COVID-19 and Air Pollution in Indian Cities: World's Most Polluted Cities

Sonal Kumari, Anita Lakhani, K. Maharaj Kumari*

Department of Chemistry, Faculty of Science, Dayalbagh Educational Institute, Dayalbagh, Agra 282110, India

ABSTRACT

In the present study, pollutants levels from 24th March–31st May in 2020 were compared with the same time period in 2019 to estimate the impact of lockdown on air pollutants levels in 39 different cities of India (including 10 Indian cities considered among the world's 20 most polluted cities). Data for air pollutants was obtained from the Central Pollution Control Board (CPCB) which was statistically analyzed. Tropospheric NO₂ column retrieved from Ozone Monitoring Instrument (OMI) were compared between 2019 and 2020 to compare the NO₂ levels. Impact of lockdown measures on Ghaziabad which is the world's most polluted city and Patiala which showed maximum reduction during the lockdown period in the present study was studied in detail. After the implementation of lockdown measures, air pollution decreased but with substantial variation among pollutants. The most significant reduction was observed for nitrogen dioxide (NO₂) (3–79%) and carbon monoxide (CO) (2–61%), pollutants which are mainly related to traffic emissions. Ozone (O₃) showed a mixed trend with increasing levels at some cities which may be attributed to lower titration of O₃ by NO. Maximum reduction observed in PM₁₀ and PM_{2.5} was 58 and 57%, respectively during the lockdown period in 2020 as compared to the previous year. Air quality of the cities also improved in 2020. During the lockdown period in 2020, AQI of only 15% of cities was in the 'Unhealthy' category (151–200) while in 2019, 56% of cities were in the 'Unhealthy' category. In Ghaziabad and Patiala all the pollutants showed significant reduction after lockdown implementation except O₃. Diurnal patterns of PM₁₀, PM_{2.5}, CO and NO₂ showed lower values during lockdown period in 2020 with less distinct bimodal patterns as compared to 2019. The present study provides evidence that widespread implementation of air pollution measures can result in immediate air quality benefits.

Keywords: Lockdown; World's most polluted cities; India; Air pollution reduction; AQI.

INTRODUCTION

In late December 2019, novel infectious coronavirus disease (COVID-19) was identified in Wuhan, China which was later on confirmed to be transmitted human to human through respiratory droplets (WHO, 2020). On 30th January, the first confirmed case of COVID-19 in India was found. As of 23rd March 2020, the number of COVID-19 cases increased to 499 in India (<https://www.worldometers.info/coronavirus/country/india/>) which was still very less than many other countries like US, Italy and China. India being the world's second most populated country with many densely populated cities had chances of spread of the virus at an accelerating rate. To prevent the spread of the COVID-19, the government of India imposed nationwide lockdown from 24th March to 31st May. As a result, all non-essential services including schools, colleges, religious worship places, government offices,

modes of transport (trains, flights and cabs), public utilities and industrial activities were closed. Citizens were advised to remain at home and to maintain social distancing.

On the basis of annual average of PM_{2.5} in 2019 IQAir identified most polluted cities in the world with 13 Indian cities among the top 20 polluted cities (IQAir Report, 2019) (Table 1). Only 1% of the Indian population is exposed to less than the global WHO guideline level of annual mean PM_{2.5} (10 µg m⁻³) (IEA, 2016). Major sources of PM_{2.5} in India are anthropogenic activities like fossil fuel combustion, transportation, industrial emission (Venkataraman *et al.*, 2018). High levels of pollutants impose significant health issues (Chowdhury and Dey, 2016). In 2017, 1.24 million deaths in India (12.5% of the total deaths) were attributable to air pollution (Balakrishnan *et al.*, 2019). Therefore, efficient monitoring of air quality at the city level would help in understanding the major contributing sources and the policy making for achieving better air quality. With the implementation of lockdown measures in India, a sudden break on all anthropogenic activities (mainly transportation and industrial activities) improved the air quality. Delhi, the world's most polluted capital city witnessed blue sky with about 49% reduction in air quality index (AQI) during the

* Corresponding author.

Tel.: 91-562-280154; Fax: 91-562-2801226

E-mail address: maharajkumari.k@rediffmail.com

Table 1. PM_{2.5} annual average in 2019 reported by IQAir and AQI of cities and name and concentration of AQI species during 24th March–31st May 2019–2020 in 39 cities. 24-h average PM_{2.5} (μg m⁻³), 8-h average O₃ (ppb), 1-h average NO₂ (ppb) levels.

State	City (Rank according to IQAir Report 2019)	Latitude (°N)	Longitude (°E)	PM _{2.5} Annual Average in 2019 (μg m ⁻³)	AQI (24 th Mar–31 st May 2019)	AQI Specie and its mean level (2019)	AQI (24 th Mar–31 st May 2020)	AQI Specie and its mean level (2020)
Punjab	Amritsar (147)	31.62	74.87	47.2	144	PM _{2.5} (53)	80	PM _{2.5} (26)
	Ludhiana (127)	30.9	75.80	49.3	137	PM _{2.5} (50)	110	NO ₂ (146)
	Patiala (310)	30.34	76.37	35.2	152	PM _{2.5} (57)	78	PM _{2.5} (25)
Rajasthan	Udaipur	24.58	73.70	-	99	PM _{2.5} (35)	87	PM _{2.5} (29)
	Bhiwadi (20)	28.20	76.83	83.4	178	PM _{2.5} (107)	147	PM _{2.5} (54)
	Jaipur (120)	26.90	75.83	50.5	122	PM _{2.5} (44)	84	O ₃ (65)
Haryana	Jodhpur (29)	26.29	73.03	77.2	177	PM _{2.5} (106)	151	PM _{2.5} (56)
	Gurugram (7)	28.42	77.15	93.1	164	PM _{2.5} (80)	124	PM _{2.5} (45)
	Jind (17)	29.32	76.30	85.4	158	PM _{2.5} (70)	126	O ₃ (78)
Delhi	Faridabad (18)	28.41	77.32	85	190	O ₃ (101)	164	O ₃ (91)
	Rohtak (63)	28.87	76.62	59.7	166	PM _{2.5} (85)	127	PM _{2.5} (46)
	Delhi (5)	28.61	76.98	98.6	166	O ₃ (92)	137	PM _{2.5} (51)
Assam	Guwahati	26.18	91.78	-	127	PM _{2.5} (46)	127	PM _{2.5} (46)
Madhya Pradesh	Bhopal (174)	23.22	77.19	44.6	168	PM _{2.5} (89)	115	O ₃ (75)
	Ujjain (187)	23.18	75.77	43.4	151	O ₃ (86)	105	PM _{2.5} (37)
Uttar Pradesh	Agra (80)	27.19	78.00	57.2	158	PM _{2.5} (69)	132	PM _{2.5} (48)
	Ghaziabad (1)	28.66	77.37	110.2	172	PM _{2.5} (97)	147	O ₃ (84)
	Noida (6)	28.63	77.36	97.7	177	O ₃ (96)	129	PM _{2.5} (47)
	Bulandshahr (13)	28.41	77.83	89.4	166	O ₃ (92)	161	O ₃ (90)
	Kanpur (132)	26.47	80.32	48.5	156	PM _{2.5} (66)	129	PM _{2.5} (47)
	Lucknow (11)	26.85	80.95	90.3	161	PM _{2.5} (75)	110	PM _{2.5} (39)
	Greater Noida (9)	28.48	77.48	91.3	169	O ₃ (93)	136	O ₃ (81)
	Varanasi	25.32	82.97	-	192	O ₃ (102)	159	O ₃ (89)
	Hyderabad (249)	17.46	78.33	39	99	PM _{2.5} (35)	74	PM _{2.5} (23)
Andhra Pradesh	Tirupati (560)	13.63	79.42	26.4	72	PM _{2.5} (22)	68	PM _{2.5} (20)
	Visakhapatnam (180)	17.69	83.22	44	97	PM _{2.5} (34)	66	PM _{2.5} (19)
Gujarat	Ahmedabad (69)	22.99	72.60	59	162	PM _{2.5} (76)	115	O ₃ (75)
Maharashtra	Mumbai (169)	19.06	72.83	45.3	68	PM _{2.5} (20)	114	NO ₂ (172)
	Nagpur (146)	21.14	79.10	47.2	129	O ₃ (79)	100	NO ₂ (100)
	Pune (299)	18.49	73.82	35.7	142	PM _{2.5} (52)	84	PM _{2.5} (28)
Tamil Nadu	Chennai (320)	13.18	80.27	34.6	137	PM _{2.5} (50)	87	PM _{2.5} (29)
Kerala	Thiruvananthapuram (496)	8.51	76.95	27.9	80	PM _{2.5} (26)	66	PM _{2.5} (19)
Jharkhand	Jorapokhar	23.71	86.41	-	150	O ₃ (85)	147	O ₃ (84)
Bihar	Gaya (65)	24.79	85.00	59.4	155	PM _{2.5} (64)	154	O ₃ (87)
	Patna (22)	25.59	85.14	82.1	152	PM _{2.5} (57)	156	PM _{2.5} (66)
West Bengal	Howrah (91)	22.57	88.30	55.9	122	PM _{2.5} (44)	72	PM _{2.5} (22)
	Kolkata (61)	22.54	88.34	59.8	105	PM _{2.5} (37)	147	O ₃ (84)
Karnataka	Bengaluru (361)	12.92	77.61	32.6	153	PM _{2.5} (60)	91	NO ₂ (92)
	Kalaburagi	17.32	76.82	-	115	PM _{2.5} (41)	97	PM _{2.5} (34)

lockdown period (<https://www.thehindu.com/news/cities/Delhi/coronavirus-lockdown-lifts-delhis-march-air-quality-to-5-year-high/article31252221.ece>).

Recent studies reported on short term exposure to air pollution and COVID-19 infection have found significant positive association of air pollutants with COVID-19 confirmed cases (Suhaimi *et al.*, 2020; Zhu *et al.*, 2020). Suhaimi *et al.* (2020) found significant positive association between COVID-19 cases and PM₁₀, PM_{2.5}, CO, NO₂ and

SO₂ pollutants in Malaysia however, Zhu *et al.* (2020) observed positive association between COVID-19 cases and PM₁₀, PM_{2.5}, NO₂ and O₃ pollutants in China. Similar studies reported in China, Singapore, New York, Norway, Italy, United States, Spain, Turkey and Indonesia have analyzed the association between climate indicators (temperature, rainfall, humidity, air quality) and COVID-19 and found a significant association between them (Bashir *et al.*, 2020; Gupta *et al.*, 2020; Méndez-Arriaga, 2020; Menebo, 2020;

Pani *et al.*, 2020; Sahin, 2020; Tobias *et al.*, 2020; Tosepu *et al.*, 2020; Xu *et al.*, 2020; Yao *et al.*, 2020). Temperature which is considered as an important parameter in development, prevention and control of an epidemic showed different correlation in different countries (Tobías and Molina, 2020). A significant positive correlation of COVID-19 cases with temperature is reported over Singapore, New York, Norway, Turkey and Indonesia highlighting the importance of temperature in COVID-19 epidemic whereas a negative correlation is reported over Mexico while no correlation between COVID-19 cases and temperature is observed in China.

Some studies have been reported in India assessing the impact of COVID-19 lockdown on air quality but for limited number of cities and for short time period (Chauhan and Singh, 2020 (2 cities, Dec 2019–March 2020); Jain and Sharma, 2020 (5 cities, 10th March–6th April 2019–2020); Kotnala *et al.*, 2020 (1 city, January–March 2020); Kumar, 2020 (6 cities, March–May 2020); Kumar *et al.*, 2020 (5 cities, March–April 2015–2020); Mahato *et al.*, 2020 (1 city, 3rd March–14th April 2020); Navinya *et al.*, 2020 (17 cities, 1st February–3rd May 2019–2020); Sharma *et al.*, 2020 (22 cities, 16th March–14th April 2017–2020); Shehzad *et al.*, 2020 (2 cities, 1st January–20th April 2019–2020); Singh and Chauhan, 2020 (5 cities, March 2019–2020); Srivastava *et al.*, 2020 (2 cities, 1st–20th February and 24th March–14th April 2020)). The present study was planned to describe the changes in air pollutants levels during the complete lockdown period (24th March–31st May) in 39 different cities of India (including 10 Indian cities considered among the world's 20 most polluted cities) by using ground-based and satellite observations.

METHODOLOGY

Data Sources

Data for particulate matter PM₁₀ (particulate matter with diameter $\leq 10 \mu\text{m}$), PM_{2.5} (particulate matter with diameter $\leq 2.5 \mu\text{m}$), nitrogen dioxide (NO₂), ozone (O₃) sulfur dioxide (SO₂) and carbon monoxide (CO) monitored by Central Pollution Control Board (CPCB) have been analyzed from 24th March–31st May in 2020 and compared with the same time period in 2019 for 39 cities of India. For Ghaziabad and Patiala a comparison of before (1st February–23rd March) and during (24th March–31st May) lockdown period in 2019 and 2020 is done. Ten India cities (Ghaziabad (rank 1), Delhi (5), Noida (6), Gurugram (7), Greater Noida (9), Lucknow (11), Bulandshahr (13), Jind (17), Faridabad (18), Bhiwadi (20)) considered in the world's 20 most polluted cities and 29 other Indian cities were analyzed (IQAir Report, 2019). Detailed information about these air quality monitoring stations is given in Table 1.

Mean concentrations of the pollutants for the lockdown period (24th March–31st May) in 2019 and 2020 were calculated to assess the variation between both periods having similar meteorology. Independent samples t-test between the mean concentration of all pollutants in 2019 and 2020 at 0.05 significance level was carried out using Statistical Package for Social Sciences (SPSS) software. Most of the cities

showed statistical significant difference.

Air Quality Index (AQI)

Air Quality Index (AQI) is a numerical index used to indicate the air quality of a region. AQI ranges in value from 0–500 with greater AQI value suggesting deteriorated air quality and lower AQI (< 100) indicating satisfactory air quality in a region. In the present study, AQI values were derived from 24 h average PM₁₀ and PM_{2.5}, 8 h average CO and O₃, 1 h average NO₂ and SO₂ levels during lockdown period in 2019 and 2020 using the U.S.EPA standard formula (U.S. EPA, 1999; Kumar and Goyal, 2011). The overall AQI considered for a city was the maximum AQI observed for that city.

Tropospheric NO₂ Column

Ozone Monitoring Instrument (OMI) daily tropospheric nitrogen dioxide column (OMNO2d version 3) at $0.25^\circ \times 0.25^\circ$ resolution is used in the study. OMI onboard Aura satellite detects the backscattered solar radiation (wavelength range of 270–500 nm) from the Earth and its atmosphere with a spatial resolution of $13 \times 24 \text{ km}$ (Krotkov *et al.*, 2017).

RESULTS AND DISCUSSION

AQI Values in Different Cities during the Lockdown Period

AQI values were determined for the lockdown period in 2019 and 2020 (24th March–31st May) (Fig. 1). In 2019, 56% of cities were in the 'Unhealthy' category (151–200) and only 16 and 28% cities lied in the 'Moderate' (51–100) and the 'Unhealthy for sensitive group' category (101–150) (Table 1). In 2020, air quality of most of the cities improved with AQI of 36% of cities lying under the 'Moderate' category and 49% of cities in the 'Unhealthy for sensitive group' category. The largest drop in AQI values was observed in Patiala (AQI improved by 74). A relatively higher number of cities in Indo-Gangetic Plain showed lower AQI than cities in other regions of India. Among the 10 most polluted Indian cities AQI in 7 cities reduced to 101–150 range from 151–200 range. This suggests that air quality has improved significantly during the lockdown period in 2020. During 2019 PM_{2.5} was the dominant pollutant in most of the cities (30 cities), however with reduction in AQI in 2020 the dominant species shifted to O₃ and NO₂ in some of the cities. For cities lying in the central region (Bhopal, Ahmedabad, Gaya, Kolkata, Jaipur, Ghaziabad and Jind) the dominant pollutant shifted to O₃ however in some cities (Mumbai, Ludhiana, Bengaluru, Nagpur) it shifted to NO₂. In 2019 dominance of PM_{2.5} in most of the cities suggests influence on air quality by anthropogenic activities such as fossil fuel combustion in road transport, industries and power generation. With reduction in PM_{2.5} levels during lockdown period in 2020 the emergence of O₃ as the dominant pollutant suggests influence on air quality by secondary pollutants in some of the cities.

Variation in Pollutants Levels during the Lockdown Period in 2019 and 2020

Further, average concentrations of pollutants in all 39 cities

Fig. 1. AQI of 39 cities of India during lockdown period (24th March–31st May) in 2019 and 2020.

were compared during the lockdown period in 2019 and 2020 to determine the impact of the lockdown measures on air pollution levels (Fig. 2). Statistically significant differences in pollutants mean levels during the lockdown period in 2019 and 2020 were observed at 0.05 significance level.

During the lockdown period in 2020, all cities showed drop in PM_{10} levels (except Guwahati and Jorapokhar) with an overall reduction of 44% as compared to 2019. PM_{10} levels decreased by 8% (Kalaburagi) to 58% (Patiala) in 2020 as compared to 2019. Among the 10 most polluted cities of India, Gurugram showed maximum reduction in PM_{10} levels (56%). Similar to PM_{10} , $PM_{2.5}$ levels also reduced during the lockdown period in 2020. Average $PM_{2.5}$ levels over all the cities decreased from 63.6 to $39.6 \mu g m^{-3}$ (38% reduction). $PM_{2.5}$ levels showed reduction in all cities ranging from 1% (Guwahati) to 57% (Patiala) except at Mumbai and Patna. Top 10 most polluted cities showed reduction in the range 33 to 51%. Higher reduction observed in PM_{10} levels than $PM_{2.5}$ can be due to the greater contribution of PM_{10} from anthropogenic activities (Klimont *et al.*, 2017). In China, a reduction by 20–30% in $PM_{2.5}$ levels during February 2020 (lockdown period) in comparison to monthly averages of February in 2017–2019 based on satellite observation was found (CAMS, 2020). Cities situated in the northern region (mainly in Uttar Pradesh) showed higher reduction in PM_{10} and $PM_{2.5}$ levels. Uttar Pradesh contributes the highest share in $PM_{2.5}$ emission as compared to other states of India (Purohit *et al.*, 2019). The number of cities with daily 24 h mean PM_{10} and $PM_{2.5}$ concentrations exceeding the National Ambient Air Quality Standards (NAAQS: $PM_{10} > 100 \mu g m^{-3}$ and $PM_{2.5} > 60 \mu g m^{-3}$) during the lockdown period in 2019 and 2020 were compared (NAAQS, 2009). 96% of cities in 2019 exceeded the NAAQS limit for PM_{10} while in 2020, only 75% of cities violated the limit. Similarly, $PM_{2.5}$ levels in 2019 were exceeded by 80% of cities however, in 2020, only 53% of cities exceeded the limit during the lockdown period.

NO_2 is a primary pollutant which is emitted mainly from

vehicular emission and industrial activities (Sahu *et al.*, 2012). The number of registered vehicles in India in 2016 was around 230 million which has increased 4 times from 2001 (<http://mospi.nic.in/statistical-year-book-india/2018/189>). This shows the dramatic increase in the vehicular population in India. With the implementation of lockdown measures in India, all transportation facilities and industrial activities were stopped immediately. As these activities have a direct effect on NO_2 levels, an immediate reduction in NO_2 is observed. During the lockdown period in 2020, NO_2 reduced by 3% (Hyderabad) to 79% (Patiala) in India (overall mean reduction 42%) (except at Agra, Jorapokhar, Ludhiana, Noida, Thiruvananthapuram and Patna). Similarly, reduction in NO_2 levels in Wuhan ($22.8 \mu g m^{-3}$) and China ($12.9 \mu g m^{-3}$) was also observed during the lockdown period (Zambrano-Monserrate *et al.*, 2020). To further substantiate the influence of lockdown measures on NO_2 levels, satellite-retrieved tropospheric NO_2 column was also analyzed for the lockdown period in 2019 and 2020 (Fig. 3) and a reduction in NO_2 levels during 2020 was found. Among 39 cities considered in the present study, maximum reduction by 54% in tropospheric NO_2 column over Patiala city (similar to ground observation) was observed during the lockdown period in 2020 as compared to 2019. NASA (National Aeronautics and Space Administration) and ESA (European Space Agency) using satellite observations have also reported reduction in NO_2 emissions in Wuhan, Spain, Italy and USA by up to 30% during the lockdown period (Muhammad *et al.*, 2020).

Tropospheric O_3 is a secondary air pollutant which is photo-chemically formed from its precursors CO, nitrogen oxides and volatile organic compounds (Kumari *et al.*, 2018). O_3 levels at a site not only depend on precursor's concentration but also on meteorological parameters. Sharma *et al.* (2020) found that meteorological parameters in India during the lockdown period in 2020 were similar to the analysis period in the previous years. This suggests that O_3 levels were mainly influenced by precursor's concentration during the

lockdown period in 2020. O₃ levels in most of the cities lying in the northern and central India were observed to be increasing (1–27.7 ppb range) during the lockdown period in 2020. This may be attributed by a decrease in NO_x levels in VOCs sensitive environment as cities in the northern and

central regions are VOC-sensitive (Sharma *et al.*, 2016). The other reasons may be reduction in NO titration of O₃ and reduced particulate matter levels as observed by similar study during the lockdown period (Tobias *et al.*, 2020). However, other cities showed reduction in O₃ levels during the lockdown

Fig. 2. Mean concentrations of PM₁₀, PM_{2.5}, NO₂, O₃, CO and SO₂ during 24th March–31st May in 2019 and 2020 (lockdown period) (cities not showing statistical difference in mean values between 2019 and 2020 at 0.05 significance level are underlined).

Fig. 3. Tropospheric NO₂ column over India during lockdown period in 2019 and 2020.

period (range 2 to 89 %). Among the 10 most polluted cities, four cities showed higher levels in 2020 as compared to 2019 with highest increase observed at Jind (47%).

CO is one of the major air pollutants released from biomass burning and incomplete combustion of fossil fuels (Hollaway *et al.*, 2000). Similar to NO₂, CO levels also decreased (range 2–61%; overall mean reduction 28%) during the lockdown period in 2020. However, in some of the cities (Delhi, Bhopal, Agra, Greater Noida, Patna, Tirupati, Pune, Kolkata, Noida and Jind) increase in CO levels during 2020 in comparison to 2019 was observed. Reduction in CO levels may be attributed to the restrictions imposed on transportation facilities during the lockdown period in 2020.

SO₂ also showed a mixed variation with reduction in most of the cities (range 3–71%; overall mean reduction 40%) and increase at some sites (Hyderabad, Kanpur, Varanasi, Jorapokhar, Thiruvananthapuram, Mumbai, Bengaluru, Ujjain, Gaya, Lucknow, Agra, Bhopal and Jind). In India, 82% of total SO₂ emission originates from the industrial sector and thermal power plants (Purohit *et al.*, 2019), however during the lockdown period in 2020 no restrictions were enforced on thermal power plants. Therefore, a decreasing trend in

SO₂ levels in all cities was not observed.

Similar to the present study reduction in PM₁₀, PM_{2.5}, NO₂, CO and SO₂ levels and a significant enhancement in O₃ is observed at Iran, China, Kazakhstan, Singapore, Morocco, Brazil, Malaysia and Spain (Table 2) (Broomandi *et al.*, 2020; Chen *et al.*, 2020; Kerimray *et al.*, 2020; Li and Tartarini, 2020; Otmani *et al.*, 2020; Siciliano *et al.*, 2020; Suhaimi *et al.*, 2020; Tobias *et al.*, 2020).

Ghaziabad: World's Most Polluted City

According to annual PM_{2.5} levels, Ghaziabad (annual PM_{2.5} mean 110.2 $\mu\text{g m}^{-3}$) was found to be the world's most polluted city in 2019 (IQAir Report, 2019), therefore an in-depth analysis of the impact of lockdown measures on pollutants levels was carried out there (Fig. 4). Ghaziabad is an industrial hub of India and comes in the part of National Capital Region (NCR) of Delhi. During lockdown period in 2020, average levels of PM₁₀ (57%), PM_{2.5} (48%), CO (41%), SO₂ (46%), O₃ (6%) and NO₂ (59%) showed reduction in comparison to 2019 (Table 3). A significant difference in all pollutants levels during the lockdown period in 2019 and 2020 at $p < 0.05$ was observed.

The time series plot of PM₁₀, PM_{2.5}, CO and NO₂ was similar in I period (1st February–23rd March) in both years while O₃ showed higher values in 2020 as compared to 2019. SO₂ values in 2020 were comparatively lower than 2019 in I period. With the implementation of lockdown measures from 24th March 2020, a sudden drop in all pollutants levels

was observed. During II period (24th March–31st May), PM₁₀, PM_{2.5}, CO and NO₂ levels in 2020 were lower than 2019 however, O₃ and SO₂ showed some comparable values.

Fig. 5 show the average diurnal patterns of PM₁₀, PM_{2.5}, O₃, CO, NO₂ and SO₂ before (1st February–23rd March) and during lockdown period (24th March–31st May) in 2019 and

Table 2. Percentage change in air pollutants levels in other countries during their lockdown period. – denotes reduction and + denotes increase in pollutant level.

City, Country	Study period	Percentage change	Reference
Tehran, Iran	21 st March–21 April 2019–2020	PM ₁₀ –11%; PM _{2.5} +10%; NO ₂ –13%; CO –13%; SO ₂ –12%; O ₃ +3%	Broomandi <i>et al.</i> (2020)
China (366 urban areas)	January–April 2017–2020	PM ₁₀ –15%; PM _{2.5} –14%; NO ₂ –16%; CO –12%; SO ₂ –12%; O ₃ +9%	Chen <i>et al.</i> (2020)
Almaty, Kazakhstan	19 th March–14 th April 2018–2020	PM _{2.5} –21%; NO ₂ –35%; CO –49%; SO ₂ +7%; O ₃ +15%	Kerimray <i>et al.</i> (2020)
Singapore (64 stations)	7 th April–11 th May 2016–2020	PM ₁₀ –23%; PM _{2.5} –29%; NO ₂ –54%; CO –6%; SO ₂ –52%; O ₃ +18%	Li and Tartarini, (2020)
Sale, Morocco	11 th March–2 nd April 2020	PM ₁₀ –75%; NO ₂ –96%; SO ₂ –49%	Otmani <i>et al.</i> (2020)
Iraja and Bangu, Brazil	1 st March–16 th April 2020	O ₃ +12.9, +6.3%, NO _x –46.1, –24.4%	Siciliano <i>et al.</i> (2020)
Kuala Lumpur (Klang Valley), Malaysia	11 th March–21 st April 2018–2020	PM _{2.5} –17 to –36%; NO ₂ –49 to –68%; CO –21 to –48%; SO ₂ –6 to –26%	Suhaimi <i>et al.</i> (2020)
Barcelona, Spain	16 th February–30 th March 2020	PM ₁₀ –28 to –31%; NO ₂ –47 to –51%; SO ₂ –19 to +2%; O ₃ +28 to +58%	Tobias <i>et al.</i> (2020)

Fig. 4. Time series of hourly average PM₁₀, PM_{2.5}, CO, O₃, NO₂ and SO₂ levels during 1st February–31st May 2019 and 2020 in Ghaziabad (dotted line show starting of lockdown period).

Table 3. Mean concentrations of PM₁₀, PM_{2.5}, CO, O₃, NO₂ and SO₂ before (1st February–23rd March) and during lockdown period (24th March–31st May) in 2019 and 2020 in Ghaziabad.

Pollutant (unit)	2019 I (1 st Feb–23 rd Mar 2019)	2019 II (24 th Mar–31 st May 2019)	2020 I (1 st Feb–23 rd Mar 2020)	2020 II (24 th Mar–31 st May 2020)
PM ₁₀ (μg m ⁻³)	205.4 ± 104.4	297.1 ± 135.1	210.9 ± 112.9	128.1 ± 76.3
PM _{2.5} (μg m ⁻³)	117.7 ± 73.7	97.1 ± 61.1	113.9 ± 71.7	50.5 ± 37.2
CO (ppb)	1146.8 ± 785.2	1176.2 ± 932.4	1068.9 ± 739.9	695.4 ± 278.4
O ₃ (ppb)	9.8 ± 7.7	25.5 ± 20.8	17.9 ± 15.8	23.9 ± 19.8
NO ₂ (ppb)	37.9 ± 11.2	36.3 ± 16.2	31.6 ± 12.4	14.7 ± 6.4
SO ₂ (ppb)	8.2 ± 6.2	12.5 ± 10.7	5.2 ± 6	6.7 ± 8.7

Fig. 5. Average diurnal variation of PM₁₀, PM_{2.5}, CO, O₃, NO₂ and SO₂ during 1st February–23rd March (I) and 24th March–31st May (II) in 2019 and 2020 in Ghaziabad.

2020 at Ghaziabad. The diurnal patterns of PM₁₀, PM_{2.5}, CO and NO₂ were characterized by a bimodal pattern with morning and evening peaks. The morning peak of these pollutants was observed at around 07:00–10:00 h and the evening peak at around 22:00 h. These peaks correspond to peak traffic emission hours. The diurnal pattern of ozone was characterized by minimum value in early morning (07:00 h) and maximum value during afternoon (~14:00 h) due to photochemical formation.

On comparing the diurnal patterns of PM₁₀, PM_{2.5}, CO and NO₂ during I period (1st February–23rd March) in 2019 and 2020, similar patterns of PM₁₀, PM_{2.5} and CO were observed however, NO₂ showed comparatively lower values in 2020. Maximum difference observed in PM₁₀, PM_{2.5}, CO and NO₂ diurnal values was 49.1 μg m⁻³, 31.7 μg m⁻³, 446.4 ppb and 17.4 ppb, respectively. During the II period (24th

March–31st May), a very large variation in values of PM₁₀, PM_{2.5}, CO and NO₂ values was observed. PM₁₀, PM_{2.5}, CO and NO₂ diurnal values were 225.8 μg m⁻³, 69.5 μg m⁻³, 1094.6 ppb and 37.3 ppb, respectively lower in 2020 (during the lockdown period) than 2019. Another significant difference in the diurnal pattern of PM₁₀, PM_{2.5}, CO and NO₂ during II period was the reduction in the amplitude of the pattern. The bimodal pattern of these pollutants was less distinct in 2020 II period as compared to other periods. The amplitudes of PM₁₀, PM_{2.5}, CO and NO₂ were 61, 50, 68 and 77%, respectively lower in II period in 2020 as compared to 2019. This may be attributed to restrictions imposed on transportation as vehicular emission is an important factor responsible for the bimodal pattern of these pollutants. On the other hand, secondary pollutant O₃ showed higher variation in 2020 during I period and similar pattern in both years

during II period. The diurnal pattern of O_3 depends on the rate of photochemical generation, meteorological parameters: temperature, solar radiation, relative humidity, wind speed, wind direction, planetary boundary layer height and rate of deposition (Kumari et al., 2020). Averaged diurnal variation of SO_2 does not show a distinct pattern. Higher diurnal values of SO_2 in 2019 during both periods than 2020 were observed.

Patiala: City with Maximum Reduction in Pollution Level

In the present study, Patiala city showed maximum reduction in pollutants levels during the lockdown period in 2020, therefore a detailed analysis of pollutants level was also carried out at Patiala. Patiala is an agriculture-based city situated in the northern Indo-Gangetic Plain. During the

lockdown period in 2020, all pollutants showed statistical significant reduction. Average levels of PM_{10} (58%), $PM_{2.5}$ (57%), CO (61%), SO_2 (13%) and NO_2 (79%) showed reduction in lockdown period in 2020 (II) however, O_3 showed an increase by 2% in comparison to 2019 (II) (Table 4). Mean pollutants levels at Patiala were comparatively lower than Ghaziabad during the study period however, comparatively higher reduction during the lockdown period was observed at Patiala.

Hourly average PM_{10} , $PM_{2.5}$, CO, O_3 , NO_2 and SO_2 levels from 1st February–31st May in 2019 and 2020 were compared for Patiala city (Fig. 6). During I period, comparative levels of $PM_{2.5}$, PM_{10} , O_3 and SO_2 were observed in both the years however, NO_2 levels were low in 2020. With the implementation of lockdown measures, pollutants showed

Table 4. Mean concentrations of PM_{10} , $PM_{2.5}$, CO, O_3 , NO_2 and SO_2 before (1st February–23rd March) and during lockdown period (24th March–31st May) in 2019 and 2020 in Patiala.

Pollutant (unit)	2019 I (1 st Feb–23 rd Mar 2019)	2019 II (24 th Mar–31 st May 2019)	2020 I (1 st Feb–23 rd Mar 2020)	2020 II (24 th Mar–31 st May 2020)
PM_{10} ($\mu g m^{-3}$)	111.3 ± 51.5	153 ± 84.3	81.8 ± 33.6	64 ± 41.7
$PM_{2.5}$ ($\mu g m^{-3}$)	40.1 ± 20.5	56.8 ± 24.3	37.2 ± 17.3	24.6 ± 15.2
CO (ppb)	557.8 ± 207.4	992 ± 518.8	679.6 ± 128.1	382.9 ± 57.9
O_3 (ppb)	5.4 ± 3.9	10.1 ± 6.4	6.3 ± 4.6	10.3 ± 6.7
NO_2 (ppb)	18.5 ± 11.3	22 ± 17.8	3.6 ± 1.5	4.6 ± 2.8
SO_2 (ppb)	1.5 ± 0.8	3.1 ± 1.9	2.7 ± 1.8	2.7 ± 2.2

Fig. 6. Time series of hourly average PM_{10} , $PM_{2.5}$, CO, O_3 , NO_2 and SO_2 levels during 1st February–31st May 2019 and 2020 in Patiala (dotted line show starting of lockdown period).

Fig. 7. Average diurnal variation of PM_{10} , $PM_{2.5}$, CO, O_3 , NO_2 and SO_2 during 1st February–23rd March (I) and 24th March–31st May (II) in 2019 and 2020 in Patiala.

sudden reduction in levels (on 24th March 2020). $PM_{2.5}$, PM_{10} , CO, NO_2 and SO_2 levels were lower in 2020 II period as compared to 2019 II period whereas O_3 levels were comparable. A similar variation was observed at Ghaziabad.

Similar to Ghaziabad, bimodal diurnal patterns of PM_{10} , $PM_{2.5}$, CO and NO_2 were observed in Patiala (Fig. 7). O_3 showed a unimodal diurnal pattern however, no distinct diurnal pattern of SO_2 was observed. During I period, diurnal patterns of PM_{10} , $PM_{2.5}$, O_3 and CO were comparable. Maximum deviation observed in PM_{10} , $PM_{2.5}$, CO, O_3 , NO_2 and SO_2 diurnal values was $53.1 \mu g m^{-3}$, $8.2 \mu g m^{-3}$, 239.6 ppb, 2.5 ppb, 17.8 ppb and 2.8 ppb, respectively. During II period, diurnal patterns were comparatively lower in 2020 except for O_3 . Maximum reduction observed in the diurnal values of PM_{10} , $PM_{2.5}$, CO, O_3 , NO_2 and SO_2 was $118.8 \mu g m^{-3}$, $31.4 \mu g m^{-3}$, 869.1 ppb, 3.1 ppb, 21.9 ppb and 2.1 ppb, respectively. The amplitude of the pattern was also lower as compared to 2019 II period and no clear bimodal patterns of PM_{10} , $PM_{2.5}$, CO and NO_2 were observed. Amplitudes of PM_{10} , $PM_{2.5}$, CO and NO_2 were 75, 61, 78 and 94% lower, respectively in 2020 II period. This may be attributed by restrictions imposed on vehicular activities.

CONCLUSION

Implementation of the lockdown measures as a preventive step to control the spread of COVID-19 resulted in restrictions on transportation and industrial activities. As a

result air pollution levels dropped significantly. The present study provides detail of the impact of lockdown on air pollution in 39 different cities of India. The primary pollutant concentrations (PM_{10} , $PM_{2.5}$, CO and NO_2) showed decreased levels in all cities however, secondary pollutant (O_3) showed both increasing and decreasing trends. Overall 44, 38, 28, 42 and 40% reduction was observed in PM_{10} , $PM_{2.5}$, CO, NO_2 and SO_2 levels, respectively during the lockdown period in 2020 as compared to 2019. Reduced primary pollutants were mainly attributed to restrictions imposed on transportation and industrial activities as these activities are their primary sources. Increase in O_3 levels may be due to reduced NO titration. Though the reduction observed in the pollutants levels during the lockdown period is expected to be short-lived, it provides evidence that widespread implementation of air pollution measures can result in immediate air quality benefits. Therefore, in worst air quality scenario restrictions on vehicles and industries can help in improving the air quality.

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