.2	8.3 ± 0.1
October	35.1 ± 1.5	38.5 ± 0.8	36.9 ± 0.9	12.8 ± 0.4	16.2 ± 0.4	9.2 ± 0.2
November	38.9 ± 1.3	41.8 ± 1.4	48.4 ± 1.0	13.7 ± 0.4	16.6 ± 0.5	12.2 ± 0.3
December	53.2 ± 1.7	51.5 ± 1.5	50.6 ± 2.1	10.5 ± 0.4	14.5 ± 0.5	11.1 ± 0.3
Annual Average	37.0 ± 2.1	34.8 ± 2.3	44.4 ± 2.7	14.8 ± 1.2	13.2 ± 0.7	12.1 ± 1.2

Lockdown (I)	36.38	23.23	44.01	21.80	13.64	19.53
Lockdown (II)	32.13	31.19	37.92	21.77	13.39	18.85
Lockdown (III)	33.45	29.11	44.19	21.40	14.54	12.47
Lockdown (IV)	32.41	28.82	42.91	19.22	16.52	9.23
Location	Ozone (O ₃) (µg/m ³)					
Delhi	2019	2020	2021			
January	25.3 ± 0.6	20.2 ± 0.7	23.7 ± 0.9			
February	27.7 ± 0.9	32.0 ± 1.1	27.9 ± 0.6			
March	35.9 ± 1.2	36.0 ± 1.0	32.7 ± 1.2			
April	46.5 ± 0.9	48.7 ± 1.3	42.6 ± 1.0			
May	49.2 ± 1.6	55.8 ± 1.6	43.0 ± 1.7			
June	50.3 ± 1.8	39.9 ± 1.8	35.8 ± 1.3			
July	28.6 ± 1.7	30.4 ± 1.5	25.5 ± 1.2			
August	23.8 ± 0.8	21.9 ± 0.7	22.5 ± 0.6			
September	26.8 ± 1.0	30.5 ± 0.9	22.9 ± 0.6			
October	35.3 ± 1.3	37.0 ± 0.5	29.6 ± 1.0			
November	26.0 ± 0.9	30.1 ± 1.0	31.3 ± 0.9			
December	20.7 ± 0.9	31.3 ± 1.0	24.2 ± 0.9			
Annual Average	33.0 ± 3.0	34.5 ± 2.9	30.1 ± 2.1			
Lockdown (I)	43.86	40.61	40.81			
Lockdown (II)	49.15	51.06	44.06			
Lockdown (III)	47.75	61.22	47.95			
Lockdown (IV)	48.62	52.30	38.21			
Location	PM _{2.5} (µg/m ³)			PM ₁₀ (µg/m ³)		
Uttar Pradesh	2019	2020	2021	2019	2020	2021
January	194.7 ± 15.4	159.4 ± 11.2	182.5 ± 13.2	291.8 ± 21.3	238.0 ± 15.2	292.2 ± 19.3
February	118.6 ± 9.9	122.5 ± 7.2	153.1 ± 8.8	192.9 ± 13.9	223.3 ± 11.1	309.1 ± 13.5
March	86.7 ± 4.5	59.2 ± 4.9	91.2 ± 4.8	193.8 ± 9.0	129.7 ± 10.5	278.8 ± 11.4
April	87.4 ± 5.1	50.1 ± 3.5	78.6 ± 6.5	268.0 ± 13.2	128.9 ± 8.8	264.3 ± 14.9
May	90.9 ± 5.7	53.5 ± 4.1	52.0 ± 3.7	292.8 ± 20.2	148.5 ± 11.2	170.5 ± 13.7
June	64.8 ± 3.9	47.0 ± 2.2	43.8 ± 3.0	241.3 ± 16.0	135.4 ± 10.1	165.5 ± 18.5
July	43.7 ± 3.2	31.9 ± 2.1	31.3 ± 1.9	135.9 ± 17.2	79.2 ± 6.2	112.5 ± 15.3
August	33.0 ± 2.7	22.1 ± 1.5	33.8 ± 2.2	86.2 ± 6.4	54.2 ± 3.2	111.0 ± 9.3
September	36.5 ± 3.3	50.6 ± 3.2	25.1 ± 1.7	93.4 ± 7.3	140.7 ± 8.9	65.0 ± 3.8
October	134.1 ± 16.4	144.3 ± 9.0	87.8 ± 7.5	262.3 ± 24.0	308.1 ± 12.4	205.5 ± 13.8
November	207.0 ± 23.9	219.4 ± 19.5	230.8 ± 15.2	337.0 ± 29.1	365.1 ± 26.7	401.6 ± 17.3
December	200.5 ± 12.9	217.0 ± 13.2	159.1 ± 9.7	311.6 ± 19.7	343.5 ± 17.9	287.0 ± 15.0
Annual Average	108.2 ± 18.4	98.1 ± 20.5	97.4 ± 19.7	225.6 ± 24.3	191.2 ± 29.9	221.9 ± 28.9
Lockdown (I)	97.03	40.42	76.59	258.12	96.03	261.31
Lockdown (II)	77.73	51.56	84.21	270.30	139.34	269.91
Lockdown (III)	110.68	52.23	58.36	357.70	126.57	171.02
Lockdown (IV)	72.76	59.02	40.97	226.75	179.12	142.58
Location	NO _x (µg/m ³)			CO (g/m ³)		
Uttar Pradesh	2019	2020	2021	2019	2020	2021
January	75.4 ± 5.3	48.2 ± 3.9	48.2 ± 2.8	1.4 ± 0.1	1.5 ± 0.1	1.7 ± 0.1
February	46.6 ± 4.3	43.1 ± 3.1	47.0 ± 2.6	1.0 ± 0.1	1.4 ± 0.1	1.8 ± 0.1
March	41.0 ± 2.4	26.4 ± 2.6	36.4 ± 1.8	0.9 ± 0.0	1.4 ± 0.1	1.1 ± 0.1
April	39.2 ± 2.4	13.4 ± 0.6	31.4 ± 2.5	1.1 ± 0.1	1.3 ± 0.0	1.1 ± 0.1
May	45.3 ± 3.0	17.0 ± 1.0	25.6 ± 1.3	1.2 ± 0.0	1.4 ± 0.0	1.0 ± 0.0
June	31.8 ± 1.9	15.8 ± 0.7	19.8 ± 0.8	1.2 ± 0.1	1.1 ± 0.0	1.3 ± 0.0
July	28.5 ± 1.4	14.4 ± 0.5	17.2 ± 0.6	1.0 ± 0.0	1.1 ± 0.0	1.0 ± 0.0
August	26.1 ± 1.3	16.0 ± 0.7	16.1 ± 0.5	1.0 ± 0.0	1.0 ± 0.0	0.9 ± 0.0
September	20.7 ± 0.5	22.7 ± 0.9	19.1 ± 0.6	1.0 ± 0.0	1.0 ± 0.0	0.9 ± 0.0
October	53.8 ± 5.1	51.9 ± 3.7	33.1 ± 2.1	1.6 ± 0.1	1.6 ± 0.1	1.3 ± 0.1
November	58.9 ± 4.4	70.9 ± 4.4	68.9 ± 3.8	1.7 ± 0.1	2.2 ± 0.1	2.3 ± 0.1
December	50.4 ± 4.3	63.6 ± 4.2	60.7 ± 4.1	1.6 ± 0.1	1.9 ± 0.1	2.0 ± 0.1
Annual Average	43.1 ± 4.5	33.6 ± 6.1	35.3 ± 5.2	1.20 ± 0.1	1.40 ± 0.1	1.39 ± 0.1

Lockdown (I)	39.66	11.76	31.51	1.13	1.27	1.08
Lockdown (II)	38.11	14.64	30.57	1.02	1.34	1.12
Lockdown (III)	47.60	14.92	25.37	1.36	1.23	0.90
Lockdown (IV)	46.38	19.58	19.57	1.19	1.33	1.16

Location		Ozone ($\mu\text{g}/\text{m}^3$)		
Uttar Pradesh	2019	2020	2021	
January	35.2 $\pm$ 0.1	24.8 $\pm$ 1.3	26.1 $\pm$ 1.3	
February	36.9 $\pm$ 1.7	40.7 $\pm$ 1.2	31.6 $\pm$ 0.9	
March	51.1 $\pm$ 1.7	42.4 $\pm$ 1.4	50.8 $\pm$ 1.5	
April	64.7 $\pm$ 1.6	58.0 $\pm$ 1.3	58.7 $\pm$ 1.4	
May	68.9 $\pm$ 2.2	67.6 $\pm$ 2.1	55.2 $\pm$ 2.5	
June	65.8 $\pm$ 2.2	54.1 $\pm$ 2.6	50.0 $\pm$ 2.5	
July	39.1 $\pm$ 2.4	43.6 $\pm$ 2.1	39.7 $\pm$ 2.7	
August	29.9 $\pm$ 1.4	24.9 $\pm$ 0.9	34.0 $\pm$ 1.6	
September	33.1 $\pm$ 2.0	41.8 $\pm$ 1.6	27.1 $\pm$ 1.0	
October	51.9 $\pm$ 1.8	44.8 $\pm$ 1.5	47.9 $\pm$ 1.9	
November	38.9 $\pm$ 2.0	37.5 $\pm$ 1.2	46.3 $\pm$ 1.2	
December	31.9 $\pm$ 2.7	36.0 $\pm$ 1.9	30.6 $\pm$ 1.2	
Annual Average	45.6 $\pm$ 4.1	43.0 $\pm$ 3.6	41.5 $\pm$ 3.2	
Lockdown (I)	59.86	53.20	56.39	
Lockdown (II)	69.19	55.24	59.55	
Lockdown (III)	66.12	69.06	61.78	
Lockdown (IV)	68.89	68.71	48.79	

Location		PM _{2.5} ($\mu\text{g}/\text{m}^3$)			PM ₁₀ ($\mu\text{g}/\text{m}^3$)		
Haryana	2019	2020	2021	2019	2020	2021	
January	130.9 $\pm$ 10.4	96.8 $\pm$ 7.2	128.2 $\pm$ 7.8	218.8 $\pm$ 16.5	177.4 $\pm$ 10.4	212.8 $\pm$ 12.2	
February	81.6 $\pm$ 5.7	85.1 $\pm$ 4.0	109.4 $\pm$ 5.0	145.4 $\pm$ 9.6	184.0 $\pm$ 7.5	241.1 $\pm$ 9.1	
March	61.4 $\pm$ 2.5	52.4 $\pm$ 3.7	83.6 $\pm$ 3.3	130.1 $\pm$ 6.4	124.0 $\pm$ 8.8	218.1 $\pm$ 10.1	
April	77.4 $\pm$ 4.5	43.5 $\pm$ 2.6	76.1 $\pm$ 4.8	196.5 $\pm$ 12.0	105.1 $\pm$ 6.4	209.9 $\pm$ 12.5	
May	88.0 $\pm$ 6.0	51.6 $\pm$ 2.3	56.9 $\pm$ 4.6	198.3 $\pm$ 14.0	135.2 $\pm$ 7.7	148.7 $\pm$ 11.3	
June	69.2 $\pm$ 3.9	48.9 $\pm$ 2.1	55.1 $\pm$ 3.4	181.2 $\pm$ 10.1	131.3 $\pm$ 7.3	155.8 $\pm$ 12.1	
July	46.4 $\pm$ 3.5	38.7 $\pm$ 2.8	41.5 $\pm$ 2.5	110.8 $\pm$ 10.9	94.9 $\pm$ 6.3	103.6 $\pm$ 9.1	
August	34.5 $\pm$ 1.6	27.7 $\pm$ 1.4	43.1 $\pm$ 2.1	87.3 $\pm$ 4.6	63.7 $\pm$ 2.3	108.6 $\pm$ 6.7	
September	39.0 $\pm$ 2.9	51.6 $\pm$ 2.6	30.2 $\pm$ 1.4	83.0 $\pm$ 5.3	121.7 $\pm$ 7.3	71.3 $\pm$ 3.6	
October	97.2 $\pm$ 9.2	121.0 $\pm$ 7.2	73.7 $\pm$ 5.5	199.1 $\pm$ 13.5	261.3 $\pm$ 10.2	166.5 $\pm$ 10.8	
November	156.2 $\pm$ 17.2	170.7 $\pm$ 16.0	185.0 $\pm$ 10.3	248.9 $\pm$ 21.5	297.5 $\pm$ 22.7	333.4 $\pm$ 12.4	
December	126.8 $\pm$ 7.6	139.3 $\pm$ 7.9	139.5 $\pm$ 8.4	210.6 $\pm$ 11.4	258.4 $\pm$ 12.6	252.8 $\pm$ 12.6	
Annual Average	84.1 $\pm$ 11.2	77.3 $\pm$ 13.1	85.2 $\pm$ 13.4	167.5 $\pm$ 16.5	162.9 $\pm$ 21.4	185.2 $\pm$ 21.1	
Lockdown (I)	74.39	35.45	74.34	187.08	79.60	204.82	
Lockdown (II)	78.69	46.66	82.24	208.56	119.52	221.45	
Lockdown (III)	110.77	50.29	60.30	248.26	126.75	148.70	
Lockdown (IV)	65.25	53.16	48.24	159.48	149.59	131.70	

Location		NO _x ($\mu\text{g}/\text{m}^3$)			CO (g/m^3)		
Haryana	2019	2020	2021	2019	2020	2021	
January	49.2 $\pm$ 0.1	39.4 $\pm$ 2.7	38.4 $\pm$ 1.9	1.1 $\pm$ 0.1	1.6 $\pm$ 0.1	1.8 $\pm$ 0.1	
February	42.8 $\pm$ 0.0	42.9 $\pm$ 1.8	35.1 $\pm$ 1.6	1.2 $\pm$ 0.0	1.2 $\pm$ 0.1	1.4 $\pm$ 0.0	
March	32.5 $\pm$ 0.0	30.4 $\pm$ 2.0	26.2 $\pm$ 1.1	1.1 $\pm$ 0.0	0.9 $\pm$ 0.0	0.8 $\pm$ 0.0	
April	33.1 $\pm$ 0.0	14.6 $\pm$ 0.3	23.8 $\pm$ 0.8	0.8 $\pm$ 0.0	0.7 $\pm$ 0.0	0.8 $\pm$ 0.0	
May	31.1 $\pm$ 0.0	25.3 $\pm$ 1.3	18.3 $\pm$ 0.5	0.9 $\pm$ 0.0	0.8 $\pm$ 0.0	0.6 $\pm$ 0.0	
June	18.6 $\pm$ 0.0	21.8 $\pm$ 0.6	18.9 $\pm$ 0.2	0.9 $\pm$ 0.0	0.8 $\pm$ 0.0	0.6 $\pm$ 0.0	
July	16.2 $\pm$ 0.0	16.8 $\pm$ 0.4	18.6 $\pm$ 0.3	0.7 $\pm$ 0.0	0.6 $\pm$ 0.0	0.6 $\pm$ 0.0	
August	15.6 $\pm$ 0.0	20.1 $\pm$ 0.6	21.7 $\pm$ 0.4	0.9 $\pm$ 0.0	0.6 $\pm$ 0.0	0.7 $\pm$ 0.0	
September	15.0 $\pm$ 0.0	21.9 $\pm$ 0.6	21.6 $\pm$ 0.4	0.9 $\pm$ 0.1	0.9 $\pm$ 0.0	0.7 $\pm$ 0.0	
October	38.5 $\pm$ 0.0	33.9 $\pm$ 1.9	28.7 $\pm$ 0.8	1.1 $\pm$ 0.1	1.3 $\pm$ 0.0	0.9 $\pm$ 0.0	
November	50.9 $\pm$ 0.1	50.5 $\pm$ 3.1	34.7 $\pm$ 1.3	1.4 $\pm$ 0.1	1.6 $\pm$ 0.1	1.7 $\pm$ 0.1	
December	67.8 $\pm$ 0.1	40.4 $\pm$ 1.9	35.8 $\pm$ 1.7	1.4 $\pm$ 0.1	1.7 $\pm$ 0.1	1.6 $\pm$ 0.1	
Annual Average	34.3 $\pm$ 0.12	29.8 $\pm$ 3.4	26.8 $\pm$ 2.1	1.0 $\pm$ 0.1	1.1 $\pm$ 0.1	1.0 $\pm$ 0.1	

Lockdown (I)	32.38	14.79	24.02	0.93	0.65	0.82
Lockdown (II)	32.93	16.11	22.39	0.78	0.72	0.82
Lockdown (III)	31.65	24.04	17.32	0.95	0.78	0.67
Lockdown (IV)	29.49	23.42	19.39	0.84	0.78	0.62

Location		Ozone ($\mu\text{g}/\text{m}^3$)		
Haryana	2019	2020	2021	
January	24.0 $\pm$ 1.0	35.4 $\pm$ 0.9	22.9 $\pm$ 1.2	
February	27.5 $\pm$ 1.0	47.6 $\pm$ 1.3	28.5 $\pm$ 0.7	
March	34.6 $\pm$ 1.1	45.2 $\pm$ 1.1	39.0 $\pm$ 1.2	
April	39.0 $\pm$ 0.9	51.0 $\pm$ 1.2	47.8 $\pm$ 1.3	
May	44.2 $\pm$ 1.2	62.8 $\pm$ 1.7	53.7 $\pm$ 2.0	
June	51.4 $\pm$ 1.8	51.1 $\pm$ 2.1	48.7 $\pm$ 1.6	
July	36.0 $\pm$ 1.8	41.2 $\pm$ 1.6	35.5 $\pm$ 1.5	
August	32.0 $\pm$ 1.0	29.5 $\pm$ 0.6	27.7 $\pm$ 1.3	
September	30.9 $\pm$ 1.3	35.5 $\pm$ 0.7	29.0 $\pm$ 0.7	
October	43.4 $\pm$ 1.2	44.8 $\pm$ 0.7	39.6 $\pm$ 1.4	
November	31.2 $\pm$ 0.9	36.3 $\pm$ 1.0	37.0 $\pm$ 1.3	
December	24.2 $\pm$ 1.3	31.7 $\pm$ 1.0	27.8 $\pm$ 1.2	
Annual Average	34.9 $\pm$ 2.5	42.7 $\pm$ 3.0	36.4 $\pm$ 2.8	
Lockdown (I)	37.20	46.98	46.30	
Lockdown (II)	41.33	57.09	49.55	
Lockdown (III)	40.89	72.14	57.83	
Lockdown (IV)	49.93	58.52	50.69	

Location		PM _{2.5} ($\mu\text{g}/\text{m}^3$)			PM ₁₀ ($\mu\text{g}/\text{m}^3$)		
Bhiwadi	2019	2020	2021	2019	2020	2021	
January	154.2 $\pm$ 9.1	121.6 $\pm$ 8.4	147 $\pm$ 7.8	288.6 $\pm$ 14.1	234.7 $\pm$ 15.7	266.3 $\pm$ 13.1	
February	108.4 $\pm$ 6.0	124.6 $\pm$ 6.1	135.5 $\pm$ 6.4	232.3 $\pm$ 18.5	222.4 $\pm$ 8.8	301.4 $\pm$ 12.9	
March	102.2 $\pm$ 5.7	73.4 $\pm$ 7.6	130.6 $\pm$ 6.3	219.8 $\pm$ 12.6	136.1 $\pm$ 13.5	292.4 $\pm$ 13.6	
April	105.2 $\pm$ 4.5	45.3 $\pm$ 2.5	147.5 $\pm$ 6.1	266.8 $\pm$ 14.4	93.8 $\pm$ 5.4	311.9 $\pm$ 12.4	
May	108.0 $\pm$ 5.3	69.1 $\pm$ 4.2	90.2 $\pm$ 8.7	256.9 $\pm$ 16.3	148.3 $\pm$ 9.7	179.7 $\pm$ 15.8	
June	87.3 $\pm$ 7.2	60.8 $\pm$ 3.0	94.6 $\pm$ 6.8	207.4 $\pm$ 14.4	130.4 $\pm$ 8.7	186.2 $\pm$ 12.0	
July	57.5 $\pm$ 3.6	46.6 $\pm$ 2.5	54.1 $\pm$ 3.4	155.4 $\pm$ 13.2	97.2 $\pm$ 6.0	127.9 $\pm$ 9.0	
August	59.4 $\pm$ 3.6	34.3 $\pm$ 2.0	57.7 $\pm$ 4.2	130.8 $\pm$ 6.7	72.0 $\pm$ 4.1	134.4 $\pm$ 8.8	
September	54.2 $\pm$ 3.3	77.7 $\pm$ 5.6	41.7 $\pm$ 2.7	118.7 $\pm$ 6.9	176.7 $\pm$ 12.4	86.7 $\pm$ 4.2	
October	92.6 $\pm$ 5.1	160.9 $\pm$ 8.0	102.7 $\pm$ 7.8	243 $\pm$ 12.0	336.1 $\pm$ 13.0	227.5 $\pm$ 15.2	
November	146.4 $\pm$ 8.5	196.1 $\pm$ 17.0	195.3 $\pm$ 12.1	299.3 $\pm$ 22.0	359.6 $\pm$ 24.0	377.6 $\pm$ 17.6	
December	147.5 $\pm$ 8.4	161.4 $\pm$ 9.1	136.5 $\pm$ 8.4	272.5 $\pm$ 14.6	295.4 $\pm$ 16.7	283.7 $\pm$ 14.3	
Annual Average	101.9 $\pm$ 10.0	97.7 $\pm$ 15.4	111.1 $\pm$ 13.2	224.3 $\pm$ 17.5	191.9 $\pm$ 28.1	231.3 $\pm$ 25.6	
Lockdown (I)	105.54	37.80	147.35	245.03	73.75	320.57	
Lockdown (II)	108.97	47.29	141.22	283.69	101.77	295.49	
Lockdown (III)	93.86	60.73	78.16	283.89	120.69	152.48	
Lockdown (IV)	118.23	80.30	91.95	224.03	173.96	181.43	

Location		NO _x ($\mu\text{g}/\text{m}^3$)			CO (g/m^3)		
Bhiwadi	2019	2020	2021	2019	2020	2021	
January	73.8 $\pm$ 5.5	87.6 $\pm$ 6.6	95.9 $\pm$ 6.6	0.8 $\pm$ 0.0	1.1 $\pm$ 0.1	1.3 $\pm$ 0.1	
February	66.3 $\pm$ 5.4	73.1 $\pm$ 4.9	89.1 $\pm$ 4.9	0.8 $\pm$ 0.0	0.9 $\pm$ 0.0	1.3 $\pm$ 0.1	
March	88 $\pm$ 7.1	72.9 $\pm$ 4.4	73.4 $\pm$ 4.4	0.8 $\pm$ 0.1	0.6 $\pm$ 0.0	0.8 $\pm$ 0.0	
April	72.3 $\pm$ 4.9	22.8 $\pm$ 4.1	83.4 $\pm$ 4.1	0.8 $\pm$ 0.0	0.5 $\pm$ 0.0	0.6 $\pm$ 0.0	
May	56.4 $\pm$ 3.4	50.1 $\pm$ 2.2	36.1 $\pm$ 2.2	0.7 $\pm$ 0.0	0.8 $\pm$ 0.0	0.7 $\pm$ 0.0	
June	37.1 $\pm$ 3.2	61.5 $\pm$ 2.2	44 $\pm$ 2.6	0.6 $\pm$ 0.0	1.1 $\pm$ 0.0	0.8 $\pm$ 0.0	
July	39.8 $\pm$ 3.9	50.4 $\pm$ 3.0	49.8 $\pm$ 3.0	0.6 $\pm$ 0.0	0.9 $\pm$ 0.0	0.8 $\pm$ 0.0	
August	30.8 $\pm$ 1.6	43.9 $\pm$ 1.4	37.6 $\pm$ 1.4	0.7 $\pm$ 0.0	0.7 $\pm$ 0.0	0.6 $\pm$ 0.0	
September	33.5 $\pm$ 1.6	80.4 $\pm$ 0.7	37.1 $\pm$ 0.7	0.5 $\pm$ 0.0	1 $\pm$ 0.0	0.8 $\pm$ 0.0	
October	100.1 $\pm$ 7.6	109 $\pm$ 6.4	67.6 $\pm$ 6.4	1.0 $\pm$ 0.1	1.3 $\pm$ 0.0	1.0 $\pm$ 0.0	
November	102.5 $\pm$ 8.0	97.9 $\pm$ 7.8	152.2 $\pm$ 7.8	1.3 $\pm$ 0.1	1.5 $\pm$ 0.1	1.4 $\pm$ 0.1	
December	80.0 $\pm$ 5.0	63.2 $\pm$ 10.6	144.1 $\pm$ 10.6	1.3 $\pm$ 0.1	1.2 $\pm$ 0.1	1.3 $\pm$ 0.0	
Annual Average	65.1 $\pm$ 7.4	67.7 $\pm$ 11.5	75.9 $\pm$ 11.5	0.8 $\pm$ 0.1	0.96 $\pm$ 0.1	0.95 $\pm$ 0.1	

Lockdown (I)	95.43	26.20	83.76	0.76	0.47	0.72
Lockdown (II)	63.53	22.06	69.72	0.85	0.50	0.60
Lockdown (III)	63.67	39.80	31.13	0.75	0.81	0.67
Lockdown (IV)	50.00	64.44	38.97	0.63	0.79	0.74
Location	NH ₃ (µg/m ³)			SO ₂ (µg/m ³)		
Bhiwadi	2019	2020	2021	2019	2020	2021
January	16.7 ± 0.6	43.2 ± 1.8	38.9 ± 1.8	41.5 ± 2.5	43.0 ± 3.0	35.4 ± 2.3
February	19.1 ± 1.1	40.5 ± 1.5	33.9 ± 1.4	42.2 ± 2.8	45.4 ± 2.3	51.9 ± 3.0
March	33.8 ± 3.7	37.9 ± 2.9	33.2 ± 1.1	54.9 ± 2.9	35.6 ± 2.2	62.6 ± 3.5
April	21.2 ± 0.8	14.0 ± 0.6	33.1 ± 0.9	51.1 ± 3.3	8.4 ± 0.6	67.3 ± 3.3
May	13.5 ± 0.4	29.9 ± 1.7	22.5 ± 0.6	46.2 ± 2.7	18.2 ± 1.4	28.0 ± 1.8
June	23.3 ± 1.0	30.3 ± 2.1	24.5 ± 0.7	25.9 ± 2.8	15.8 ± 1.1	24.3 ± 2.3
July	12.4 ± 0.3	37.6 ± 1.5	25.6 ± 1.5	11.9 ± 0.4	13.1 ± 0.8	13.4 ± 1.3
August	16.3 ± 1.2	32.1 ± 1.3	23.6 ± 0.5	9.4 ± 0.4	13.1 ± 1.0	10.9 ± 0.5
September	28.4 ± 1.0	44.7 ± 3.0	25.2 ± 0.3	6.9 ± 0.4	28.1 ± 1.5	7.1 ± 0.4
October	47.1 ± 2.6	73.8 ± 1.8	36.6 ± 2.5	33.6 ± 2.7	55.9 ± 3.1	21.7 ± 3.0
November	56.3 ± 3.5	53.2 ± 3.7	76.7 ± 4.1	28.8 ± 2.0	53.5 ± 3	24.6 ± 1.5
December	43.5 ± 1.7	39.4 ± 1.6	73.1 ± 6.5	28.8 ± 2.1	42.6 ± 2.8	21.2 ± 1.4
Annual Average	27.6 ± 4.2	39.7 ± 4.1	37.2 ± 5.3	31.8 ± 4.6	31.1 ± 4.5	30.7 ± 5.2
Lockdown (I)	23.80	16.80	32.26	55.55	14.33	73.81
Lockdown (II)	19.47	14.97	31.76	47.49	7.31	54.82
Lockdown (III)	12.85	23.70	21.98	43.97	15.39	29.01
Lockdown (IV)	14.00	37.62	22.08	49.00	23.60	24.92
Location	Ozone (µg/m ³)					
Bhiwadi	2019	2020	2021			
January	15.3 ± 0.9	24.5 ± 1.0	21.6 ± 1.6			
February	15.5 ± 1.2	29.6 ± 1.5	28.8 ± 1.1			
March	26.1 ± 1.5	23.8 ± 1.6	36.1 ± 2.0			
April	37.4 ± 1.4	38.4 ± 1.5	32.2 ± 0.9			
May	36.5 ± 1.5	38.4 ± 1.4	33.9 ± 1.8			
June	45.5 ± 2.7	33.8 ± 2.0	31.9 ± 0.9			
July	30.5 ± 1.4	27.6 ± 1.5	25.5 ± 1.2			
August	25.5 ± 1.1	19.2 ± 0.9	25.2 ± 1.1			
September	30.6 ± 1.0	20.3 ± 0.5	33.6 ± 1.9			
October	28.4 ± 1.0	26.7 ± 1.3	26.4 ± 2.0			
November	27.6 ± 1.0	28.1 ± 2.8	21.9 ± 2.1			
December	24.5 ± 1.6	22 ± 1.3	8.2 ± 0.4			
Annual Average	28.6 ± 2.5	27.7 ± 1.8	27.1 ± 2.2			
Lockdown (I)	35.92	36.18	32.55			
Lockdown (II)	34.97	36.64	32.57			
Lockdown (III)	34.68	38.12	39.40			
Lockdown (IV)	38.79	38.07	28.28			

Monthly averaged particulate matter showed a strong seasonal variation. A significantly higher PM_{2.5} level was observed particularly during the winter seasons (November–January) in all the considered years. With a few peaks of relatively higher concentration during pre-monsoon seasons, there is a gradual declining trend in PM_{2.5} mass concentration from the month of February over all the studied sites in all the years. The concentration was further reduced to its lowest level in the monsoon seasons (July to September). The PM_{2.5} mass concentration shows an increasing trend from October onwards over all the studied sites (Figures 2 and 3). At this time, a significant increase of 205% in 2019, 176% in 2020, and 132% in 2021 was observed in the monthly mean concentration of PM_{2.5} compared to September. In terms of PM₁₀, several peaks of relatively higher concentration were seen during pre-monsoon/monsoon seasons. PM₁₀ concentration showed a steep increasing trend immediately after the monsoon seasons. A considerable increase of 144% in 2019, 130% in 2020, and 145% in the mean monthly

concentration of PM_{10} was observed over Delhi in the month of October compared to September (Table 1). A similar trend of particulate matter seasonal variability was seen over the studied regions of Uttar Pradesh, Haryana, and Bhiwadi (Figures 2 and 3; Table 1). The increasing trend of particulate matter continues in November and reaches its highest concentration in this month over all the studied regions.

Time series of the daily mean of NO_x and CO concentration over Delhi, the studied regions of Uttar Pradesh, Haryana, and Bhiwadi from 2019 to 2021 are plotted in Figures 4a–d and 5a–d. Like particulate matter, the higher concentration of gaseous pollutants during winter starts to decrease with the onset of summer and reaches its lowest level in monsoon depending on the amount of rainfall over the years. The concentration of gaseous pollutants also starts increasing after the monsoon seasons. A significant increase of 113% in 2019, 150% in 2020, and 91% in 2021 in the mean monthly concentration of NO_x , and a 60% increment in 2019, 98% in 2020, and 22% in 2021 over Delhi in October compared to September were observed (Table 1). Among all the studied sites, the highest NO_x distribution was found in Bhiwadi, followed by Delhi, the studied locations of Uttar Pradesh, and Haryana (Figure 4a–d).

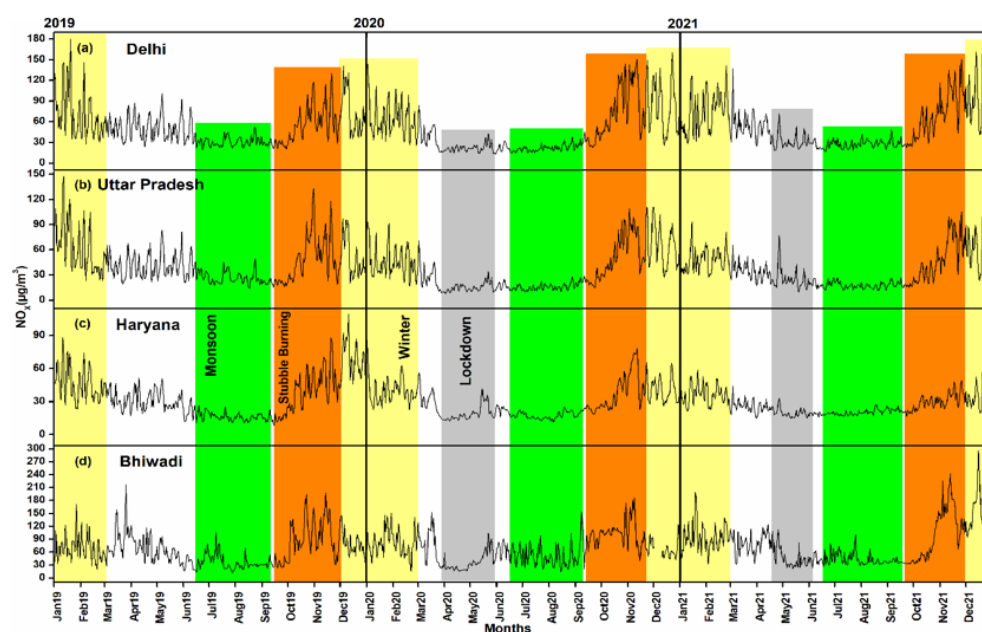


Figure 4. Graphs showing day to day variations of NO_x concentration over (a) Delhi, (b) studied regions of Uttar Pradesh, (c) studied regions of Haryana, and (d) Bhiwadi from the year 2019 to 2021. The highlighted grey region represents lockdown periods (25 March to 31 May 2020 and 20 April to 7 June 2021), the green color represents monsoon seasons (July to September), the light yellow color represents winter seasons, and the orange color represents the stubble burning period over the study area.

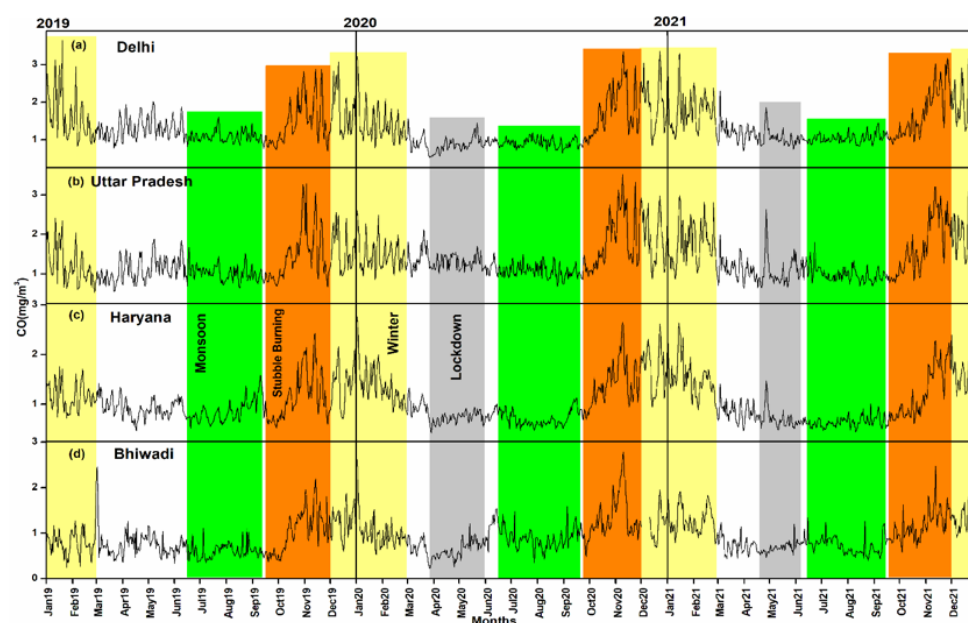


Figure 5. Graphs showing day to day variations of CO concentration over (a) Delhi, (b) studied regions of Uttar Pradesh, (c) studied regions of Haryana, and (d) Bhiwadi from the year 2019 to 2021. The highlighted grey region represents lockdown periods (25 March to 31 May 2020 and 20 April to 7 June 2021), the green color represents monsoon seasons (July to September), the light yellow color represents winter seasons, and the orange color represents the stubble burning period over the studied area.

The increasing trend of NO_x and CO continues in November and relatively higher concentrations persist during the winter seasons. But, unlike particulate matters, the highest NO_x concentration was observed during December/January in all the years except during the lockdown year (2020) (Figure 4). In 2020, the highest NO_x concentration coincided with the parali burning time (October–November). The highest CO level was seen during the post-monsoon parali burning period over almost all the studied sites except Delhi and Bhiwadi in the year 2019. This year, the highest CO distribution was found during January in Delhi. In 2019, the highest NO_x and CO in Bhiwadi was found during the summer season (Figures 4 and 5). The annual average NO_x level was found to be $51.9 \pm 5.1 \mu\text{g}/\text{m}^3$ in 2019, $47.2 \pm 8.1 \mu\text{g}/\text{m}^3$ in 2020 (lowest), and $53.7 \pm 8.2 \mu\text{g}/\text{m}^3$ (highest) in 2021 over Delhi; $43.1 \pm 4.5 \mu\text{g}/\text{m}^3$ in 2019 (highest), $33.6 \pm 6.1 \mu\text{g}/\text{m}^3$ in 2020 (lowest), and $35.3 \pm 5.2 \mu\text{g}/\text{m}^3$ in 2021 over the studied regions of Uttar Pradesh; $34.3 \pm 0.12 \mu\text{g}/\text{m}^3$ (highest) in 2019, $29.8 \pm 3.4 \mu\text{g}/\text{m}^3$ in 2020, and $26.8 \pm 2.1 \mu\text{g}/\text{m}^3$ in 2021 (lowest) over Haryana; and $65.1 \pm 7.4 \mu\text{g}/\text{m}^3$ (lowest) in 2019, $67.7 \pm 11.5 \mu\text{g}/\text{m}^3$ in 2020, and $75.9 \pm 11.5 \mu\text{g}/\text{m}^3$ in 2021 (highest) at Bhiwadi. With slight variability among the years, the average annual CO concentration level was found to be $1.4 \pm 0.1 \text{ mg}/\text{m}^3$ in 2019, $1.2 \pm 0.1 \text{ mg}/\text{m}^3$ in 2020 (lowest), and $1.40 \pm 0.1 \text{ mg}/\text{m}^3$ (highest) in 2021 over Delhi, and $1.2 \pm 0.1 \text{ mg}/\text{m}^3$ in 2019 (lowest), $1.4 \pm 0.1 \text{ mg}/\text{m}^3$ in 2020 (highest), and $1.39 \pm 0.1 \text{ mg}/\text{m}^3$ in 2021 over the studied regions of Uttar Pradesh. A slightly lower average annual CO concentration was found over the studied regions of Haryana (1.0 ± 0.1 in 2019, 1.1 ± 0.1 in 2020, and 1.0 ± 0.1 in 2021), and Bhiwadi ($0.82 \pm 0.1 \text{ mg}/\text{m}^3$ in 2019, $0.96 \pm 0.1 \text{ mg}/\text{m}^3$ in 2020, and $0.95 \pm 0.1 \text{ mg}/\text{m}^3$ in 2021).

Due to the large data gaps in Haryana and UP, NH₃ and SO₂ distributions were studied only for Delhi and Bhiwadi from 2019 to 2021. The time series of the daily mean of SO₂ and NH₃ over Delhi and Bhiwadi are shown in Figure 6 a–d. Considerable variation was observed in the mean monthly concentration of SO₂ between Delhi and Bhiwadi (Figure 6 a,b). A significantly higher SO₂ concentration was found in Bhiwadi compared to Delhi in almost all the years. Relatively higher SO₂ values were observed during summer/pre-monsoon time, and the lower SO₂ concentration was found during monsoon,

followed by post-monsoon/winter seasons. In 2020, the SO_2 concentration was consistently lower during pre-monsoon (lockdown period) and monsoon seasons in Bhiwadi. In terms of NH_3 , a relatively higher concentration was found during post-monsoon/winter seasons and a lower NH_3 level was observed during pre-monsoon/monsoon seasons (Figure 6 c,d). The average annual SO_2 level was found to be $14.8 \pm 1.2 \mu\text{g}/\text{m}^3$ in 2019 (highest), $13.2 \pm 0.7 \pm 0.7 \mu\text{g}/\text{m}^3$ in 2020, and $12.1 \pm 1.2 \mu\text{g}/\text{m}^3$ (lowest) in 2021 over Delhi, and $31.95 \mu\text{g}/\text{m}^3$ in 2019 (highest), and $30.80 \mu\text{g}/\text{m}^3$ in 2020, and 30.74 in 2021 (lowest) over Bhiwadi. In terms of NH_3 , the annual mean concentration was found to be $37.02 \pm 2.1 \mu\text{g}/\text{m}^3$ in 2019, $34.8 \pm 2.3 \mu\text{g}/\text{m}^3$ in 2020 (lowest), and $44.4 \pm 2.7 \mu\text{g}/\text{m}^3$ (highest) in 2021 over Delhi, and $27.6 \pm 4.2 \mu\text{g}/\text{m}^3$ in 2019 (lowest), $39.7 \pm 4.1 \mu\text{g}/\text{m}^3$ in 2020 (highest), and $37.2 \pm 5.3 \mu\text{g}/\text{m}^3$ in 2021 over Bhiwadi (Table 1).

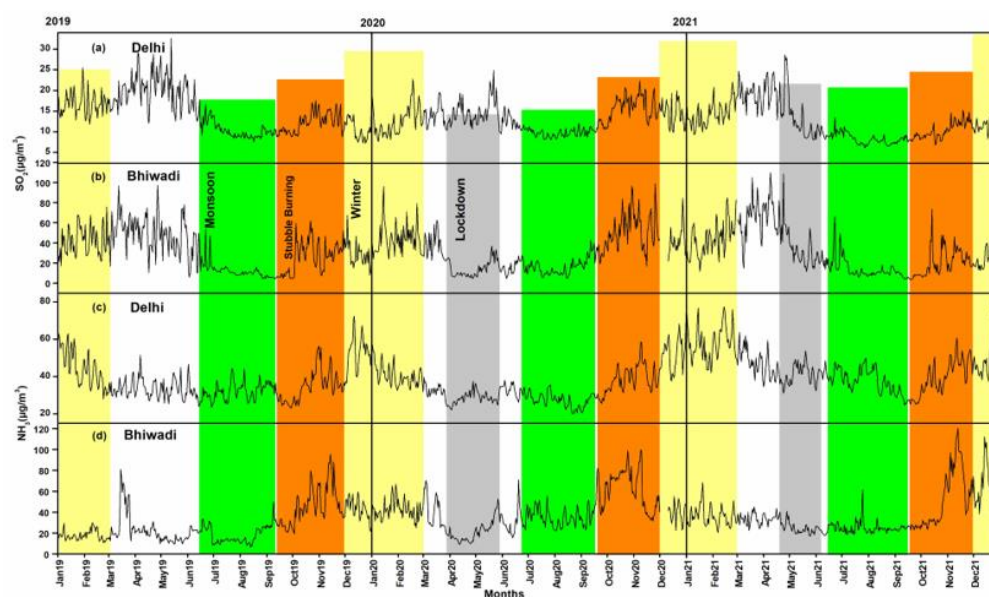


Figure 6. Graphs showing day to day variations of SO_2 over (a) Delhi, (b) Bhiwadi, and NH_3 concentration over (c) Delhi and (d) Bhiwadi. The highlighted grey region represents lockdown periods (25 March to 31 May 2020 and 20 April to 7 June 2021), the green color represents monsoon seasons (July to September), the light yellow color represents winter seasons, and the orange color represents the stubble burning period over the study area.

Unlike other pollutants, the monthly mean concentration of O_3 exhibited significant variability (increase and decrease) over the studied regions. Figure 7 shows the time series of daily average ozone values over Delhi, Uttar Pradesh, Haryana, and Bhiwadi from 2019 to 2021. Month-wise average O_3 distribution shows a strong seasonal variation. In all the years, the O_3 level was significantly lower in winter seasons (November–January) and Monsoon seasons (July to September) due to a lesser amount of insolation and cloud cover. The surface ozone concentration starts increasing gradually from March onwards due to the rise in temperature and reaches its maximum concentration during pre-monsoon seasons (May and June). The O_3 level starts decreasing in monsoon seasons and reaches its lowest values during peak-monsoon seasons. After the monsoon seasons, the surface O_3 level again starts increasing in October (again due to clear sky conditions and a higher amount of insolation), and a further decrease in November and similar lower values continues up to February (Figure 7).

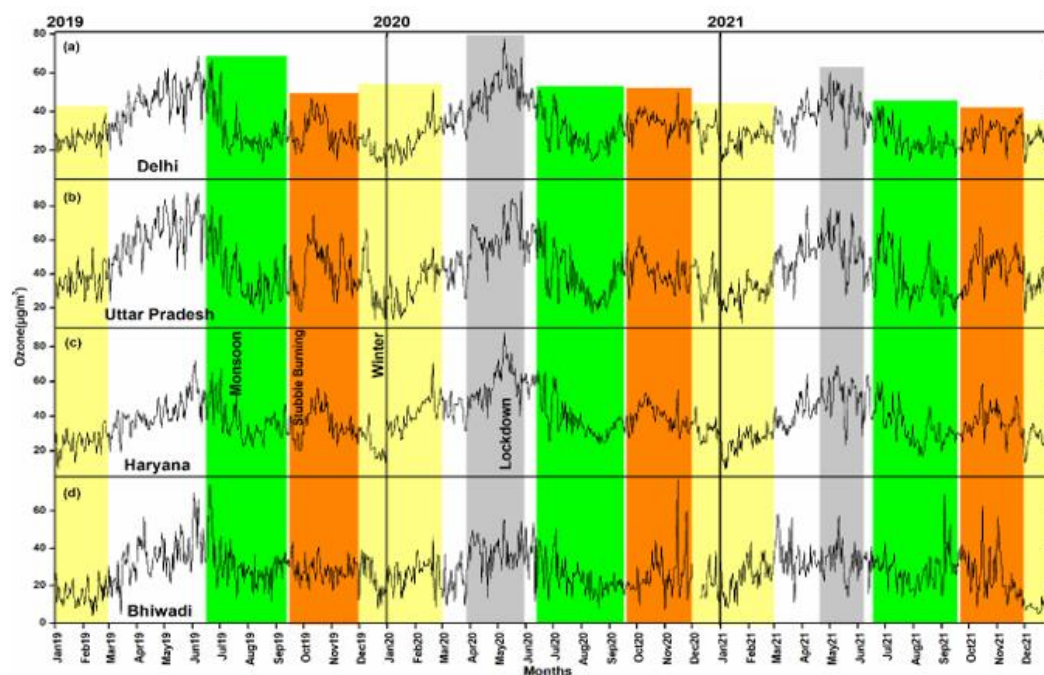


Figure 7. Graphs showing day to day variations of surface ozone (O_3) concentration over (a) Delhi, (b) studied regions of Uttar Pradesh, (c) studied regions of Haryana, and (d) Bhiwadi from the year 2019 to 2021. The highlighted grey region represents lockdown periods (25 March to 31 May 2020 and 20 April to 7 June 2021), the green color represents monsoon seasons (July to September), the light yellow color represents winter seasons, and the orange color represents the stubble burning period over the study area.

An almost similar trend was seen over the studied regions of Uttar Pradesh (Figure 7b) with slight variation in Haryana and Bhiwadi (Figure 7c,d). The average annual surface ozone level was found to be $33.0 \pm 3.0 \mu\text{g}/\text{m}^3$ in 2019, $34.5 \pm 2.9 \mu\text{g}/\text{m}^3$ in 2020 (highest), and $30.1 \pm 2.1 \mu\text{g}/\text{m}^3$ (lowest) in 2021 over Delhi; $45.6 \pm 4.1 \mu\text{g}/\text{m}^3$ in 2019 (highest), $43.0 \pm 3.6 \mu\text{g}/\text{m}^3$ in 2020, and $41.5 \pm 3.2 \mu\text{g}/\text{m}^3$ in 2021 (lowest) over the studied regions of Uttar Pradesh; $34.9 \pm 2.5 \mu\text{g}/\text{m}^3$ in 2019 (lowest), $42.7 \pm 3.0 \mu\text{g}/\text{m}^3$ in 2020 (highest), and $36.4 \pm 2.8 \mu\text{g}/\text{m}^3$ in 2021 over Haryana; and $28.6 \pm 2.5 \mu\text{g}/\text{m}^3$ in 2019 (highest), $27.7 \pm 1.8 \mu\text{g}/\text{m}^3$ in 2020 (lowest), and $27.1 \pm 2.2 \mu\text{g}/\text{m}^3$ in 2021 (lowest) at Bhiwadi. Significant changes were not seen in the average annual O_3 surface level over the years. Contrary to Delhi and Bhiwadi, a relatively higher average surface O_3 concentration was found over the studied regions of Uttar Pradesh and Haryana in all the years.

The estimated average annual particulate matter concentration ($\text{PM}_{2.5}$ and PM_{10}) over the studied regions were ~ 2.5 to 3.5 times higher than the National Air Quality Standards ($\text{PM}_{2.5}$: $40 \mu\text{g}/\text{m}^3$ and PM_{10} : $60 \mu\text{g}/\text{m}^3$) (NAQS; <http://cpcb.nic.in/airquality-standard>). With slight temporal and spatial variability, the above estimates were ~ 20 times (for $\text{PM}_{2.5}$) and ~ 15 (for PM_{10}) times higher than the revised annual limits set by the World Health Organization (WHO) for $\text{PM}_{2.5}$ ($10 \mu\text{g}/\text{m}^3$) and PM_{10} ($20 \mu\text{g}/\text{m}^3$) [15]. However, the estimated annual average gaseous concentration was either only slightly higher (for NO_x) or within (for SO_2 , and NH_3) the National Air Quality Standard (NO_x : 40; SO_2 : 50; and NH_3 : 100). We also calculated how many days in a year the average concentration of particulate matter fell below the NAQS. For $\text{PM}_{2.5}$, we found 117 days in 2019 (lowest), 172 days in 2020 (highest), and 150 days in 2021 in Delhi, and 120 days in 2019 (lowest), 161 days in 2020 (highest), and 155 days in 2021 in the studied location of Uttar Pradesh. Likewise, there were 140 days (2019, lowest), 185 (2020, highest), and 151 days in the studied site of Haryana, and 78 days in 2019 (lowest), 133 days in 2020 (highest), and 84 days in 2021 in Bhiwadi. In terms of PM_{10} concentration, the number of days is lower than the fine particulate matter ($\text{PM}_{2.5}$). For PM_{10} , 64, 112, and 75 days were observed in Delhi;

63, 102, and 82 days in the studied location of Uttar Pradesh; 76, 103, and 81 days in the studied sites of Haryana; and 33, 101, and 48 days in Bhiwadi. Like $PM_{2.5}$, the highest number of days when PM_{10} was under the National Air Quality Standard was observed in 2020 only. The majority of these days, when the particulate matter concentration was under the NAQS category, were found during summer seasons (Monsoon/pre-monsoon).

A combination of many factors was behind the high particulate matter, and most of the gaseous pollutants' levels during post-monsoon and winter seasons, including prolonged and intense stubble burning in the neighboring states (Punjab and Haryana), which coincided with the setting off of fireworks and a meteorological event. During this time, the unfavorable meteorological conditions (lower temperature, lower planetary boundary layer (PBL) height, and very low amount of rainfall) restrict vertical turbulent transport and increase the surface pollution level [66,67]. After the stubble burning stopped (November end), there was a slight reduction in particulate matter, and this trend continues up to January. As the temperature starts increasing in summer, the height of PBL increases, which enhances the convection and eventually the reduction in particulate matter and gaseous pollutants concentration over the study area. In monsoon seasons, rainwater washes out (wet scavenging) the atmospheric pollutants and improves the air quality significantly over the study area [68].

Several peaks of a relatively higher PM_{10} concentration during pre-monsoon/monsoon seasons compared to $PM_{2.5}$ clearly suggest the natural source of pollution. Frequent occurrences of dust storms are a very common phenomenon during this time over the studied sites and could be the possible source of higher coarse particulate matter. The higher SO_2 concentration in Bhiwadi compared to Delhi is obvious due to (a) Bhiwadi is a well-known industrial site, and (b) there is only one monitoring station in Bhiwadi. However, for Delhi, we have used the average SO_2 values of 35 monitoring stations including industrial and nonindustrial sites. This explanation also applied for the other pollutants' variability. Using only one or two air quality monitoring station data of Bhiwadi and an average value of 35 monitoring stations of Delhi, a recently published World Air Quality report (2022) [69], which claimed that Bhiwadi is the most polluted city in the world. Our research unequivocally shows that Delhi has the highest levels of pollution among all cities. Further details on this matter will be presented in the upcoming sections.

The cause of the relatively lower pollutants' concentration after the lockdown till September was attributed to higher rainfall and a greater number of rainy days in 2020 compared to 2019 and 2021. From October onwards, the pollution level was higher in 2020 compared to 2019 and 2021 due to intensive stubble burning, firecracker activities, and unfavorable meteorological conditions. In 2020, farm fires started early and continued till late November. In addition, in the year 2019, Diwali was early (27 October) as compared to the 2020 (14 November).

3.2. Lockdown Activities

Due to the spread of the COVID-19 pandemic, four phase-wise lockdowns were implemented in India from 25 March to 31 May 2020. A significant reduction in almost all the pollutants level was noted during the lockdown 2020 period. Despite a significant monthly variation, a considerable dip in average monthly $PM_{2.5}$ was observed in 2020 compared to 2019 (pre-lockdown) and 2021 (post-lockdown). But, it has been noted here that pollutant levels were already lower (improved) in 2020 over Delhi before the implementation of the lockdown (1 March to 23 March 2020) ($PM_{2.5}$ = 65.36 $\mu\text{g}/\text{m}^3$, PM_{10} = 206.8 $\mu\text{g}/\text{m}^3$, NO_x = 58 $\mu\text{g}/\text{m}^3$, CO = 1.29 mg/m^3 , SO_2 = 13.4 $\mu\text{g}/\text{m}^3$, and NH_3 = 38.6 $\mu\text{g}/\text{m}^3$) compared to 2019 ($PM_{2.5}$ = 83.79 $\mu\text{g}/\text{m}^3$, PM_{10} = 243.7 $\mu\text{g}/\text{m}^3$, NO_x = 64.5 $\mu\text{g}/\text{m}^3$, CO = 1.5 mg/m^3 , SO_2 = 16.7 $\mu\text{g}/\text{m}^3$, and NH_3 = 54.7 $\mu\text{g}/\text{m}^3$) and 2021 ($PM_{2.5}$ = 99.46 $\mu\text{g}/\text{m}^3$, PM_{10} = 285.7 $\mu\text{g}/\text{m}^3$, NO_x = 70 $\mu\text{g}/\text{m}^3$, CO = 1.64 mg/m^3 , SO_2 = 15.8 $\mu\text{g}/\text{m}^3$, and NH_3 = 56.3 $\mu\text{g}/\text{m}^3$). Over Delhi, during this period, the levels of $PM_{2.5}$ were 22% and 35% lower, and PM_{10} was 15% and 27% lower than the levels recorded in 2019 and 2021, respectively. Likewise, NO_x

was 10% and 7%, CO was 14% and 21%, SO₂ was 20% and 15%, and NH₃ was 30% lesser than 2019 and 2021, respectively. A similar reduction in pollutant concentration was observed over the studied regions of Uttar Pradesh, Haryana, and Bhiwadi (Table 2).

Table 2. Monthly and annual changes in pollutant concentration in terms of percentage during the years 2019 and 2021 compared to 2020 (lockdown year).

Delhi	PM _{2.5}		PM ₁₀		NO _x		CO	
Months	2019	2021	2019	2021	2019	2021	2019	2021
January	-23	-20	-26	-20	-20	0.3	-19	-13
February	-1	-20	4	-23	8	-27	-4	-27
March	-31	-39	-32	-49	-25	-32	-25	-27
April	-43	-45	-54	-53	-56	-53	-43	-34
May	-38	3	-45	-3	-55	-18	-33	-5
June	-26	-10	-42	-22	-45	-23	-20	-8
July	-26	-12	-45	-28	-30	-19	-17	-9
August	-29	-38	-33	-50	-29	-20	-17	-13
September	18	48	23	62	15	11	-5	-17
October	9	79	17	53	35	46	7	23
November	5	-11	11	-10	41	-2	27	-9
December	-4	-5	3	-2	13	-17	11	-5
Annual	-16	-6	-18	-12	-12	-13	-12	-12
Lockdown (I)	54	48	63	62	65	64	49	41
Lockdown (II)	40	48	51	51	56	39	36	22
Lockdown (III)	50	3	59	14	63	31	40	18
Lockdown (IV)	16	-26	17	-31	52	16	21	-12

Delhi	NH ₃		SO ₂		Ozone	
Months	2019	2021	2019	2021	2019	2021
January	-13	-22	-33	-14	-20	-15
February	-3	-38	-7	-7	15	15
March	-5	-37	-23	-25	0.34	10
April	-14	-28	-34	-30	5	14
May	-11	-31	-21	38	13	30
June	5	-23	-12	25	-21	11
July	-10	-27	-2	16	6	19
August	-23	-33	4	20	-8	-3
September	-11	-0.06	10	22	14	33
October	10	4	32	74	5	25
November	7	-14	24	30	16	-4
December	-3	2	38	24	52	30
Annual	-6	-20	-2	15	6	14
Lockdown (I)	28	40	37	30	7	0
Lockdown (II)	3	18	39	29	-4	-16
Lockdown (III)	13	34	32	-17	-28	-28
Lockdown (IV)	11	33	14	-79	-8	-37

Uttar Pradesh	PM _{2.5}		PM ₁₀		NO _x		CO	
Months	2019	2021	2019	2021	2019	2021	2019	2021
January	-18	-13	-18	-19	-36	0.09	8	-13
February	3	-20	16	-28	-8	-8	38	-21
March	-32	-35	-33	-53	-36	-27	53	27
April	-43	-36	-52	-51	-66	-57	27	25
May	-41	3	-49	-13	-63	-34	10	38
June	-28	7	-44	-18	-50	-20	-3	-10
July	-27	2	-42	-30	-50	-16	10	18
August	-33	-35	-37	-51	-38	-0.64	5	13
September	38	101	51	116	9	19	5	13
October	8	64	17	50	-3	56	5	22

November	6	−5	8	−9	20	3	30	−6
December	8	36	10	20	26	5	23	−2
Annual	−13	6	−14	−7	−24	−7	18	9
Lockdown (I)	58	47	63	63	70	63	−12	−17
Lockdown (II)	34	39	48	48	62	52	−32	−20
Lockdown (III)	53	10	65	26	69	41	9	−36
Lockdown (IV)	19	−44	21	−26	58	0	−14	−23

Uttar Pradesh		Ozone	
Months	2019	2021	
January	−29	−5	
February	10	29	
March	−17	−16	
April	−10	−1	
May	−2	22	
June	−18	8	
July	12	10	
August	−17	−27	
September	26	54	
October	−14	−7	
November	−4	−19	
December	13	18	
Annual	−4	6	
Lockdown (I)	11	6	
Lockdown (II)	20	7	
Lockdown (III)	−4	−12	
Lockdown (IV)	0	−40	

Haryana	PM _{2.5}		PM ₁₀		NO _x		CO	
Months	2019	2021	2019	2021	2019	2021	2019	2021
January	−26	−25	19	−17	−20	3	42	−8
February	4	−22	27	−24	0.37	22	−2	−16
March	−15	−37	−5	−43	−6	16	−15	6
April	−44	−43	−47	−50	−56	−39	−12	−16
May	−41	−9	−32	−9	−19	38	−14	18
June	−29	−11	−28	−16	17	15	−0.68	36
July	−17	−7	−14	−8	4	−10	−15	3
August	−20	−36	−27	−41	29	−7	−29	−3
September	32	71	47	71	46	2	−8	21
October	24	64	31	57	−12	18	16	49
November	9	−8	20	−11	−0.86	46	17	−6
December	10	0	23	2	−40	13	23	9
Annual	−9	−5	−2	−7	−5	10	0.31	8
Lockdown (I)	52	52	57	61	54	38	29	20
Lockdown (II)	41	43	43	46	51	28	8	12
Lockdown (III)	55	17	49	15	24	−39	19	−17
Lockdown (IV)	19	−10	6	−14	21	−21	7	−27

Haryana	Ozone	
Months	2019	2021
January	47	55
February	73	67
March	31	16
April	31	7
May	42	17
June	−0.59	5
July	15	16
August	−8	7
September	15	23
October	3	13

November	16	−2						
December	31	14						
Annual	25	20						
Lockdown (I)	−26	−1						
Lockdown (II)	−38	−15						
Lockdown (III)	−76	−25						
Lockdown (IV)	−17	−15						
Bhiwadi	PM_{2.5}		PM₁₀		NO_x		CO	
Months	2019	2021	2019	2021	2019	2021	2019	2021
January	−21	−17	−19	−12	19	−9	47	−14
February	15	−8	−4	−26	10	−18	15	−27
March	−28	−44	−38	−53	−17	−0.61	−17	−15
April	−57	−69	−65	−70	−68	−73	−38	−21
May	−36	−23	−42	−17	−11	39	7	10
June	−30	−36	−37	−30	66	40	70	38
July	−19	−14	−37	−24	27	1	47	6
August	−42	−40	−45	−46	42	17	14	24
September	43	86	49	104	140	117	75	16
October	74	57	38	48	9	61	25	24
November	34	0	20	−5	−5	−36	14	8
December	9	18	8	4	−21	−56	−6	−9
Annual	−5	−8	−14	−11	16	7	21	3
Lockdown (I)	64	74	70	77	73	69	38	35
Lockdown (II)	57	67	64	66	65	68	41	17
Lockdown (III)	35	22	57	21	37	−28	−8	−21
Lockdown (IV)	32	13	22	4	−29	−65	−26	−7
Bhiwadi	NH₃		SO₂		Ozone (O₃)			
Months	2019	2021	2019	2021	2019	2021		
January	158	11	4	22	60	14		
February	112	19	8	−12	91	3		
March	12	14	−38	−45	−9	−34		
April	−34	−58	−83	−87	3	19		
May	122	33	−60	−35	5	13		
June	30	24	−39	−35	−26	6		
July	202	47	10	−2	−9	8		
August	96	36	39	20	−25	−24		
September	58	77	304	294	−34	−40		
October	57	102	66	157	−6	1		
November	−5	−31	86	118	2	28		
December	−9	−46	48	97	−10	169		
Annual	67	19	29	41	4	14		
Lockdown (I)	29	48	74	81	−1	−11		
Lockdown (II)	23	53	85	87	−5	−12		
Lockdown (III)	−84	−8	65	47	−10	3		
Lockdown (IV)	−169	−70	52	5	2	−35		

The implementation of the lockdown coincides with favorable meteorological conditions, further reducing the pollutants' concentration over Delhi and the adjacent regions. During the first phase of the lockdown (25 March to 14 April 2020), PM_{2.5} concentration showed a significant reduction of 54% compared to 2019, and 48% compared to 2021 over Delhi. During the second phase of the lockdown (15 April to 3 May 2020), a similar reduction of 40% and 48% compared to 2019 and 2021, respectively, was observed. In terms of PM₁₀, a significant reduction of more than 60% and 50% during the first and second phases of the lockdown was observed (Table 2). During the third phase of the lockdown, between 4 May to 17 May 2020, no considerable changes in particulate matter concentration were noticed compared to 2021, but there was a significant reduction

of 50% for $PM_{2.5}$ and 59% for PM_{10} compared to 2019. During the last phase of the lockdown of 2020 (18 to 31 May), the influence of the lockdown was not reflected in $PM_{2.5}$ distribution over Delhi. During this time, a slight reduction of 16% was noticed compared to 2019, with a 26% increment compared to 2021.

NO_x concentration showed a significant reduction of 65% during the first phase, 56% and 39% during the second phase, 63% and 31% during the third phase, and 52% and 16% during the last phase of the lockdown compared to 2019 and 2021, respectively, in Delhi (Table 2). In terms of CO, there was a 49% and 41% reduction during the first phase, 36% and 22% during the second phase, 40% and 18% during the third, and a 21% reduction and 12% increment during the last phase of the lockdown compared to 2019 and 2021. NH_3 showed a considerable dip of 28% and 40% during the first phase of the lockdown in 2020 compared to 2019 and 2021, respectively, in Delhi. During the latter phases of the lockdown, there was no considerable reduction in NH_3 compared to 2019, but there was a marked reduction of 33% during the last two phases. SO_2 concentration also showed a decreasing trend in all the phases compared to 2019, with the highest reduction in the initial phases (37% and 39% in the I and II phases) than in the later phases (32% and 14% in the III and IV phases). The SO_2 level was found to decrease during the first two phases of the lockdown compared to 2021 (~30%) (Table 2). Unlike other pollutants, the O_3 concentration was slightly decreased in the first phase of the lockdown (7%), followed by a slight increment in the second phase (4%) to a considerable increment of 28% during the third phase of the lockdown in Delhi compared to the 2019 data. However, compared to 2021, a slight increment in O_3 was seen in Delhi (Table 2). Almost similar, but a variable trend of reduction in pollutant concentration was observed over the other studied regions of UP, Haryana, and Bhiwadi. Over the studied regions of Uttar Pradesh, the reduction is slightly more than Delhi. Here, a significant reduction of $PM_{2.5}$: 58% and 47%, PM_{10} : 63%, and NO_x : 70% and 63% during the first phase, and $PM_{2.5}$: 34% and 39%, PM_{10} : 48%, and NO_x : 62% and 52% during the second phase of the lockdown in 2020 compared to 2019 and 2021, respectively, was observed. In the third phase of the closure at UP, $PM_{2.5}$, PM_{10} , and NO_x levels were reduced by 53%, 65%, and 69%, respectively, compared to 2019 and 2021 (Table 2). The effect of the lockdown was not seen in CO concentration in UP (15% to 30% increase during the initial phases of the lockdown). Over the studied sites of Uttar Pradesh, the O_3 level slightly dipped in the first phase (11% and 6%), with a considerable reduction in the second phase (20%), followed by a slight increment of 4% in the third phase of the lockdown compared to 2019. Over Haryana, a reduction of $PM_{2.5}$: 52%, PM_{10} : 57% and 61%, NO_x : 54% and 38%, and CO: 29% and 20% during the first phase and $PM_{2.5}$: 41% and 43%, PM_{10} : 43% and 46%, NO_x : 51% and 28%, and CO: 8% and 12% was observed during the second phase of the lockdown in 2020 compared to 2019 and 2021, respectively (Table 2). Furthermore, a considerable reduction of 50% in terms of particulate matter and a slight reduction close to 20% for NO_x and CO during the third phase of the lockdown was noted over the studied sites in Haryana (Table 2). During the first to third phases of the lockdown in 2020, O_3 concentration was observed to rise by 26%, 38%, and 76%, respectively, compared to 2019 (Table 2). At this time in Haryana, no considerable changes in the O_3 values were seen in 2021. The distribution of pollutant concentration showed that the influence of the lockdown was highest over Bhiwadi, particularly during the first two phases of the lockdown. During the first lockdown phase, a significant dip of 64% and 74% in $PM_{2.5}$, 70% and 77% in PM_{10} , 73% and 69% in NO_x , 38% and 35% in CO, and 29% and 48% in NH_3 concentration compared to 2019 and 2021, respectively, was observed. Similarly, a considerable reduction of 57% and 67% in $PM_{2.5}$, 65% in PM_{10} , 65% and 68% in NO_x , 41% and 17% in CO, and 23% and 53% in NH_3 concentrations compared to 2019 and 2021, respectively, during the second phase of the lockdown was observed (Table 2). SO_2 concentration was found to decrease significantly in Bhiwadi during all the lockdown phases of 2020 compared to the pre-lockdown (2019) and post-lockdown years (2021). Here, a reduction of 74% and 80% in the I phase, ~85% in the II phase, 65% and 47% in the III phase, and 52% and 5% in the IV phase of the lockdown was observed (Table

2). No considerable changes in O_3 were seen during the different phases of the lockdown in Bhiwadi (Table 2).

A variable but declining trend in the $PM_{2.5}$ level following the lockdown period continues up to June, July, and August over Delhi and the adjacent regions in 2020 compared to 2019 and 2021. During these months, there is a reduction of $PM_{2.5}$ (26% and 10% in June, 26% and 12% in July, and 29% and 38% in August over Delhi; 29% and 11% in June, 17% and 7% in July, and 20% and 36% in August over the studied regions of Haryana; and 30% and 36% in June, 19% and 14% in July, and 42% and 40% in August over Bhiwadi) compared to 2019 and 2021, respectively (Table 2). Over the studied regions of Uttar Pradesh, a reduction of 28% in June, 27% in July, and 33% in August was observed in 2020 compared to 2019, and an increment of 7% in June and 2% in July 2020 compared to 2021 was observed (Figures 2 and 3; Table 2). Likewise, the decreasing trend of the mean monthly concentration of PM_{10} in 2020 compared to 2019 and 2021 continued even after the lockdown. Here, a considerable reduction of 42% and 22% in June, 45% and 28% in July, and a 33% and 50% were noticed over Delhi. Similar but relatively less variation was observed over the studied regions of Uttar Pradesh (44% and 18% dip in June, 42% and 30% reduction in July, and 37% and 51% reduction in August), Haryana (28% and 16% dip in June, 14% and 8% decrease in July, and 27% and 41% decrease in August), and Bhiwadi (37% and 30% reduction in June, 37% and 24% dip in July, and 45% and 46% reduction in August) in 2019 and 2021, respectively (Figures 2 and 3; Table 2). Our results suggest a considerable reduction of 16% and 6% in terms of the annual average $PM_{2.5}$, and 18% and 12% in terms of the annual mean PM_{10} levels in 2020 compared to 2019 and 2021, respectively. The monthly and annual average changes in the concentration of particulate matter in 2019 and 2021 compared to 2020 are compiled in Table 2.

Like particulate matter, the decreasing trend of NO_x levels continued over Delhi (45% in June, 30% in July, and 29% in August) and UP (50% in June and July, and 38% in August) in 2020 compared to 2019 (Figure 3). However, during the same period, the observed concentration of NO_x was higher over Haryana (17% in June, 4% in July, and 29% in August) and Bhiwadi (66%, 27%, and 42% in June, July, and August, respectively). Compared to 2021, a slight reduction in the NO_x level (23% in June, 19% in July, and 20% in August) over Delhi, (20% in June, 16% in July, and only 1% in August over UP) was observed in 2020. Over Haryana and Bhiwadi, variable changes were observed in the NO_x concentration (Figure 4 and Table 2). Compared to 2021, there was a 15% increment in June and a 10% and 7% fall in July and August, respectively, over Haryana, and a 40%, 1%, and 17% increment over Bhiwadi in 2021. In terms of CO, the decreasing trend continued after the lockdown (20% and 8% in June, 17% and 9% in July, and 17% and 13% in August compared to 2019 and 2021, respectively). Over the studied sites in UP, there was a decrease of only 3% and 10% in June, followed by an increment of 10% and 18% in July and 5% and 13% in August 2020 compared to 2019 and 2021, respectively. Similarly, a variable change in the monthly mean CO concentration was observed in Haryana and Bhiwadi (Table 2). Unlike other pollutants, a decreasing trend for NH_3 , SO_2 , and O_3 after the lockdown was not seen in any of the years (except in 2021 for NH_3) (Table 2). After the monsoon seasons and the onset of winter, the concentration of particulate matter and gaseous pollutants increases significantly (several folds), as shown in Tables 1 and 2 and briefed in the previous sections. In terms of the average annual concentration, our results suggest a considerable reduction of 12% and 13% in NO_x levels in Delhi, and 24% and 7% over the studied location of Uttar Pradesh in 2020 compared to 2019 and 2021, respectively. The annual mean NO_x concentration was found to be higher in Bhiwadi in 2020 (16% and 7% compared to 2019 and 2021). There were only slight changes over Haryana in the NO_x annual average level (5% decrease in 2019 and 10% increase in 2021 compared to the 2020 estimates). The variations in the monthly and annual average concentrations of particulate matter and gaseous pollutants in 2020 compared to 2019 and 2021 over Delhi and the studied regions of UP, Haryana, and Bhiwadi are compiled in Table 2.

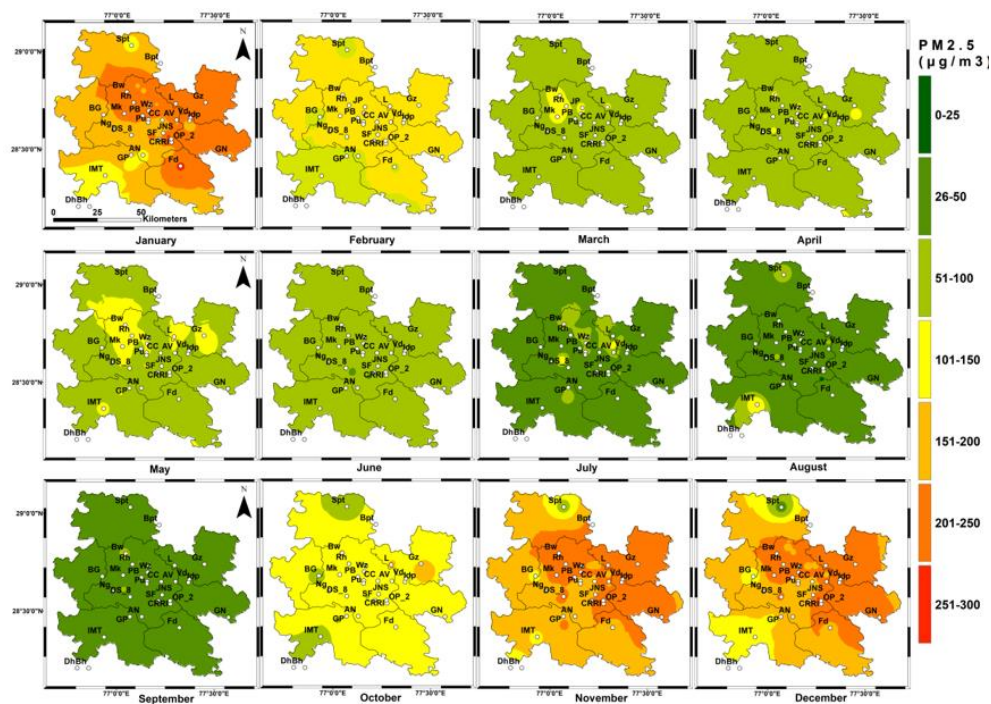
In 2021, the government again imposed a lockdown from 19 April to 07 June 2021 over Delhi NCR. During this period also (Figures 2–7), there was a considerable reduction of 25% in $PM_{2.5}$, 34% in PM_{10} , 39% in NO_x , 24% in CO, 19% in NH_3 , 37% in SO_2 and 13% in O_3 concentrations over Delhi compared to the non-lockdown year (2019). Likewise, a reduction of 29% in $PM_{2.5}$, 34% in PM_{10} , 41% in NO_x and 19% in O_3 over the studied regions of UP. During this time, the influence of lockdown was not strong in the studied regions of Haryana and Bhiwadi. A slight reduction of close to 25% in PM, 29% in NO_x and 25% in CO with a slight increment of 10% in O_3 concentration. Similarly, 7% reduction in $PM_{2.5}$, 23% reduction in PM_{10} , 20% reduction in NO_x , and 17% in O_3 with a significant increment of 50% in NH_3 concentration compared to the non-lockdown year (2019).

Meteorology played an important role in emission reduction during the lockdown, in particular, and seasonal, in general. By comparing the pre-lockdown (2019), lockdown (2020), and post-lockdown years' (2021) analysis, we found that the concentration of atmospheric pollutants was already lower (20% to 30%) due to a significantly higher amount of rainfall in March 2020 (81.1 mm; 500% more than the non-lockdown years) compared to March 2019 (13.4 mm) and March 2021 (5.4 mm). The rainfall was relatively higher in May 2020 (44.3 mm) compared to May 2019 (24.4 mm) and significantly lower compared to May 2021 (123 mm). No significant differences in the monthly average temperature were seen in 2020 compared to 2019. However, a slightly higher temperature was observed in March 2021 (25.6 °C) compared to 2020 (20.8 °C) and 2019 (21.1 °C). Also, the study area experienced relatively more dust storm incidents in 2019 compared to 2020 during the lockdown period. Thus, our results suggest that the lockdown's impact in Delhi NCR was not as significant as prior workers had stated. It was found that the pollutants were greatly reduced only during the first two phases of the lockdown by comparing the air pollution figures from the year before the lockdown (2019) and the year after the lockdown (2021), as well as the rainfall estimates.

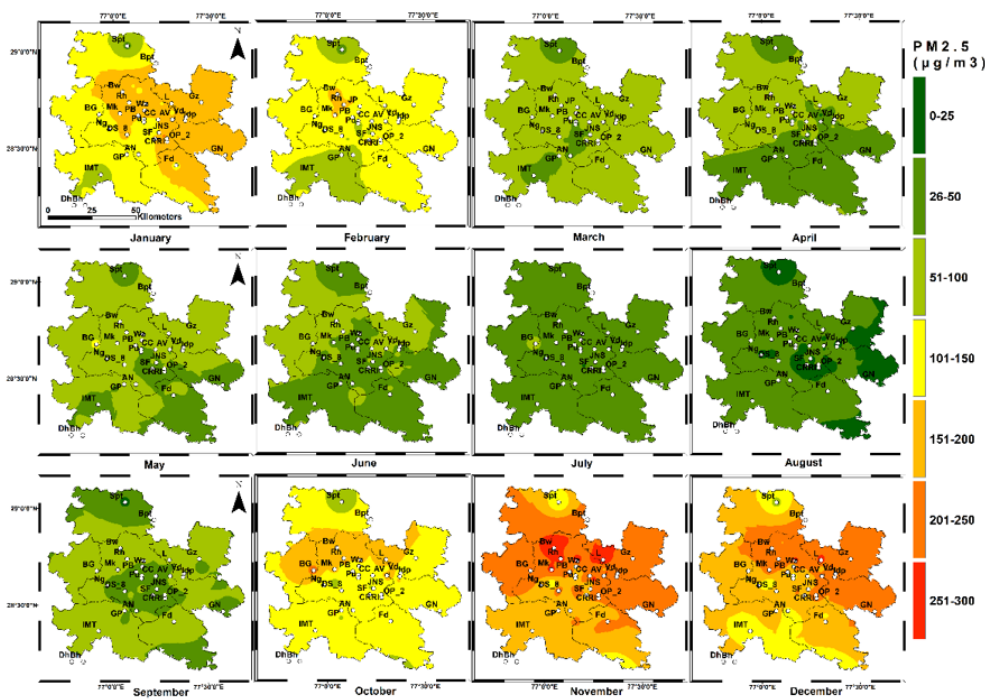
After careful evaluation, our findings suggest that the concentration of gaseous pollutants (apart from surface ozone) decreased by only 20–30% during the initial phases of the lockdown. The amount of ozone at the surface, however, increased even as the other contaminants were reduced. Thus, the concentration of air pollutants over Delhi NCR during the lockdown period of 2020 was significantly lowered due to minimum anthropogenic activities as well as favorable meteorological conditions (especially rainfall) before and during the lockdown, as well as by minimum anthropogenic activities.

3.3. Spatial Variability

Significant spatial variability is clearly seen in month-wise averaged $PM_{2.5}$ distribution maps in 2019, 2020, and 2021. In all the years, despite considerable seasonal variation, the highest pollution concentration was mostly found in the North and East Delhi regions (DTU, Bawana, and Jahangirpuri), Ghaziabad, Noida, Faridabad, IMT-Manesar, and Bhiwadi (Figure 8a–c).



(a)



(b)

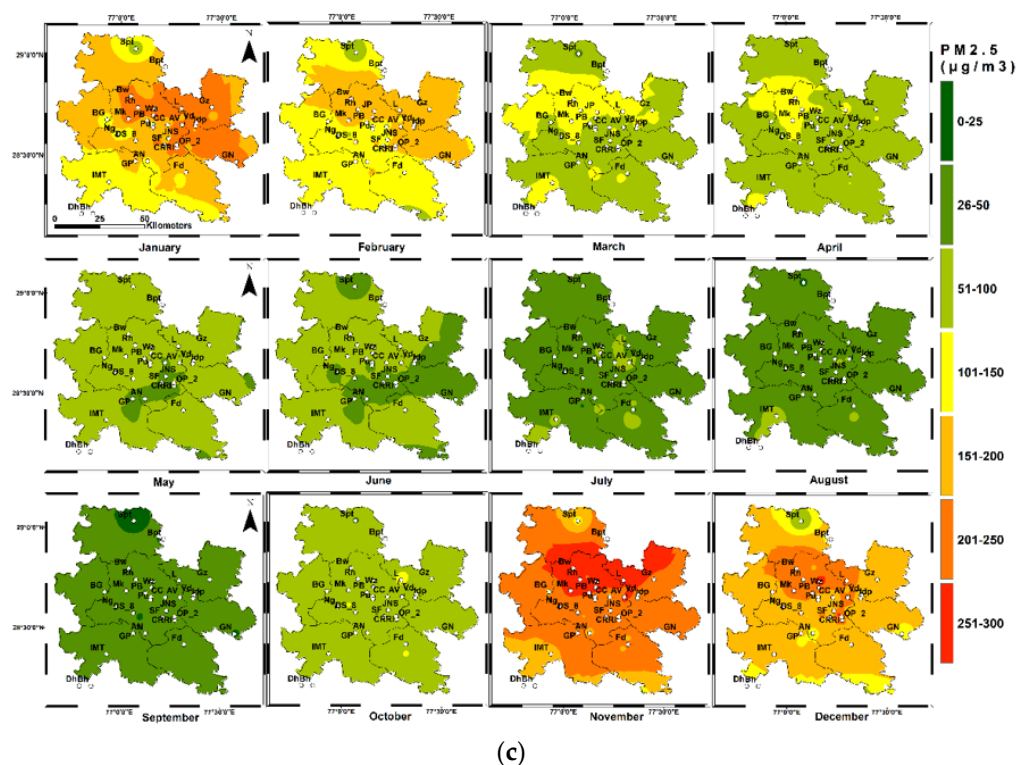
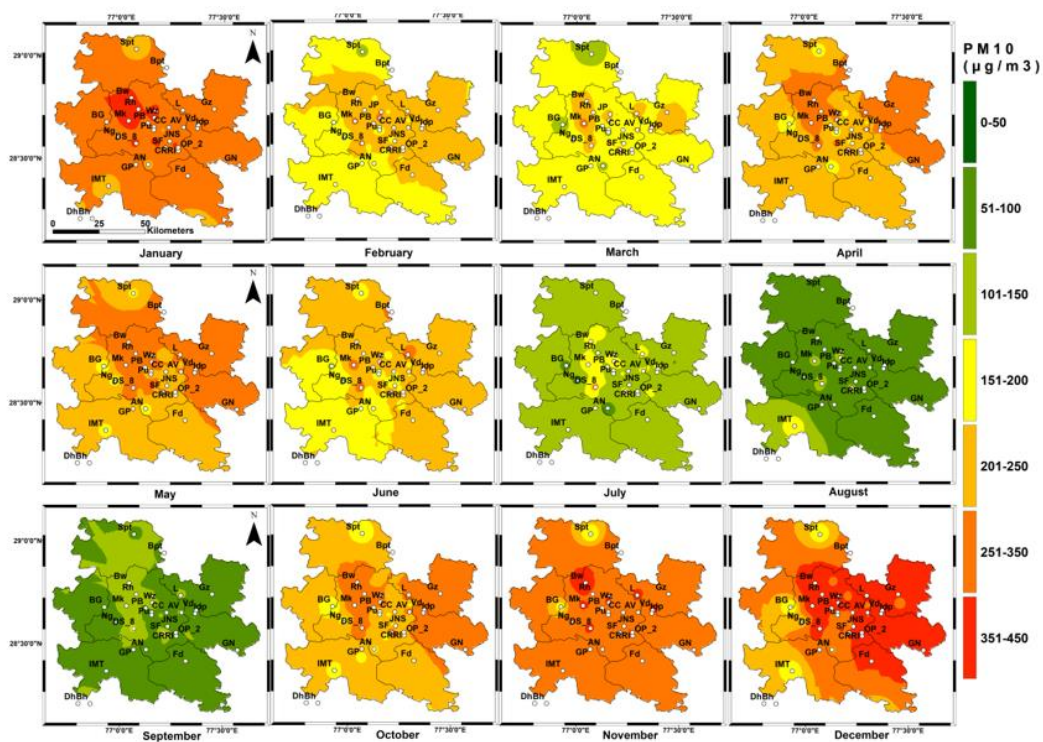


Figure 8. Map showing the month-wise spatial distribution of PM_{2.5} over the study area (Delhi NCR) in (a) 2019, (b) 2020, and (c) 2021.

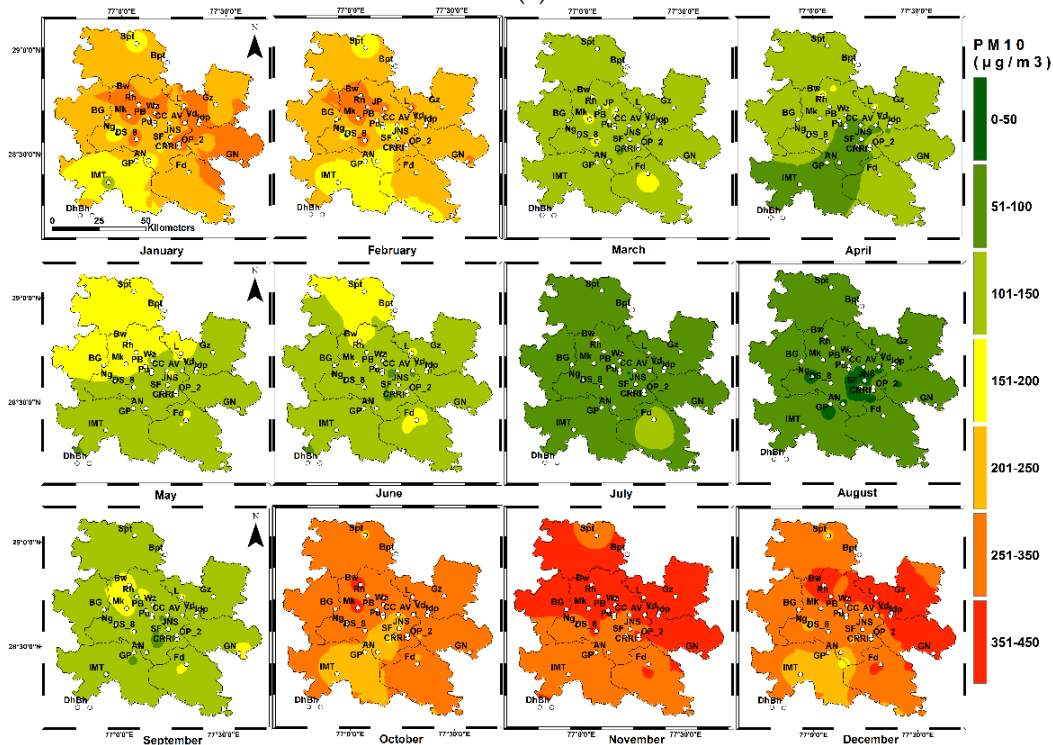
The concentration of PM_{2.5} varies from $82.5 \pm 3.6 \mu\text{g}/\text{m}^3$ over Pusa Road/Bahadurgarh to $134.8 \pm 5.6 \mu\text{g}/\text{m}^3$ at Wazirpur in 2019 and from $46.7 \pm 8.2 \mu\text{g}/\text{m}^3$ at Sonipat to $124.2 \pm 5.8 \mu\text{g}/\text{m}^3$ over Bahadurgarh in 2020. In 2021, the lowest concentration was seen over Shadipur ($76 \pm 2.9 \mu\text{g}/\text{m}^3$) and the highest over Jahangirpuri ($136 \pm 6.3 \mu\text{g}/\text{m}^3$). Higher concentration and variability were seen during winter seasons and lower variability and concentration during summer, particularly in monsoon (Figure 8a–c). Among the studied locations of Delhi NCR, the most polluted sites in terms of PM_{2.5} was found to be Wazirpur ($134.8 \pm 5.6 \mu\text{g}/\text{m}^3$), followed by Bawana ($130.8 \pm 5.2 \mu\text{g}/\text{m}^3$), Rohini ($128.1 \pm 5.4 \mu\text{g}/\text{m}^3$), Anand Vihar ($128.4 \pm 5.4 \mu\text{g}/\text{m}^3$), and Jahangirpuri ($128.0 \pm 5.0 \mu\text{g}/\text{m}^3$) in 2019. Vasundhara was the most polluted site in UP in 2019.

In 2020, the most polluted sites were Bahadurgarh ($124.2 \pm 5.8 \mu\text{g}/\text{m}^3$), Jahangirpuri ($122.7 \pm 5.7 \mu\text{g}/\text{m}^3$), Loni ($119.7 \pm 5.6 \mu\text{g}/\text{m}^3$), Bawana ($119.1 \pm 5.2 \mu\text{g}/\text{m}^3$), and Rohini ($115.8 \pm 5.2 \mu\text{g}/\text{m}^3$). In 2021, the most polluted site was Loni ($138.2 \pm 5.9 \mu\text{g}/\text{m}^3$), Jahangirpuri ($136.2 \pm 6.3 \mu\text{g}/\text{m}^3$), Mundka ($130.4 \pm 5.6 \mu\text{g}/\text{m}^3$), Anand Vihar ($129.2 \pm 5.1 \mu\text{g}/\text{m}^3$), and Bawana ($128.5 \pm 4.9 \mu\text{g}/\text{m}^3$). The most polluted site in Haryana was found to be Sector 51 Gurugram ($112.1 \pm 4.9 \mu\text{g}/\text{m}^3$) in 2021. The annual average PM_{2.5} over Bhiwadi was found to be $102 \pm 2.4 \mu\text{g}/\text{m}^3$ in 2019, $97.6 \pm 3.4 \mu\text{g}/\text{m}^3$ in 2020, and $111.2 \pm 3.0 \mu\text{g}/\text{m}^3$, which is much lesser than the average PM_{2.5} concentration in most of the locations in Delhi.

Unlike PM_{2.5}, relatively less spatial variability was observed in the PM₁₀ mass concentration during the three years over the study area (Figure 9a–c). The higher concentration of PM₁₀ was mostly found in the North and East Delhi regions (Bawana, Jahangirpuri, Wazirpur, Mundka, Rohini, and Anand Vihar), Ghaziabad (Loni and Vasundhara), Greater Noida, Faridabad, Gurugram and Bhiwadi, which can be clearly seen in Figure 9.



(a)



(b)

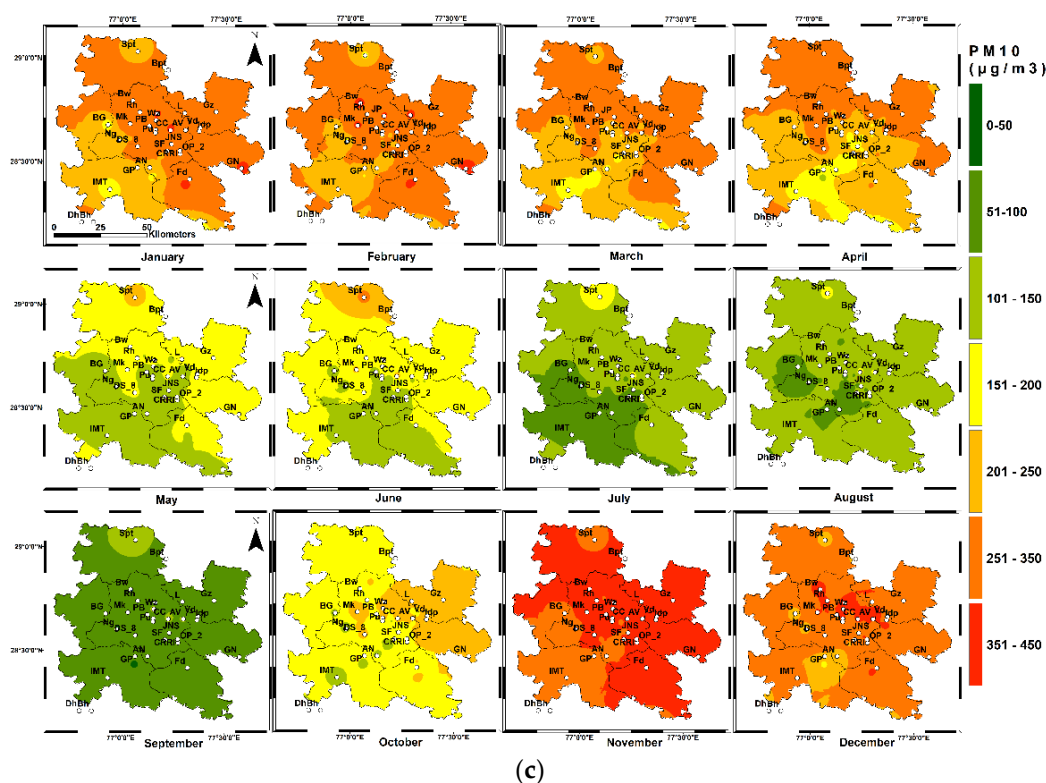
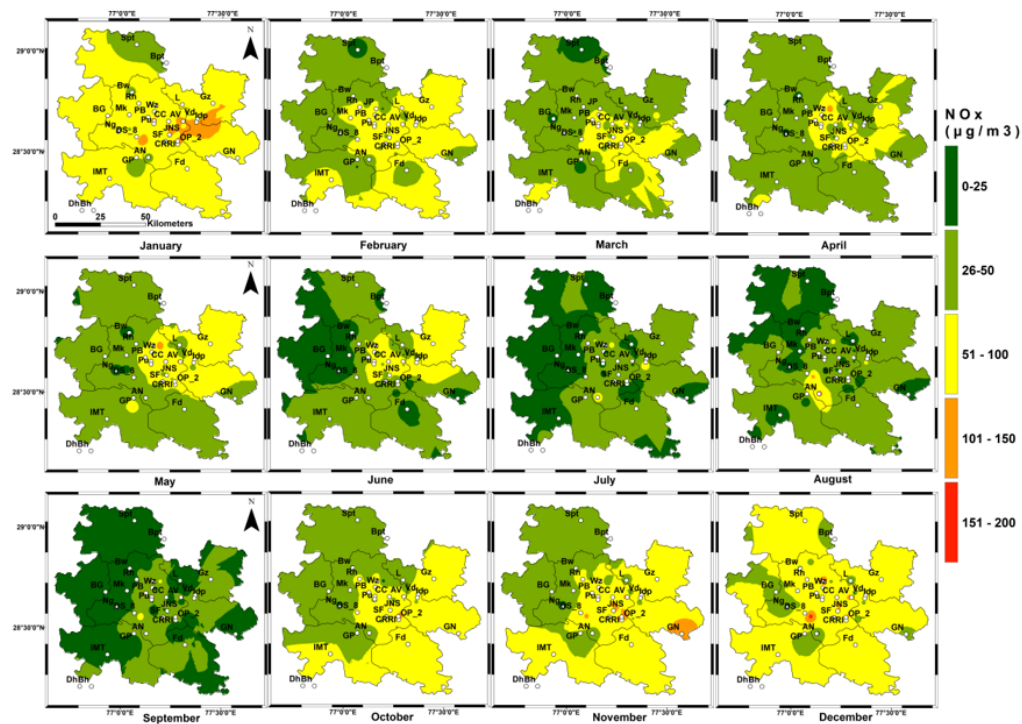


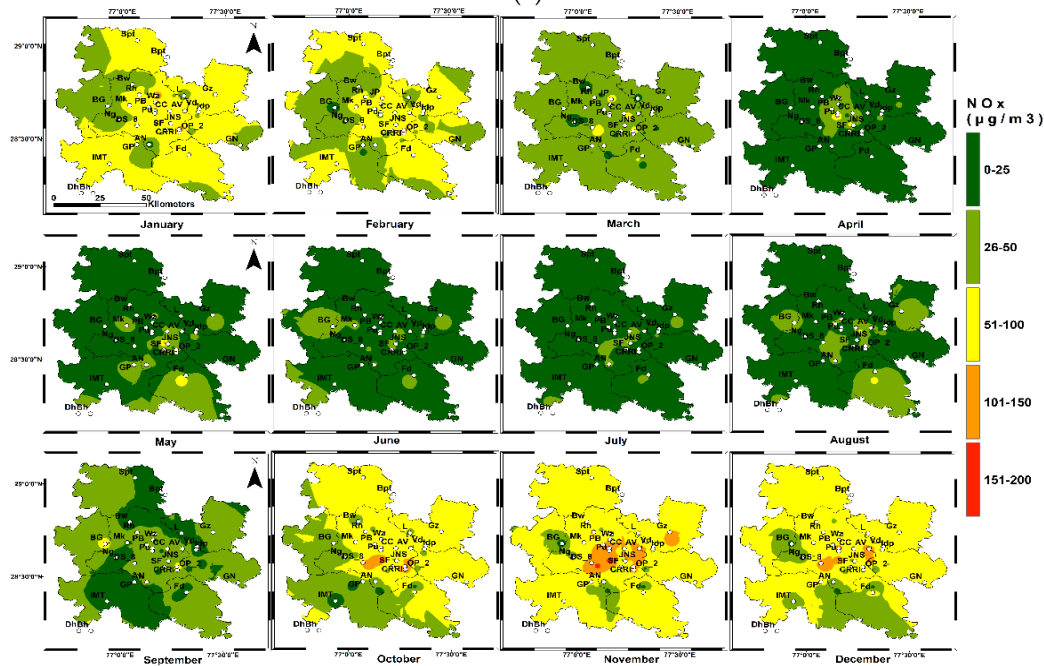
Figure 9. Map showing the month-wise spatial distribution of PM₁₀ over the study area (Delhi NCR) in (a) 2019, (b) 2020, and (c) 2021.

Relatively higher concentration and variability were seen during winter seasons and lower variability and concentration during summer (particularly in monsoon) (Figure 9 a–c). Among the studied locations of Delhi NCR, the most polluted sites in terms of PM₁₀ was found to be Dwarka Sector 8 ($294.7 \pm 7.1 \mu\text{g}/\text{m}^3$), followed by Wazirpur ($286.9 \pm 7.2 \mu\text{g}/\text{m}^3$), Sirifort ($282.5 \pm 6.5 \mu\text{g}/\text{m}^3$), Mundka ($281.2 \pm 7.9 \mu\text{g}/\text{m}^3$), and Anand Vihar ($273.2 \pm 7.7 \mu\text{g}/\text{m}^3$) in 2019. During this time, Loni ($265 \pm 8.8 \mu\text{g}/\text{m}^3$) was the most polluted site in Uttar Pradesh and Gwal Pahari and Gurugram ($189.5 \pm 6.2 \mu\text{g}/\text{m}^3$) in Haryana. In 2020, the most polluted sites were Loni ($231.63 \pm 7.7 \mu\text{g}/\text{m}^3$), Park 5-Greater Noida ($226.87 \pm 7.7 \mu\text{g}/\text{m}^3$), Bawana ($227.22 \pm 7.5 \mu\text{g}/\text{m}^3$), Jahangirpuri ($224.94 \pm 8.0 \mu\text{g}/\text{m}^3$), and Mundka ($224.66 \pm 7.4 \mu\text{g}/\text{m}^3$). During this time, Panipat ($206.16 \pm 5.7 \mu\text{g}/\text{m}^3$) was the most polluted in PM₁₀ levels. In 2021, the most polluted site was Chandni Chowk ($301.5 \pm 7.9 \mu\text{g}/\text{m}^3$), Anand Vihar ($274.4 \pm 7.8 \mu\text{g}/\text{m}^3$), Loni ($267.1 \pm 7.7 \mu\text{g}/\text{m}^3$), Wazirpur ($265.7 \pm 9.3 \mu\text{g}/\text{m}^3$, ten months average), Mundka ($260.4 \pm 7.4 \mu\text{g}/\text{m}^3$), and Dwarka Sector 8 ($250.6 \pm 7.2 \mu\text{g}/\text{m}^3$) in 2021. During this time, the new industrial town, Faridabad, was the most polluted in Haryana. The annual average PM₁₀ over Bhiwadi was found to be $224.3 \pm 5.0 \mu\text{g}/\text{m}^3$ in 2019, $191.8 \pm 6.1 \mu\text{g}/\text{m}^3$ in 2020, and $231.3 \pm 5.7 \mu\text{g}/\text{m}^3$ in 2021, which is much lesser than the average PM₁₀ concentration over most of the locations in Delhi and UP.

Like particulate matter, the spatial distribution of the monthly average NO_x level shows considerable variability (Figure 10a–c). Higher NO_x concentration with lesser variability was in winter seasons, and less concentration with relatively more variability in summer seasons over the study area. In 2019, the highest annual average NO_x concentration was seen at Anand Vihar ($126.98 \pm 3.6 \mu\text{g}/\text{m}^3$), followed by CRRM Mathura Road ($98.79 \pm 3.8 \mu\text{g}/\text{m}^3$), JN stadium ($84.3 \pm 2.9 \mu\text{g}/\text{m}^3$), IGI Airport ($81 \pm 3.1 \mu\text{g}/\text{m}^3$), and MCDN stadium ($79.6 \pm 2.9 \mu\text{g}/\text{m}^3$). In 2019, the highest NO_x concentration was over Indrapuram ($60.50 \pm 2.1 \mu\text{g}/\text{m}^3$) in UP and in Panipat ($62.17 \pm 3.5 \mu\text{g}/\text{m}^3$) in Haryana.



(a)



(b)

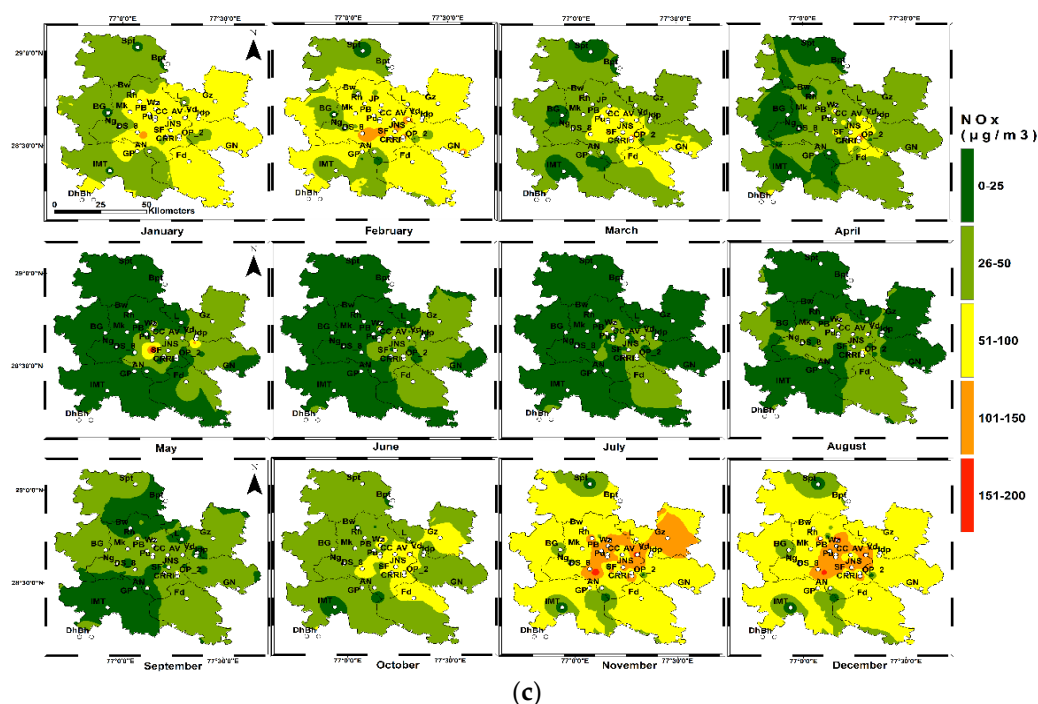
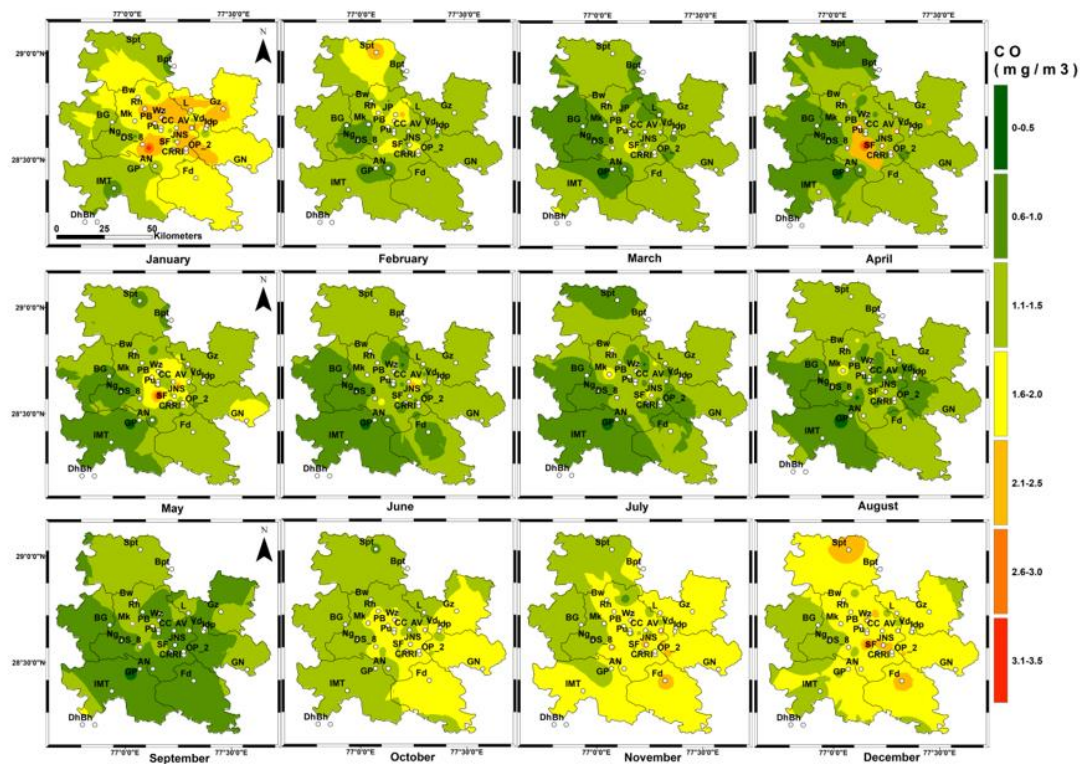


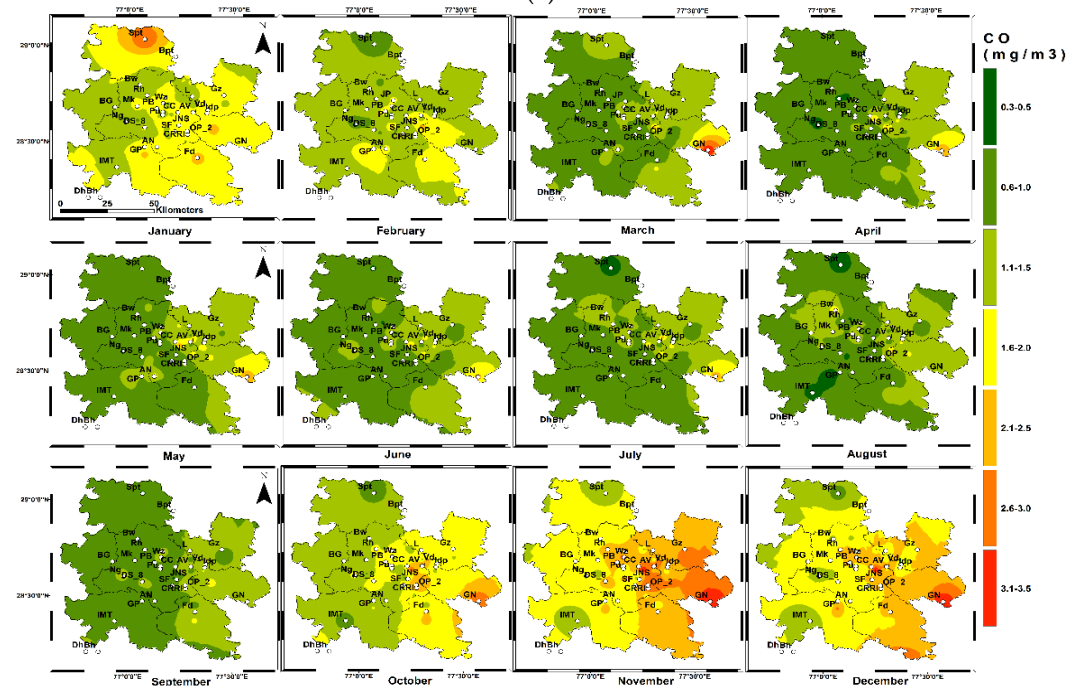
Figure 10. Map showing the month-wise spatial distribution of NO_x over the study area (Delhi NCR) in (a) 2019, (b) 2020, and (c) 2021. High-quality images can be retrieved from the previous version of the revised manuscript.

In 2020, the highest annual average NO_x concentration was seen at CRRI Mathura Road ($94.7 \pm 4.0 \mu\text{g}/\text{m}^3$), followed by Anand Vihar ($81.4 \pm 3.5 \mu\text{g}/\text{m}^3$), IGI Airport ($72.5 \pm 3.4 \mu\text{g}/\text{m}^3$), Jahangirpuri ($66.3 \pm 2.7 \mu\text{g}/\text{m}^3$), and MCDN stadium ($64.8 \pm 3.5 \mu\text{g}/\text{m}^3$). In 2021, the highest annual average NO_x concentration was seen at Anand Vihar ($123.1 \pm 3.9 \mu\text{g}/\text{m}^3$), followed by CRRI Mathura Road ($112.6 \pm 4.6 \mu\text{g}/\text{m}^3$), IGI Airport ($97.5 \pm 4.9 \mu\text{g}/\text{m}^3$), MCDN stadium ($81.1 \pm 3.2 \mu\text{g}/\text{m}^3$), and Pusa Road ($72 \pm 4.0 \mu\text{g}/\text{m}^3$). The annual average NO_x concentration over Bhiwadi was found to be $65.1 \pm 1.9 \mu\text{g}/\text{m}^3$ in 2019, $67.7 \pm 1.8 \mu\text{g}/\text{m}^3$ in 2020, and $75.2 \pm 2.5 \mu\text{g}/\text{m}^3$ in 2021, which is much lesser than the average NO_x concentration over most of the locations in Delhi.

Like other pollutants, a relatively higher concentration of CO was seen mostly in winter and a relatively lower concentration during summer (Figure 11 a–c). The highest annual average concentration was found over North Campus Delhi University ($2.22 \pm 0.07 \text{ mg}/\text{m}^3$), followed by Anand Vihar ($2.16 \pm 0.04 \text{ mg}/\text{m}^3$), JN stadium ($1.91 \pm 0.04 \text{ mg}/\text{m}^3$), Jahangirpuri ($1.92 \pm 0.03 \text{ mg}/\text{m}^3$), and Punjabi Bagh ($1.73 \pm 0.03 \text{ mg}/\text{m}^3$) in 2019.



(a)



(b)

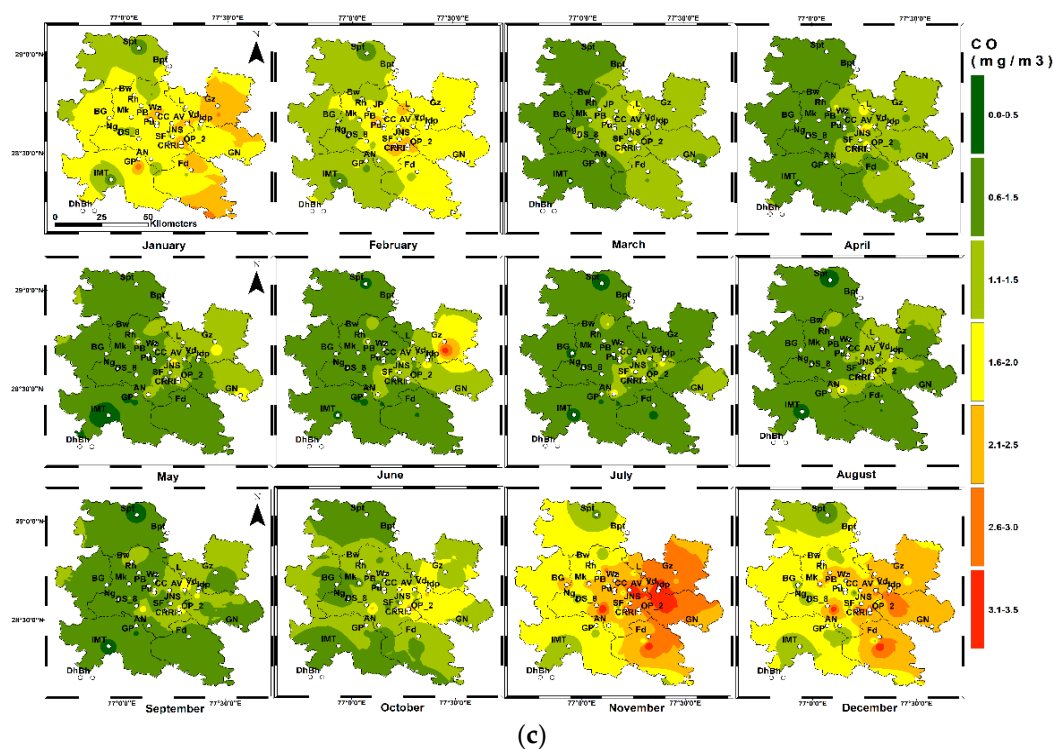


Figure 11. Map showing the month-wise spatial distribution of CO over the study area (Delhi NCR) in (a) 2019, (b) 2020, and (c) 2021. High-quality images can be retrieved from the previous version of the revised manuscript.

In 2020, the highest CO pollutants' concentration was over Park 3-Greater Noida ($2.320.03 \text{ mg/m}^3$), followed by Anand Vihar ($2.28 \pm 0.05 \text{ mg/m}^3$), ITO ($2.26 \pm 0.06 \text{ mg/m}^3$), Sector 1 Noida ($1.95 \pm 0.01 \text{ mg/m}^3$), and Wazirpur ($1.95 \pm 0.04 \text{ mg/m}^3$). However, in 2021, CRRI Mathura Road ($2.33 \pm 0.06 \text{ mg/m}^3$) was the most polluted site in terms of CO pollutants, followed by ITO ($2.21 \pm 0.07 \text{ mg/m}^3$), Anand Vihar ($2.17 \pm 0.03 \text{ mg/m}^3$), IGI Airport ($1.84 \pm 0.07 \text{ mg/m}^3$), and Sector 62 Noida ($1.95 \pm 0.06 \text{ mg/m}^3$). The average annual CO concentration over Bhiwadi was found to be $0.82 \pm 0.01 \text{ mg/m}^3$ in 2019, $0.96 \pm 0.02 \text{ mg/m}^3$ in 2020, and $0.95 \pm 0.34 \text{ mg/m}^3$ in 2021, which is much lesser than the average CO concentration over most of the locations in Delhi (Table 1).

The highest surface O_3 concentration was seen over Loni (55.16 ± 0.01 ten months average), followed by Baghpat/Bulandshahar ($52.0 \pm 1.13 \text{ } \mu\text{g/m}^3$), Najafgarh ($50.0 \pm 1.39 \text{ } \mu\text{g/m}^3$), Faridabad Sector 16A ($49.73 \pm 1.26 \text{ } \mu\text{g/m}^3$), and Sri Aurobindo Park ($48.8 \pm 1.49 \text{ } \mu\text{g/m}^3$) in 2019 over the study area. In 2020, the highest surface O_3 concentration was found over Sirifort ($69.58 \pm 2.01 \text{ } \mu\text{g/m}^3$), followed by Bahadurgarh ($65.0 \pm 1.01 \text{ } \mu\text{g/m}^3$), Dr. Karni Singh Shooting Range (DKSSR) ($65.7 \pm 1.31 \text{ } \mu\text{g/m}^3$), Sector 16A, Faridabad ($58.8 \pm 1.36 \text{ } \mu\text{g/m}^3$), and Bulandshahar ($57.1 \pm 1.08 \text{ } \mu\text{g/m}^3$). The highest pollutant sites in terms of the surface ozone concentration during 2021 were found to be Sector 16A, Faridabad ($68.88 \pm 1.96 \text{ } \mu\text{g/m}^3$), Rohtak ($53.46 \pm 1.48 \text{ } \mu\text{g/m}^3$), East Arjun Nagar ($52.9 \pm 1.77 \text{ } \mu\text{g/m}^3$), DKSSR ($52.6 \pm 1.20 \text{ } \mu\text{g/m}^3$), and Bulandshahar ($51.4 \pm 1.07 \text{ } \mu\text{g/m}^3$). In 2019, the average annual O_3 concentration over Bhiwadi was $28.65 \pm 0.59 \text{ } \mu\text{g/m}^3$. In 2020, it was $27.79 \pm 0.55 \text{ } \mu\text{g/m}^3$, and in 2021, it was $27.07 \pm 0.58 \text{ } \mu\text{g/m}^3$. These concentrations were significantly lower than the annual average surface ozone concentration measured in most locations in Delhi, Uttar Pradesh, and Haryana. (Table 1). Most of the locations with relatively higher or the highest pollutant concentration (particulate matters, NO_x , and SO_2) were found in industrial/residential sites in all the years considered (Figures 9–11). This trend clearly suggests a strong influence of industrial pollution on the air quality over Delhi NCR. Additionally, these already polluted areas became worse throughout the winter because

of additional pollutants and smoke from parali burning, fireworks, and unfavorable meteorological conditions.

In terms of PM_{2.5} distribution, Wazirpur (Delhi), Bahadurgarh (Haryana), and Loni (Ghaziabad) were the most polluted sites in 2019, 2020, and 2021, respectively. In terms of PM₁₀, Dwarka Sector 8 (Delhi) in 2019, Loni (Ghaziabad) in 2020, and Chandni Chowk (Delhi) were the most polluted sites. Anand Vihar, in 2019 and 2021, and CRRI Mathura road were the most polluted sites in terms of the average annual NO_x concentration. According to our findings, the location of Bhiwadi did not exhibit the highest levels of pollution in regard to both particulate matter and gaseous pollutants in 2021. This contrasts with the assertions made in the IQ Air report from 2022 [69].

4. Conclusions

The present study examined the temporal and spatial variability of seven pollutants (PM_{2.5}, PM₁₀, NO_x, CO, NH₃, SO₂, and O₃), over Delhi and the adjacent regions from 2019 to 2021. We have also analyzed the variability of the concentration of pollutants during the pre, lockdown, and post-lockdown periods of the year 2019, 2020, and 2021. We summarized the findings of the present work as follows:

- There was a significant temporal and spatial variability in the particulate matter and gaseous pollutants concentrations over the Delhi NCR regions. The highest pollutant concentration was during winter while the lowest was during the summer (least in monsoon), suggesting the strong influence of meteorology on the atmospheric pollutants' variability. Our estimates are in close agreement with other studies [70,71]. Among the three years, 2020 was the least polluted year compared to 2019 and 2021.
- There was a considerable reduction of more than 10% in terms of annual average PM_{2.5}, 15% in annual average PM₁₀ levels, and 10% in annual average NO_x level in 2020 compared to 2019 and 2021, respectively, over Delhi.
- Our findings suggest that the lockdown's impact in Delhi NCR was not as significant as earlier workers had claimed via a direct comparison of the pre- and lockdown year. By comparing air pollution statistics from the year before (2019) and the year after the lockdown (2021), as well as the rainfall estimates, it was found that the pollutants were significantly reduced only during the first two phases of the lockdown. In due consideration, our findings imply that the concentration of particulate matter and gaseous pollutants (except surface ozone) fell only 30% during the first stages of the lockdown due to COVID-19 restrictions. However, even as other pollutants decreased, the concentration of ozone at the surface increased.
- The concentration of atmospheric pollutants was already lower (20% to 30%) due to favorable meteorological conditions for pollution dispersion before the lockdown started in 2020. Furthermore, a significantly higher amount of rainfall in March 2020 (>500% more than 2019 and 2021), May 2020 (80% more rainfall compared to 2019), and a greater number of rainy days in these two months considerably reduced the pollutant concentration over the study area. Our findings are supported by a recently published report by the Commission for Air Quality Management on 31 July 2023 [72]. According to this report, the average value of particulate matter from January to July 2023, (which was not a lockdown year) almost exactly matches with the average value of particulate matter in 2020 (lockdown year) during the same time period.
- In terms of PM_{2.5} mass concentration, Wazirpur in Delhi, Bahadurgarh in Haryana, and Loni in Ghaziabad were the most polluted sites in 2019, 2020, and 2021, respectively. In terms of PM₁₀, Dwarka Sector 8 in Delhi, Loni in Ghaziabad, and Chandni Chowk in Delhi were the most polluted sites in 2019, 2020, and 2021, respectively.

- The most polluted sites in terms of particulate matter and gaseous pollutants distribution were in Delhi only in all three years (2019–2021).
- Bhiwadi was not the most polluted site both in terms of particulate matter and gaseous pollutants in 2021, which is contrary to what was recently claimed by IQ Air report, 2022.

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