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Research Article

Impact of Lockdown on Air Pollutants during COVID-19 at Patna, India

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ABSTRACT Many countries shut their borders, imposed nationwide lockdown, and restricted several anthropogenic activities to arrest the spread of COVID-19. In the present study, the concentration of several air pollutants (PM_{10}, $PM_{2.5}$, NO_2, NH_3, SO_2, CO and O_3) during different phases of lockdown from monitoring stations of Patna was analyzed to assess the effect of lockdown restriction on air quality. Reduction in $PM_{2.5}$, NH_3, NO_2, PM_{10} and CO concentration was observed by 59.79%, 58.2%, 49.49%, 39.57% and 24.04%, respectively during the lockdown period. National Air Quality Index (NAQI) value in the year 2020 had been observed to lower by 57.88% compared to the year 2019, during the same period. A more significant fall in the concentration of air pollutants was observed during the early phase of post-lockdown compared to the late stages of post-lockdown. The study reflects the significance of restriction on anthropogenic activities in improving air quality and provides clues for future action plans for improving air quality.

KEY WORDS Lockdown, NAQI, $PM_{2.5}$, Air pollutants, Patna

1. INTRODUCTION

The world has recently faced a global pandemic COVID-19, first detected in Wuhan, Central China, in December 2019 (He *et al.*, 2020; Zhang *et al.*, 2020; Zhu *et al.*, 2020). The virus has gradually affected all nations since December 2019 (Rajbhandari *et al.*, 2020; Wang *et al.*, 2020). Until 13th December 2020, nearly 70 million confirmed COVID cases, and 1.6 million deaths owing to COVID-19 was reported (WHO, 2020a). In response to the increase in the number of cases and contagion nature of COVID-19, the Government of India has imposed a 14-hour Janta Curfew on 22nd March 2020, followed by a complete nation-wide lockdown from 24th March to 30th June 2020 in four phases. During that time, all commercial, industrial and educational activities were closed to limit the spread of infection. The unlock phase was slow, gradual, and completed in seven stages, and restricted commercial and transportation activities were permitted in non-containment zones. Lockdown has slowed down the pace of living, but it has positive outcomes regarding environmental issues including air quality across many cities in India (Agarwal *et al.*, 2020; Gautam, 2020; Kumari and Toshniwal, 2020; Mahato *et al.*, 2020; Sharma *et al.*, 2020;

Singh and Chauhan, 2020; Srivastava *et al.*, 2020) and in other countries also (Hashim *et al.*, 2021; Baldasano, 2020; Dantas *et al.*, 2020; Mesas-Carrascosa *et al.*, 2020; Tobías *et al.*, 2020; Wang *et al.*, 2020; Zhu *et al.*, 2020).

Patna, the capital of Bihar, is among the most populous and developing city in the Indo-Gangetic Plain. It has emerged as the second-largest economic center of eastern India after Kolkata and was ranked 32nd among the top 100 polluted cities in the world and 24th in India as per The World Air Quality report, 2020 (IQAir, 2020). The increasing population, economic and urban development have enhanced the burden on different sectors (industrial, transportation, domestic, constructional, biomass burning, etc.) as significant sources of air pollutants at Patna (Guttikunda *et al.*, 2019). The literature review reveals that vehicular emissions (Jain *et al.*, 2019; Sharma *et al.*, 2016; Pandey and Venkataraman, 2014), use of biofuels in traditional cookstoves (Singh *et al.*, 2021; Sen *et al.*, 2018; Saud *et al.*, 2012), municipal solid waste and agricultural biomass burning and 388 functional brick kilns (Joshi, 2019) were the major contributors to $PM_{2.5}$ and PM_{10} in the Indo-Gangetic Plains (Kumar *et al.*, 2020a; Arif *et al.*, 2018). Several researchers reported a high concentration of air pollutants over the Indo-Gangetic plain (Mhawish *et al.*, 2020; Mishra and Kulshrestha, 2020; Ojha *et al.*, 2020; Shastri *et al.*, 2017; Acharya and Sreekesh, 2013).

Among air pollutants, $PM_{2.5}$ and PM_{10} constitute significant concern at Patna as these parameters often exceed the standard limits prescribed by NAAQS. Under the business-as-usual (BAU) scenario, the concentration level of $PM_{2.5}$ is expected to increase by 28%, from 104.4 $\mu g/m^3$ in 2018 to 134.0 $\mu g/m^3$ by 2030 (PCAAP, 2019). An increase in emission load for $PM_{2.5}$ in the city is also attributed to natural phenomena like climatic and meteorological conditions, the presence of very soft alluvial soil and atmospheric reactions generating secondary particulate matters (PCAAP, 2019).

The degradation in air quality has caused an increase in significant health risks and enhanced considerable premature mortality (Arif and Parween, 2021; Barzeghar *et al.*, 2020; Hama *et al.*, 2020; Sharma *et al.*, 2020; Shukla *et al.*, 2020; Stanaway *et al.*, 2018). Nearly 980,000 deaths reported in India in 2019 were attributable to $PM_{2.5}$, which has increased by 61% or 343,000 deaths between 2010–2019 (HEI and IHME, 2020 (https://www.stateofglobalair.org/resources)). As per the (BSPCB, 2014) report, 2,600 premature deaths were recorded in 2012 at Patna that could reach 4,900 premature deaths in 2030 if no control measures are introduced and enforced.

During this lockdown, it has been noticed that the air pollution levels came within or below the permissible limit set by the CPCB of India (Gour *et al.*, 2015). Most of the recent literature published in air quality during the COVID-19 pandemic lockdown in various Indian cities is illustrated in Table 1. The majority of the studies conducted (Bedi *et al.*, 2020; Gautam, 2020; Kotnala *et al.*, 2020; Kumar *et al.*, 2020b; Mahato *et al.*, 2020; Singh and Chauhan, 2020) revealed early trends as they were confined to the lockdown period only and ignored the post-lockdown scenario. Our area of interest, Patna, is part of the Indo-Gangetic Plain where air pollution is at its peak in the last quarter of the year (Mishra and Kulshrestha, 2020; Ojha *et al.*, 2020). Moreover, the study conducted by Bedi *et al.* 2020 and Navinya *et al.* 2020 focused on various Indian cities at a time. However, only a single monitoring station was considered per city, which is insufficient for spatial analysis. The obtained data cannot truly depict the air quality of the entire city. Masum and Pal (2020) reported that changes in air quality due to the COVID-19 pandemic do not follow a similar trend in different regions; hence, a regional study is essential to determine the pattern of changes. Therefore, this paper aimed to study the impact of complete lockdown on the air quality of Patna by comparing air quality parameters during pre-lockdown, lockdown and post-lockdown phases in the year 2020 with those of the corresponding period in 2019. In our study, Correlational analysis GIS-based spatial maps was also used to provide in-depth insights to the authorities concerned to formulate a better management plan to improve the anthropogenic air pollutant exposure in Patna and provide a baseline for other important cities of the Indo-Gangetic Plain.

2. MATERIALS AND METHODS

2.1 Study Area

The area under investigation is Patna, the capital and largest city of Bihar situated 15 km along the bank of River Ganga between 25°56′N to 25°69′N latitude and 85°02′E to 85°25′E longitude in the Indo-Gangetic Plains. The city experiences a subtropical climate with a hot summer, a cold winter, and heavy rainfall during the monsoon season. Relative humidity can reach up to 100% during the summer season. At present, the Bihar

Table 1. Summarizing the recent studies conducted in various cities of India related to air quality during nationwide lockdown due to COVID-19 pandemic.

Study area	Study phase	Pollutants	Findings
Delhi, Hyderabad, Kolkata, Mumbai, Chennai (Kumar *et al.*, 2020b)	25th March, 2020 to 11th May, 2020 and compared with 2015–2019	$PM_{2.5}$	During lockdown, significant reduction in hourly $PM_{2.5}$ concentration were observed in Delhi (52%), Chennai (28%), Hyderabad (26%) and Kolkata (22%) compared to the same period in 2019.
Delhi, Mumbai, Kolkata, Chennai (Bedi *et al.*, 2020)	10th–24th March, 2020 (pre-lockdown) and 25th March–8th April, 2020 (lockdown)	PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, NH_3, O_3	Compared to pre-lockdown, NO_2 showed significant reduction ($p < 0.05$) in all the four cities during lockdown.
Delhi, Mumbai, Kolkata, Chennai, Hyderabad (Ravindra *et al.*, 2021)	Pre-lockdown, lockdown and post-lockdown and compared with 2016–2019	$PM_{2.5}$	Significant reduction in $PM_{2.5}$ during peak hour by 21.3%, 48.5%, 63.4%, 56.4% and 23.8% for Delhi, Chennai, Kolkata, Mumbai and Hyderabad respectively.
17 cities of India including Patna (Navinya *et al.*, 2020)	1st February–24th March, 2020 (pre-lockdown) and from 25th March–3rd May, 2020 (lockdown)	PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO	Major improvement in air quality was recorded in metropolitan cities namely Bangalore (86%) and Delhi (70%) followed by Ahmedabad (67%) and Nagpur (63%).
Delhi (Kotnala *et al.*, 2020)	15th–24th March, 2020 (pre-lockdown) and from 25th–31st March, 2020 (lockdown)	$PM_{2.5}$, PM_{10}, NO, NO_2, NO_x, SO_2, CO, NH_3	Improvement in air quality was observed throughout Delhi with nearly 14 times reduction in NO_x from its peak value.
National Capital Territory (NCT) Delhi (Mahato *et al.*, 2020)	3rd March–23rd March (pre-lockdown) and from 24th March– 14th April, 2020 (lockdown) and compared for lockdown during 2017–2019.	PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, NH_3, O_3	Reduction in NAQI was about 54% in Central Delhi followed by Eastern (49%), Southern (43%), Western (37%) and Northern (31%) regions of the city. When compared with 2019, significant improvement in air pollutants was observed with reduction of 60% (PM_{10}), 39% ($PM_{2.5}$), 53% (NO_2) and 30% for CO.
India (Gautam, 2020)	31st March to 5th April from 2016–2020	Aerosol Optical Depth	The level of aerosol is found to be lowest in the last 20 years owing to 50% reduction during the lockdown period.
Lucknow and New Delhi (Srivastava *et al.*, 2020)	Pre-lockdown (1st February–21st February) and lockdown (25th March–14th April, 2020)	$PM_{2.5}$, NO_2, SO_2 and CO	A significant improvement in air quality in both the cities was noticed due to major reduction in concentration of $PM_{2.5}$, NO_2 and CO.
Delhi, Kolkata, Mumbai, Chennai, Hyderabad (Singh and Chauhan, 2020)	March, 2020 and compared with March, 2019	$PM_{2.5}$ and NO_2	Major reduction in $PM_{2.5}$ concentration was recorded for Kolkata (34.52%), Delhi (27.57%) and Mumbai (19.25%) during nationwide lockdown.
Jamshedpur (Ambade *et al.*, 2021)	2nd March–24th March (pre-lockdown), 25th March–31st May (four phases of lockdown) and unlock 1.0 (1st–30th June, 2020)	Black carbon (BC), $PM_{2.5}$, Polycyclic Aromatic Hydrocarbon (PAHs)	PAHs, $PM_{2.5}$ and BC concentrations were much lower during the lockdown and unlock phase than on normal days.

State Pollution Control Board (BSPCB) monitors the air quality of Patna with the help of 6 Continuous Air Monitoring Stations (CAMS) distributed throughout the city (Fig. 1).

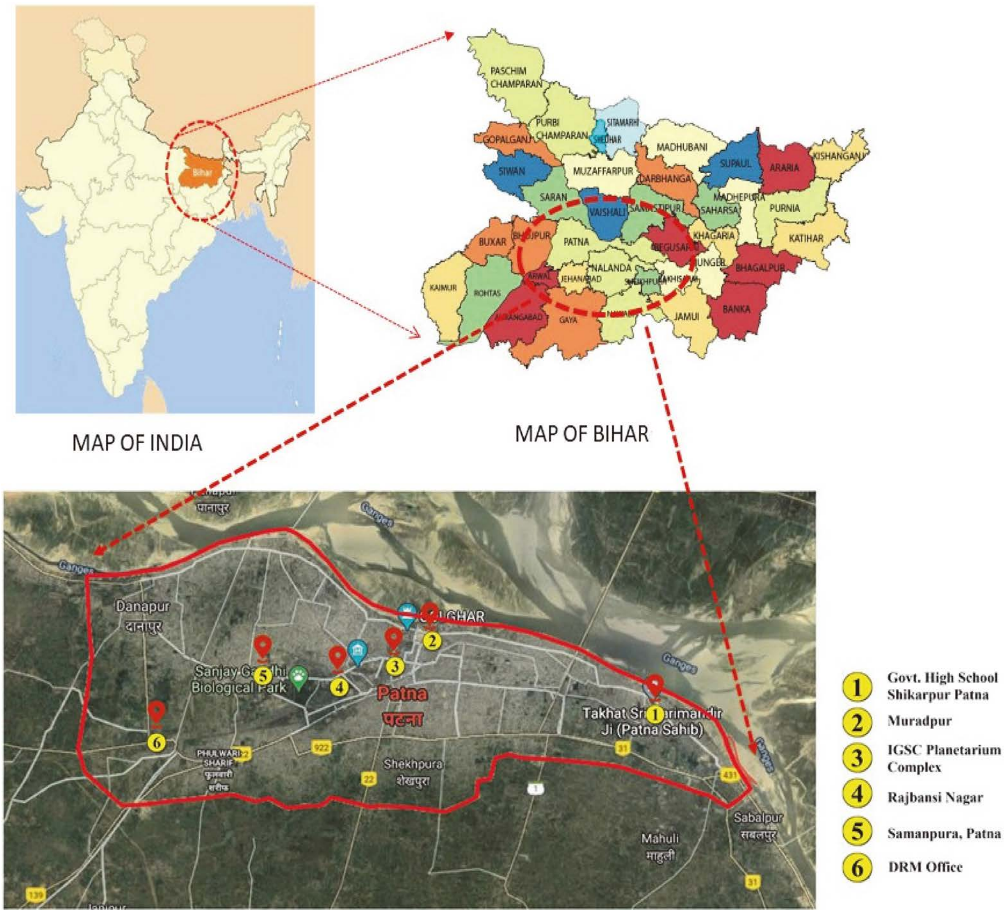

Fig. 1. Map showing the study area along with monitoring stations.

2.2 Data Collection and Methodology

To study the effect of lockdown on the air quality of Patna, primary data from 6 different monitoring stations was collected from the CPCB online portal (https://app.cpcbccr.com/AQI_India/) and the BSPCB online portal (http://bspcb.bih.nic.in/environment-monitoring-data.html). The concentration of 7 different air pollutants was considered, including $PM_{2.5}$, PM_{10}, NO_2, NH_3, SO_2, O_3 and CO. For contaminants such as $PM_{2.5}$, PM_{10}, NO_2, NH_3 and SO_2, the daily average (24h) sub-index value and CO and O_3 daily maximum (8h) average sub-index value had been taken. This was further analysed to see the change in their mean concentration between different phases. The fluctuation in AQI value and mean concentration have been studied in four phases in the year 2020 from pre-lockdown (1st January to 24th March) to lockdown (25th March to 31st May) to early phases of post-lockdown (1st June to 31st August) to the late phase of post-lockdown (1st September to 15th December). The method adopted to calculate NAQI is tabulated in (CPCB, 2014) briefly outlined here. AQI uses $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO and O_3 as criteria pollutants, where the selection of parameters depends on AQI objective(s), data availability, averaging period and monitoring frequency (CPCB, 2014). Of all the air pollutants, the calculation of AQI requires a concentration of a minimum of three pollutants, with at least one being either $PM_{2.5}$ or PM_{10}. The maximum sub-index AQI_i of the corresponding pollutant is the overall AQI, where the sub-index AQI_i of each pollutant can be calculated using Eq. (1).

$$SI\text{-}AQI_i = [\{(I_{HI}-I_{LO})/(B_{HI}-B_{LO}) \times (C_i-B_{LO})] + ILO \quad (1)$$

Where C_i is the concentration of pollutant 'i'; B_{HI} and B_{LO} are breakpoint concentrations higher and lower than C_i and I_{HI} and I_{LO} are corresponding AQI values equivalent to B_{HI} and B_{LO} respectively. The health breakpoint of each pollutant is given in Table 2.

3. RESULTS AND DISCUSSION

3.1 Variation in Air Pollutants Concentration

The minimum, maximum and mean value of the daily average concentration of different air pollutants have been summarized in Table 3. The results revealed particulate matter ($PM_{2.5}$ and PM_{10}) as the dominant and indicatory air pollutant during the entire study period. The concentration of PM_{10} ranged from 17.33 μg/m^3 to 382.12 μg/m^3 while $PM_{2.5}$ was observed between 9.00 μg/m^3 to 236.38 μg/m^3 during the study period. The dominance of particulate matter among the air pollutants in the study area might be due to various anthropogenic activities like re-suspension of road dust, construction activities, open burning of solid waste, emission from vehicles and brick kilns etc. Patna is situated along the bank of river Ganga and ¾th of its soil is alluvial and makes the soil soft and prone to the formation of dust which is blown into the city from the sandy riverbank adding to the particulate matter level as outside contributors (PCAAP, 2019). Various atmospheric reactions producing secondary particulate matter also add to the level of $PM_{2.5}$ and PM_{10} in the study area. Fig. 2 represents the variation in daily average (24h) concentration of PM_{10}, $PM_{2.5}$, NO_2, SO_2, NH_3 and daily maximum (8h) average of O_3 and CO between 1st January 2020 and 15th December 2020 in the city of Patna. The result revealed a reduction in the daily average value of PM_{10}, $PM_{2.5}$, NO_2, SO_2, NH_3 and CO from pre-lockdown to lockdown and from lockdown to early phases of post-lockdown. The daily average PM_{10} value was beyond the NAAQS standard limit of 100 μg/m^3 during the pre-lockdown. The daily average concentration of PM_{10} and $PM_{2.5}$ has been reduced by 39.57% and 59.79%, respectively, from pre-lockdown to lockdown (Table 3). A higher decrease in $PM_{2.5}$ value compared to PM_{10} could be due to reduction in transport activities as the contribution of vehicular emissions and emissions from the combustion of gasoline or other such fuels to $PM_{2.5}$ is much more pronounced than that of PM_{10} (PCAAP, 2019; ARAI and TERI, 2018; Guttikunda and Jawahar, 2014). Interestingly, the scenario gets reversed when the percent change between lockdown and the early stages of post-lockdown are analyzed. PM_{10} declined by 49.49%, while $PM_{2.5}$ dropped only by 36.44%, which might be due to the relaxation in

Table 2. National AQI classes, range, health impacts and health breakpoints for the seven pollutants (scale: 0–500).

AQI class (Range)	Health impact	PM_{10} 24 h (μg/m^3)	$PM_{2.5}$ 24 h (μg/m^3)	SO_2 24 h (μg/m^3)	NO_2 24 h (μg/m^3)	O_3 8 h (μg/m^3)	CO 8 h (mg/m^3)	NH_3 24 h (μg/m^3)
		Concentration range						
Good (0–50)	Minimal impact	0–50	0–30	0–40	0–40	0–50	0–1	0–200
Satisfactory (51–100)	Minor breathing discomfort to sensitive people	51–100	31–60	41–80	41–80	51–100	1.1–2	201–400
Moderately polluted (101–200)	Breathing discomfort to people with lung disease	101–250	61–90	81–380	81–380	101–168	2.1–10	401–800
Poor (201–300)	Breathing discomfort to people on prolonged exposure	251–350	91–120	381–800	181–280	169–208	10–17	801–1200
Very poor (301–400)	Respiratory illness to people on prolonged exposure	351–430	121–250	801–1600	281–400	209–748	17–34	1200–1800
Severe (401–500)	Respiratory illness to people on prolonged exposure	>430	>250	>1600	>40	>748	>34	>1800

Table 3. Summarizing daily average concentration and % change of air pollutants in different phases of the year 2020.

		Daily average concentration				% Change		
		PL	L	ePOL	lPOL	PL-L	L-ePOL	ePOL-lPOL
PM_{10} ($\mu g/m^3$)	Max	269.67	196.75	115.9	382.12	−27.04	−41.09	229.7
	Min	40.2	24	17.33	21	−40.3	−27.78	21.15
	Avg	163.19	98.62	49.81	137.77	−39.57	−49.49	176.57
$PM_{2.5}$ ($\mu g/m^3$)	Max	206.6	72.36	50.4	236.38	−64.97	−30.35	369.01
	Min	31.2	11.4	9	11.25	−63.46	−21.05	25
	Avg	92.82	37.33	23.72	79.48	−59.79	−36.44	235.01
NO_2 ($\mu g/m^3$)	Max	76.35	55	33.87	90.64	−27.96	−38.42	167.64
	Min	12	8	6.93	10	−33.33	−13.33	44.23
	Avg	44.64	21.19	17.27	40.98	−52.52	−18.74	137.29
NH_3 ($\mu g/m^3$)	Max	46.67	20	49.75	30	−57.14	148.75	−39.7
	Min	13.33	6	10.4	4	−55	73.33	−61.54
	Avg	27.08	11.32	8.44	15.82	−58.2	−25.42	87.36
SO_2 ($\mu g/m^3$)	Max	15.2	21.6	14.8	13.33	42.11	−31.48	−9.91
	Min	5.6	2	1.87	5.2	−64.29	−6.67	178.57
	Avg	9.42	9.06	4.06	8.32	−3.82	−55.24	105.18
O_3 ($\mu g/m^3$)	Max	50.07	64.76	49.75	57.63	29.35	−23.18	15.85
	Min	4	9.25	10.4	10	131.25	12.43	−3.85
	Avg	16.12	28.02	23.81	24.77	73.75	−15.02	4.06
CO (mg/m^3)	Max	3.48	1.97	1.18	3.16	−43.33	−40.16	167.8
	Min	0.54	0.35	0.35	0.45	−34.78	0	29.52
	Avg	1.34	1.02	0.6	1.18	−24.04	−40.54	94.94

L = Lockdown, ePOL = early Post-Lockdown, lPOL = late Post-Lockdown

inter-state and intra-state travel in the early post-lockdown period as vehicular emission contributes more to $PM_{2.5}$ (Kumar *et al.*, 2020b). Further, negligible construction, industrial activities, waste burning reduction, landfills, and intermittent rainfall might be responsible for a significant drop in PM_{10} level during the early post-lockdown period (CARB 2021; Sahoo *et al.*, 2021; Sathe *et al.*, 2021; Kumar *et al.*, 2020a). A decline in the average concentration of NO_2 and NH_3 was also observed. The NO_2 value can be seen at an alarming level during pre-lockdown and has decreased by 52.52% from pre-lockdown to lockdown and 18.74% from lockdown to initial unlock stages, mainly due to a reduction in the transport sector. The NH_3 daily average concentration has been reduced by 58.20% from pre-lockdown to lockdown. Although the anthropogenic source of NH_3 originates mainly from agricultural activities, including the use of soil fertilizer, domestic animal waste and the use of ammonia-based fertilizers, the reduction of NH_3 can be attributed to industrial and traffic emissions in the urban areas (Farren *et al.*, 2020; Li *et al.*, 2020; Wang *et al.*, 2015). No significant change in SO_2 concentration has been observed during the entire study period except in early post-lockdown (June to September) that suggests vehicular restriction might have not much impact on SO_2 concentration (Lokhandwala and Gautam, 2020). Decrease in SO_2 concentration during the early post-lockdown period is due to substantial rainfall during this period (Fig. 2). Several researchers reported a reduction in the concentration of SO_2 during the rainy season, probably due to the washout effect (Ngarambe *et al.*, 2021; Xue *et al.*, 2020). The result revealed that the average concentration of CO had declined by 24.04% during the lockdown, and it had further decreased by 40.54% during the early post-lockdown period. A decrease in CO concentration during the lockdown period might be due to restrictions on combustion engines, heating furnaces and automobile exhaust. Further decrease in CO concentration during

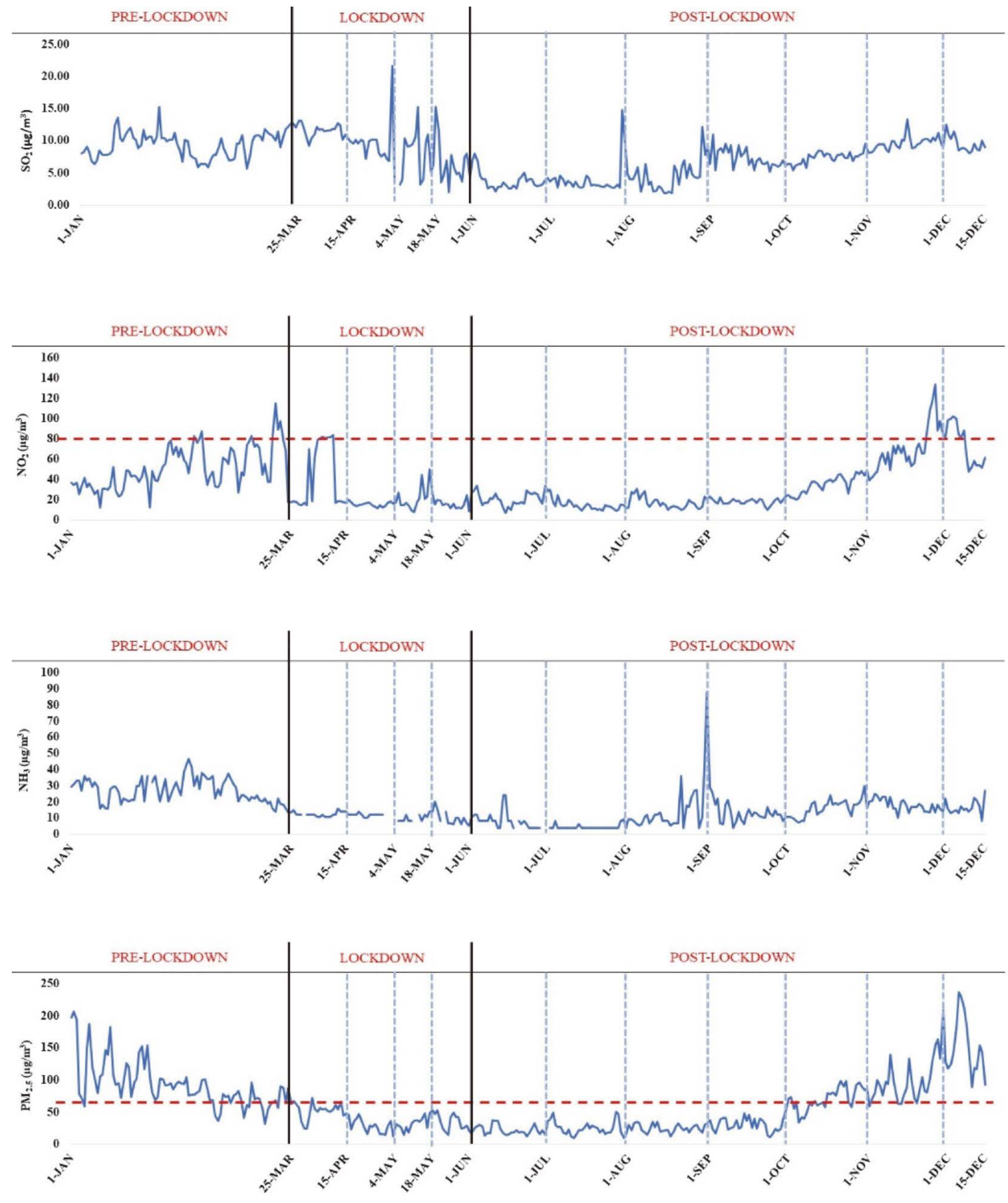

Fig. 2. Variation in criteria air pollutants level from pre-lockdown to post-lockdown in the year 2020.

the early post-lockdown period may be due to the precipitation washout effect (Ngarambe *et al.*, 2021; Yoo *et al.*, 2014). Strikingly, the mean average concentration of O_3 has increased by 73.75% from pre-lockdown to lockdown, which is due to a decrease in NO_x and VOCs concentration because of the complete restriction on industrial activity and vehicular movement (Filonchyk and Hurynovich, 2020; Kumari and Toshniwal, 2020; Mahato *et al.*, 2020). Sharma *et al.* (2020) reported that a decrease in the concentration of particulate matter could result in more sunlight penetration, thereby increasing the photochemical reaction that can uplift O_3 production.

The pollutant concentration data also revealed the effect of sequential unlock phases on air pollutants. $PM_{2.5}$ has experienced a maximum increase of about 235.01% from the early stages of post-lockdown to the late stages, followed by PM_{10} (176.57%), NO_2 (137.29%), SO_2

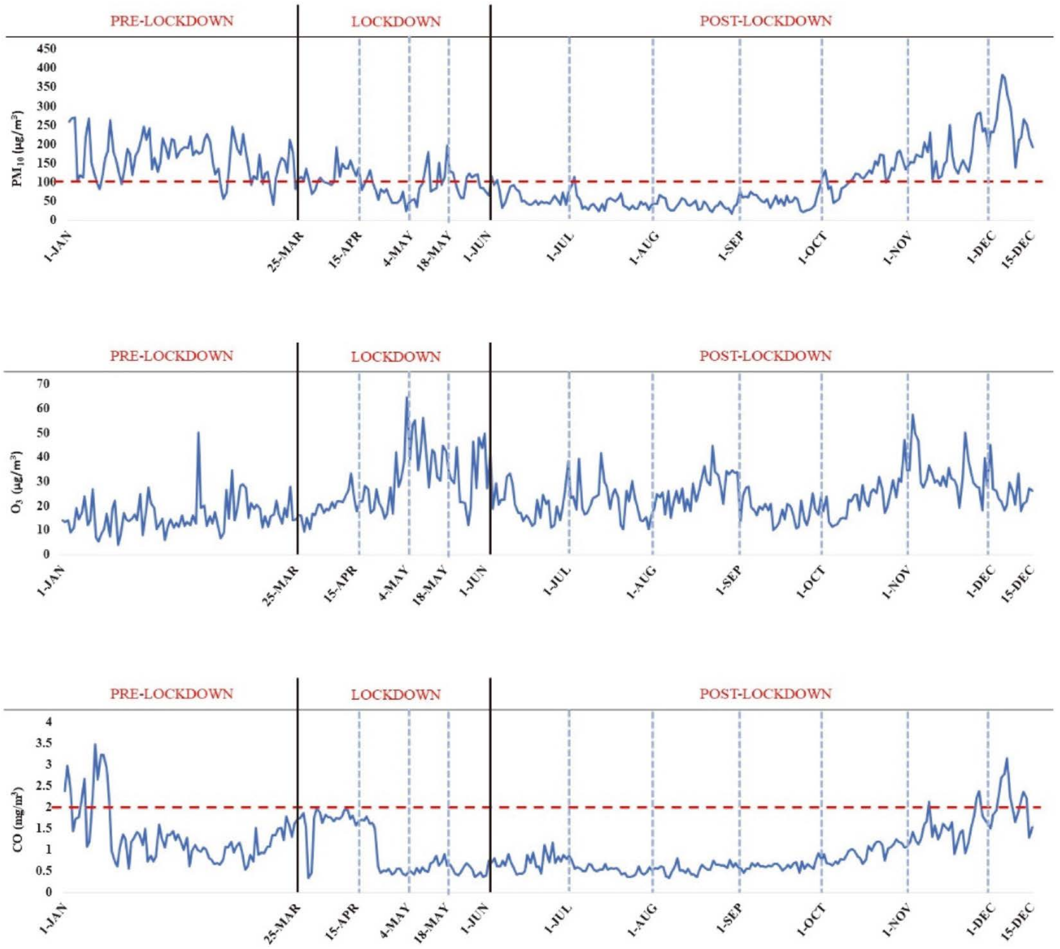

Fig. 2. Continued.

(105.18%), CO (94.94%), NH_3 (87.36%) and O_3 (4.06%). An increase in the concentration of these pollutants during sequential unlock phases might have resulted from resumption of anthropogenic origin pollutants and changing weather and meteorological conditions (Mahato *et al.*, 2020; Sharma *et al.*, 2020; Srivastava *et al.*, 2020).

The daily, weekly, and monthly variations of different air pollutants are conditionally formatted (Fig. 3). The higher value has been colored by red that decreases to green at the lower values. PM_{10}, $PM_{2.5}$, NO_2, NH_3 and CO remained high during the pre-lockdown (January to March) and late post-lockdown (October to December). During the lockdown, each of them experiences a reduction in their daily average concentration. The concentration of O_3 on the other hand, was observed to be high in May. The result suggests the reduction in transportation and industrial activities has a predominant impact on the concentration of particulate matter, NO_2, and NH_3, as their concentration started dropping with the implementation of the lockdown (near the end of March). CO and SO_2 have begun to decline at the tail end of April, suggesting restrictions on vehicular emissions might not have much to do with these pollutants, specifically SO_2, and incomplete combustion of fossil fuel from biomass burning might have contributed to CO. The concentration of NH_3 shows an unusual increase towards the end of August (Fig. 3). This increase was explicitly marked in the data collected from the Danapur site, which might be due to some agriculturally based activities (CGWB, 2015) in addition to vehicular emissions.

The concentration of pollutants showed a further decrease in their daily average concentration during the early stages of the post-lockdown (1st June to 31st August). The effect of lockdown coupled with substantial monsoon rainfall, the contribution of clean air from the Bay of Ben-

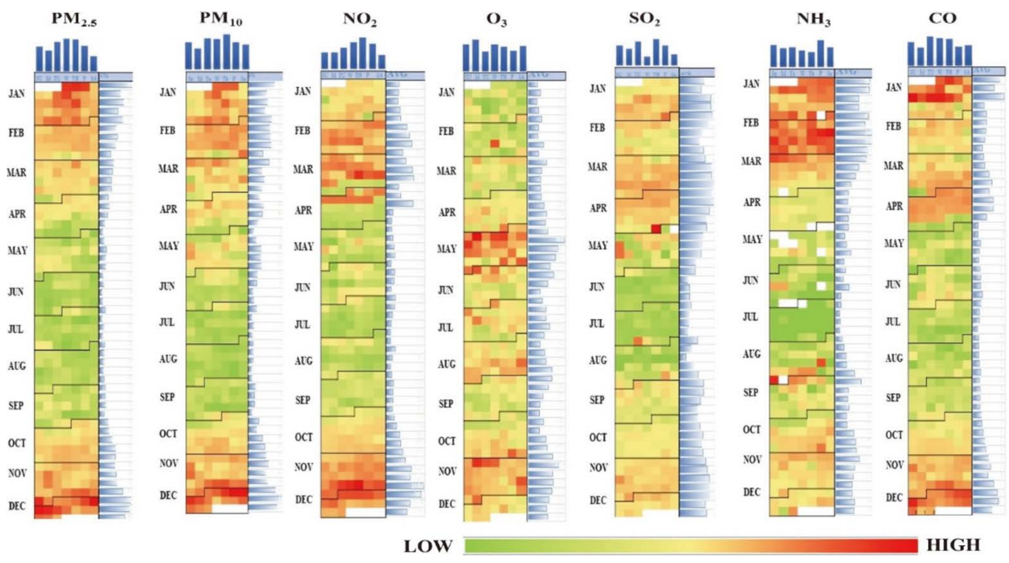

Fig. 3. Conditional formatting representing daily, weekly and monthly variation in air pollutants level in 2020.

gal and Arabian Sea, and little input from brick kilns and biomass burning might be the reason behind such a drop (Arif *et al.*, 2018). The diagrams also reveal a gradual increase in the deterioration of air quality from October onwards due to the relaxation in lockdown, the emergence of the winter season, prevailing westerly wind, and other anthropogenic factors that sum up to degrade air quality during the late phase of lockdown.

3.2 Spatial Variation

Fig. 4 depicts the spatial variation of different air pollutants in the study area. $PM_{2.5}$ showed a significant reduction during the lockdown phase at nearly every sampling site in the city. During the first week of lockdown, it was reduced to 47.22% from the pre-lockdown level. NO_2, on the other hand, has recorded maximum reduction of 63.18% within seven days since lockdown, suggesting restrictions on transport and other anthropogenic activities have played an essential role in lowering their concentrations. The concentration of NO_2 and CO was found to be greater at site 3 during the lockdown phase than that of the pre-lockdown phase, which might be due to biomass burning (Beig *et al.*, 2020; Biswal *et al.*, 2020; Ravindra *et al.*, 2020) for household purposes by the population residing in two densely populated slum areas located near this monitoring site. An increase in NO_2 levels during the early phases of post-lockdown, especially in the western and central pockets of the study area (Fig. 4) might be due to relaxation in transport activity. Towards the end of the year, an increase in air pollutants was noticed owing to various anthropogenic and natural factors. Spatial variation revealed that pollutants load prevailed mainly in the city's central region during the entire study period. The result is confined to the pollutants including $PM_{2.5}$, NO_2, and CO; the rest do not vary very much or are excluded due to the unavailability of data for some phases.

3.3 Statistical Correlation between Air Pollutants

Correlation between different air pollutants was computed for the study period (Fig. 5). The correlation analysis revealed the daily average concentration of PM_{10} to be very strongly correlated with $PM_{2.5}$ ($r = 0.87$), which suggests they both contribute to the air from common sources. PM_{10} and $PM_{2.5}$ showed moderate correlation with NH_3 ($r = 0.47$; $r = 0.46$), indicating a favorable role of ammonia conversion from gas to particle phase in particulate matter formation (Wang *et al.*, 2015). The correlation of particulate matter with NO_2 ($^{r}10 = 0.74$, $^{r}2.5 = 0.63$) and SO_2 ($^{r}10 = 0.50$, $^{r}2.5 = 0.46$) suggests the presence of secondary pollutants generated by the photochemical reaction of gaseous pollutants mainly SO_2 and NO_2 (CARB, 2021; Botkin and Keller, 2000; Xu *et al.*, 2020a). O_3 showed a negative correlation with all other pollutants, predominantly with $PM_{2.5}$, and NH_3 during our study period and similar findings were also observed by Kumari and Toshniwal, 2020; Mahato *et al.*, 2020; Sharma *et al.*, 2020; Xu *et al.*, 2020b.

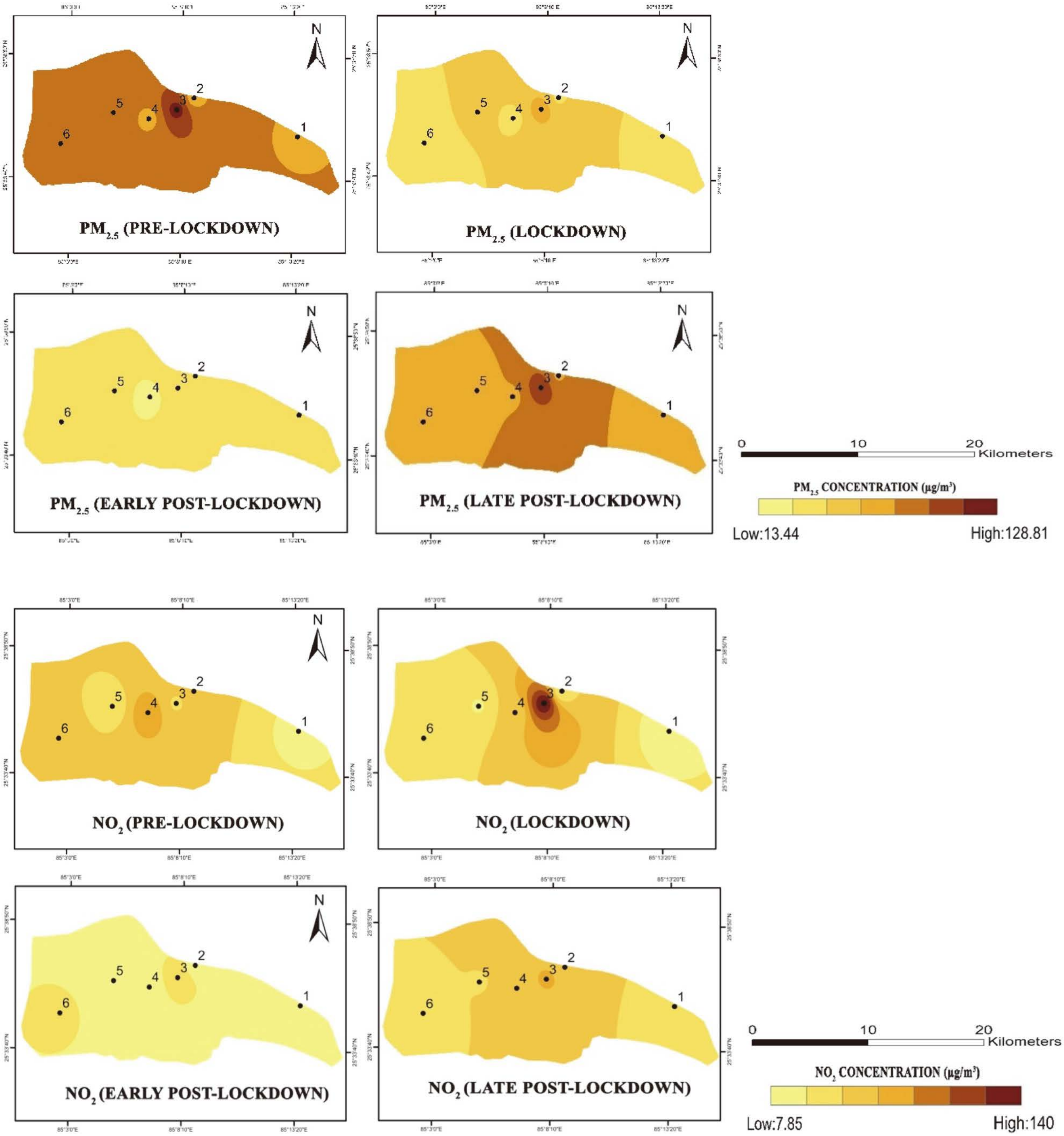

Fig. 4. Comparing the spatial distribution of air pollutants concentration during pre-lockdown, lockdown, early and late post-lockdown phases in Patna for the year 2020.

3.4 Comparison of Air Pollutants between 2019 and 2020

A comprehensive comparison of the concentration of five air pollutants ($PM_{2.5}$, NO_2, SO_2, CO, O_3) during pre-lockdown, lockdown and different phases of post-lockdown in the year 2020 was made with corresponding period in the year 2019 (Fig. 6). The result revealed that a significant impact of lockdown is noticeable when the deviation was evaluated from lockdown to early stages of post-lockdown (from 1st June 2020 to 31st August 2020).

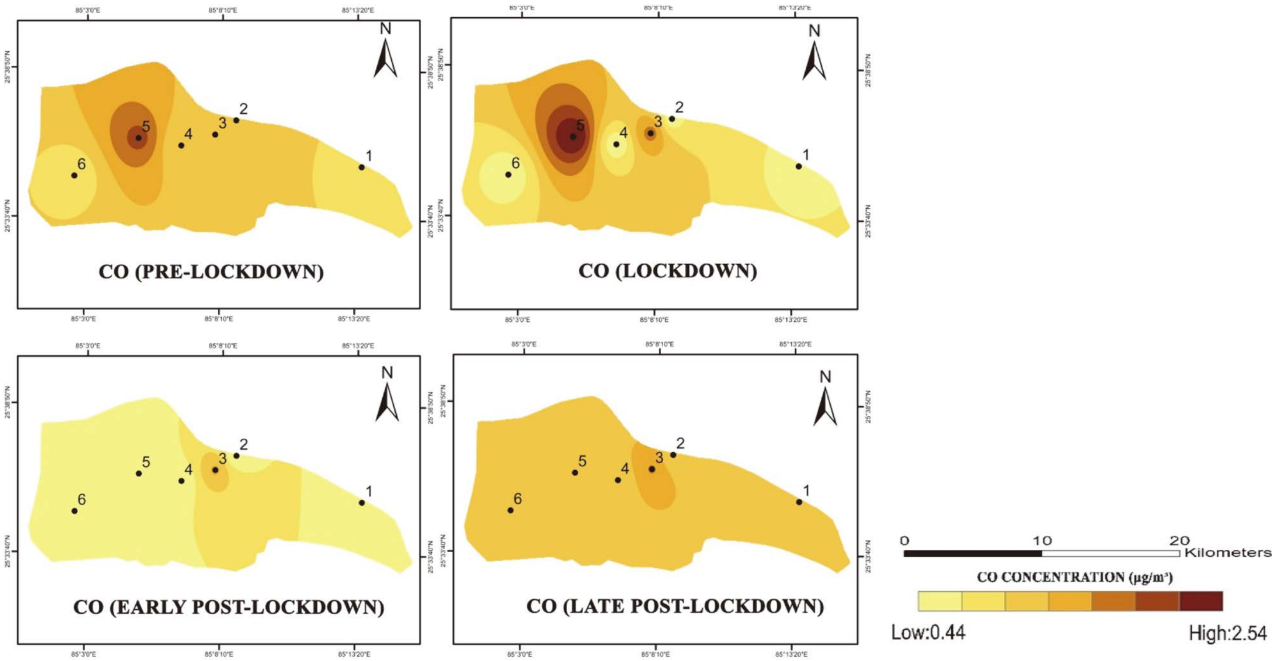

Fig. 4. Continued.

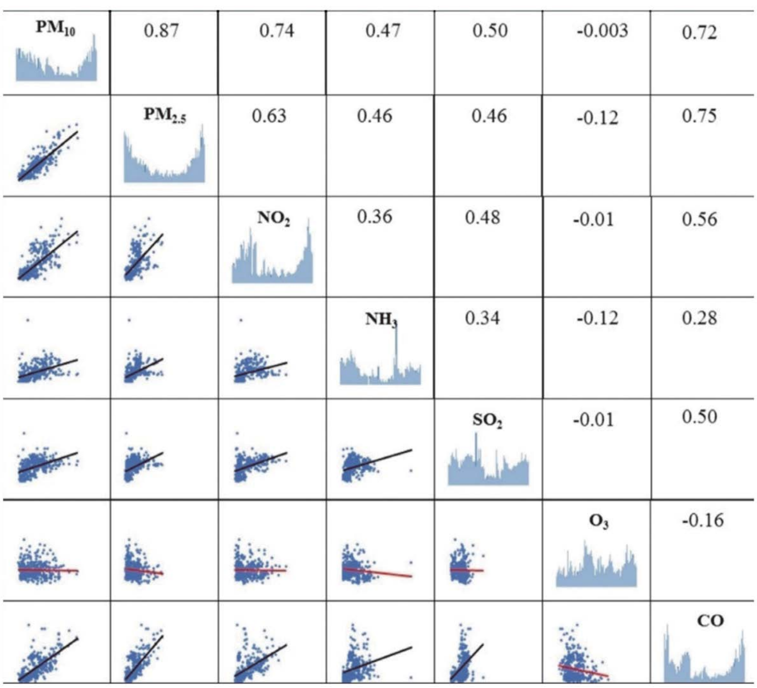

Fig. 5. Showing correlation between different air pollutants.

In 2020, all the air pollutants showed a negative % change where the maximum reduction was observed for SO_2 that has decreased from 8.79 μg/m^3 to 4.05 μg/m^3 (53.95%) in 2020, followed by CO (38.57%), $PM_{2.5}$ (36.38%), NO_2 (20.82%) and O_3 (19.37%). Compared with the previous year's data, the monthly average concentration of NO_2,

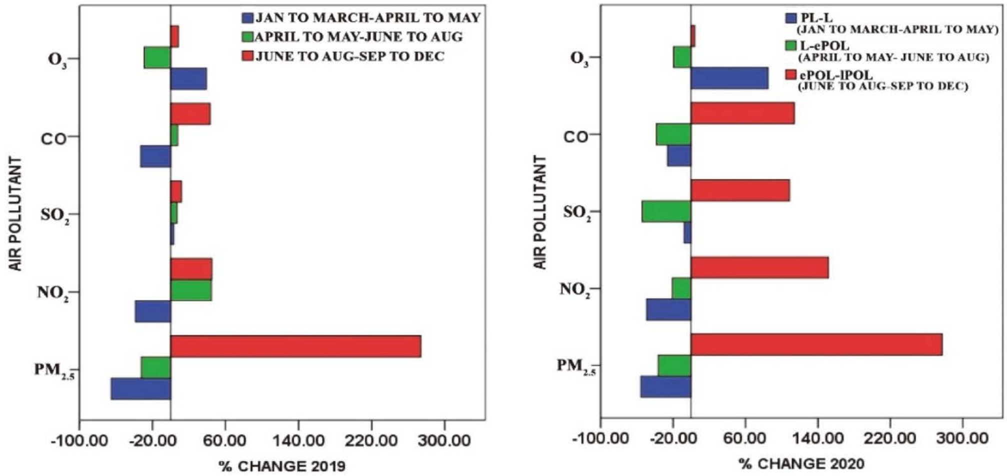

Fig. 6. Comparative analysis of percentage change in air pollutants level between 2019 and 2020.

SO_2, CO was indeed higher during the same time (Fig. 6). Nearing the end of the study period, air pollutants have remarkably shown an increase in their concentration for both years. However, air pollutants have come across a more tremendous % increase in the year 2020 compared to 2019. The monthly average concentration of $PM_{2.5}$ has been maximum during the late phase of post-lockdown, which was noted at 88.70 $\mu g/m^3$ in 2020 and 139.35 $\mu g/m^3$ in 2019. Similarly, NO_2 has increased from 17.26 $\mu g/m^3$ to 43.42 $\mu g/m^3$ in the year 2020 and from 21.53 $\mu g/m^3$ to 31.23 $\mu g/m^3$ in the corresponding period of the year 2019. 43.18% and 113.70% increase can also be noticeable for CO in 2019 and 2020 respectively (Fig. 6). An increase in the concentration of these pollutants during this phase might be due to the lowering of mixing layer height hindering the complete dispersion of pollutants (Guttikunda and Jawahar, 2014), winter inversion (Mahato *et al.*, 2020; Mishra and Kulshrestha, 2020). Increase in biomass burning during winter that contributes 18–30% of the total concentration level during winter (PCAAP, 2019), burning of crackers during festive and marriage occasions at the tail end of the year (Mahato *et al.*, 2020; Chauhan and Singh, 2017) also increase the concentration of pollutants. Besides these factors, high biomass residue burning in Northwest countries and the Northern regions of India sums up with dust aerosol from the west during winter and premonsoon (Srivastava *et al.*, 2020; Arif *et al.*, 2018), resumption of brick manufacturing during winter and premonsoon period and westerly air mass coming from Indo-Gangetic Plain resulted in a comparatively elevated level of $PM_{2.5}$ and PM_{10} during winters (Agarwal *et al.*, 2020; Singh and Chauhan, 2020; Arif *et al.*, 2018).

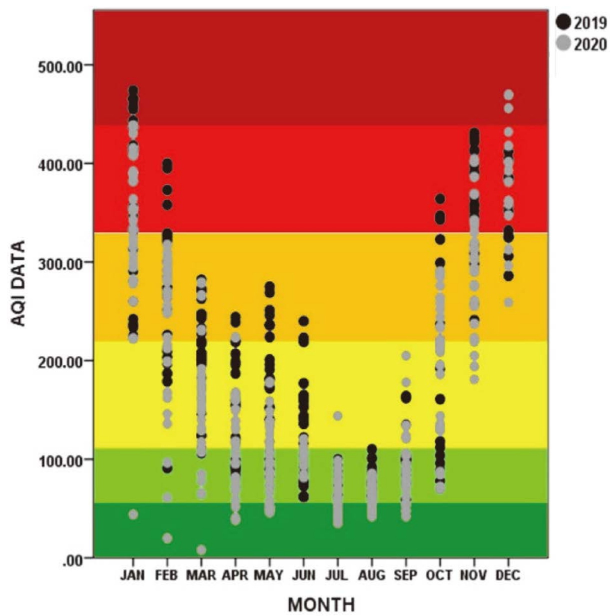

Fig. 7. Variation in AQI value between the years 2019 and 2020 at Patna.

3.5 Aqi Interpretation

Fig. 7 shows changes in the monthly average AQI value from 1st January to 15th December for 2019 and 2020. Since the beginning of the year, the air quality has improved slightly compared to the previous year. However, compared to the AQI value for the same period in 2019, the most significant drop in the AQI value in 2020 occurs from April to June. The AQI value ranged from 30 to 224 in 2020, peaking at 275 in 2019 with a 30.91% decline in the average AQI value during the lockdown period. The AQI value remained in a good to the moderately polluted zone during the lockdown and early post-lockdown phases that were in the poor category last year (Fig. 7). Compared to 2019, the AQI value this year has declined by 57.88% from pre-lockdown to lockdown, which was recorded as 47.57%. Such a drop in the AQI values in the pandemic and early stages of post-pandemic phases again justifies our discussion that the implementation of lockdown was a powerful reason for the changes observed in the air quality this year.

4. CONCLUSION

The main focus of the study was to investigate the influence of emission reductions due to restrictions on transportation, industrial and various anthropogenic contributors of air pollutants on the air quality of Patna during the COVID-19 lockdown and also to examine the changes in air pollutants levels throughout the year. The study concludes that the implementation of lockdown certainly had a significant positive impact on improving the quality of the air in Patna. The pollutants that experienced maximum reduction during the lockdown period include particulate matter, NO_2, and NH_3. On the contrary, SO_2 had not declined by much and O_3 rose amid this period due to a drop in PM and NO_2 levels. A higher pollution load was reported by spatial analysis in the central part of the city. The results also revealed a notable contribution of biomass burning to NO_2 during the lockdown. A drop observed in the early stages of post-lockdown was due to the influence of the monsoon season and southerly wind. Together with the lockdown, the consequences have lowered the pollutant's concentration even further to a greater extent than the previous year. In addition, the relaxation in pandemic restrictions and the impact of climatic conditions once again paved the way for an increase in these pollutants towards the end of the year. The study eventually concluded that the problem determining air quality is mainly anthropogenic. However, lockdown is not a permanent solution to expect improvement in water or air quality. Instead, it provides us with evidence that improvement in air quality can be achieved if proper measures are drafted/worked out in the existing regulatory plans and are implemented strictly by the concerned authorities in a phase-wise manner.

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