Urban air pollution reduction: evidence from phase-wise analysis of COVID-19 pandemic lockdown

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Received: 21 February 2021 / Accepted: 26 June 2021 / Published online: 16 July 2021
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Abstract

Until 31 May 2020, more than six million confirm COVID-19 cases had been reported worldwide. Lockdown has resulted in significant air quality improvement, especially in urban regions. The lockdown has acted as a natural experiment empowering researchers, policymakers, and governing bodies. The present study focuses on quantifying and analysing the effect of lockdown on India's metropolitan cities, namely New Delhi, Mumbai, Kolkata, Chennai, and Bangalore. The study analyses the phase-wise and diurnal variations in the air quality from 24 March 2020 to 31 May 2020 while focussing on-peak and off-peak duration concentrations. To investigate the reason behind pollutant reduction, correlation of drop percentages in pollutant concentrations with vehicle population, extent of construction activity, and meteorological parameters are analysed. The 24-h drop in PM₁₀ and PM_{2.5} showed a high correlation ($R^2 = 0.97$ and 0.72 , respectively) with the city's vehicle population. During peak hours, the inland cities (Delhi and Bangalore), with a more extensive vehicle fleet, recorded a higher drop in PM₁₀ and PM_{2.5} concentrations than coastal cities (Mumbai, Chennai, and Kolkata). With respect to 2019 concentration, the maximum decrease in pollutant concentrations averaged across the five study locations was recorded in NO₂ (46%), followed by PM_{2.5} (40%), PM₁₀ (37%), and CO (19%). SO₂ and O₃ contrarily recorded an overall increase of 40% and 41%. These results wherein vehicular pollutants recorded the maximum drop indicate that reduced vehicular traffic primarily influenced air quality improvement during the lockdown.

Keywords Air quality · COVID-19 · Metro cities · Traffic peaks hours

Introduction

In late December 2019, an outbreak of a highly contagious disease caused by the novel coronavirus, SARS-CoV-2, emerged in Wuhan City, China, reported as a cluster of pneumonia cases in earlier stages. The disease was identified as coronavirus disease (COVID-19) by the Chinese authorities on 7 January 2020. Furthermore, with the outbreak of disease

spreading throughout the world, the World Health Organization (WHO) recognised it as a 'pandemic' on 11 March 2020 (Cucinotta and Vanelli 2020). The critical sources of infection are patients infected with the novel coronavirus. Since then, there have been an enormous number of detected cases worldwide; as of 31 May 2020, the world has recorded 5,934,936 cases and 367,166 deaths due to the novel coronavirus disease (World Health Organisation 2020). Without any vaccine in hand, the authorities worldwide resorted to lockdown, a unique and only solution to constraint the exponential increase in cases. The first coronavirus case was reported in India on 30 January 2020, in Kerala (Nair 2020). Soon the virus spread to other Indian states and metros like Delhi and Mumbai. On 22 March 2020, the Indian Prime Minister called for a 'Janata Curfew', a 14-h informal curfew to practice social distancing nationwide. After the 14-h social distancing initiative, India's government decided to impose a nationwide lockdown on 24 March 2020 to contain the rapidly spreading epidemic (Chaurasiya et al. 2020). Under this first

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phase of lockdown, there was a complete clampdown on government offices, commercial and private establishments, industrial establishments, educational institutions, places of worship, and all transport services—air, water, and land, barring essential services such as healthcare, grocery shops, pharmacies, milk booths, banks, ATMs, petrol pumps, and fire and emergency services (Indian Council of Medical Research 2020). To mitigate hardships experienced by the public, the second phase of lockdown was announced with effect from 15 April 2020, under which additional activities were operationalised outside containment zones (Ministry of Home Affairs 2020). Lockdown guidelines and phases were revised periodically to ease outdoor activity restrictions, with the 2nd, 3rd, and 4th phase culminating on 3 May, 17 May, and 31 May, respectively. On 1 June 2020, the Government of India announced Unlock 1.0, in which prevailing restrictions in non-containment areas were lifted, accounting for the economic downturn resulting from a halt on commercial activity (Saha and Chouhan 2020). Lockdown was imposed to reduce the spread of COVID-19 infection, and it has emerged as one of the mitigating measures to reduce the virus's spread and flatten the curve. Furthermore, restrictions on anthropogenic activities in the country have further improved air quality in various cities. Numerous academic studies have found evidence regarding the reduction in the concentration of criteria pollutants, viz. particulate matter (PM₁₀ and PM_{2.5}), nitrogen dioxide (NO₂), carbon monoxide (CO), ozone (O₃), and sulphur dioxide (SO₂). Sarfraz et al. (2020) evaluated satellite images disclosing strong evidence in reducing NO₂ in Delhi, Mumbai, and parts of Gujarat. Throughout March, a declining trend was observed in concentration levels of PM and tropospheric NO₂ in Delhi, Mumbai, Hyderabad, Kolkata, and Chennai (Singh and Chauhan 2020). Another study analysed reduction in PM_{2.5} levels along with spatial distribution of aerosol optical depth (AOD) using satellite imagery; a significant reduction in PM_{2.5} levels was found due to lockdown in cities with larger traffic volumes in five Indian cities of about 54% (Kumar et al. 2020). Likewise Mahato et al. (2020) studied seven pollutant parameters (PM₁₀, PM_{2.5}, SO₂, NO₂, CO, O₃, and NH₃) for 34 stations in Delhi; the results of this study concluded that PM₁₀ and PM_{2.5} witnessed maximum reduction followed by NO₂, CO, and NH₃; along with that, a slight increase in O₃ concentration was found due to decrease in NO₂ and particulate matter concentrations. Agarwal et al. (2020) conducted a comparative study on air quality in India and China's cities during the lockdown. The study found a gradual decline of PM_{2.5} levels; on the other hand, a sharp decline in concentrations on NO₂ was found during the first lockdown. Sharma et al. (2020) also studied the six criteria pollutants in 22 different regions, and the studies concluded a significant reduction in AQI compared to previous years. Additionally, a significant correlation in northern and eastern regions was also observed in 2020 due to significant regional

transport than in previous years. Similarly, some studies have focussed on air quality change due to lockdown in specific Indian states, like Sharma et al. (2020), focussed on criteria pollutants in Rajasthan.

With several studies conducted throughout India on the effects of lockdown on air quality, most studies have focussed upon the 24-h average pollutant concentration. The present research focuses upon 1-h ambient air pollutant concentration of six criteria pollutants in five centres while studying the role and effect of transport in pollutant concentration in peak and off-peak (non-peak) hours. Peak and off-peak hours are representative periods of high and moderate road traffic, respectively. They are characterised by high traffic volume, and peak hours record the most significant pollutant concentrations during the day. Furthermore, to investigate the role of other parameters like a halt in construction and meteorology, correlations have also been studied between drop-in pollutant concentrations and relevant parameters.

Methodology

Study locations

In the present study of air quality comparison before and after the imposition of lockdown, India's most commerciality-active hubs, including major metropolitan cities of Bangalore, Chennai, Delhi, Kolkata, and Mumbai, have been selected (Table S1, Fig. 1). The reason behind choosing these

Fig. 1 Study locations and metropolitan cities of India

cities is the high degree of economic, industrial, commercial, and tourism activities associated with them, cessation in which the lockdown will cause a statistically significant drop in aerosol emissions. Despite their similarities as the country's economic engine, these metro cities vary considerably in their topographical and meteorological characteristics. The lockdown period, i.e. 24 March to 31 May, represents the summer season in all the study locations, but different geographical locations present vacillating conditions for the transportation of pollutants. Detailed information on the meteorological conditions and individual features of the 5 Indian cities has been shown in Tables S2 and S3.

Data collection

Hourly data for the criteria pollutants, viz. $PM_{2.5}$, PM_{10} , NO_2 , SO_2 , O_3 , and CO , have been acquired from Continuous Ambient Air Quality Monitoring Stations (CAAQMS) (CPCB 2010), which is managed by Central Pollution Control Board (CPCB), Delhi. This data has been collected for the period of 1 February to 31 May for 2019 and 2020. Apart from pollutants, meteorological data, viz. wind speed, wind direction, solar radiation, and rainfall, have also been collected from CAAQMS.

Data analysis

Hourly data from all the monitoring stations in a city have been averaged to obtain mean hourly pollutant concentrations. The hourly data collected has been grouped into three averaged types: first into 24-h average, then into evening peak hours average, morning peak hours average, and off-peak hours average. The time slot for evening peaks and morning peaks are 08:00 to 10:00 h and for morning peak and evening peak from 18:00 h to 21:00 h. The lockdown period 25 March to 31 May 2020 has been divided into 4 phases as per government guidelines: phase 1, 25 March to 14 April; phase 2, 15 April to 3 May; phase 3, 4 May to 17 May; and phase 4, 18 May to 31 May. The data analysis also involved finding the drop percentages trend between the different phases of lockdown with respect to (wrt.) the pre-lockdown period and the base year 2019.

The drop percentages were calculated using the following equations:

Percentage drop wrt.before lockdown

$$= [(C_{BL} - C_{LD}) / C_{BL}] \times 100 \quad (1)$$

Percentage drop wrt.2019

$$= [(C_{2019} - C_{2020}) / C_{2019}] \times 100 \quad (2)$$

where C_{BL} is the pollutant concentration before the lockdown, C_{LD} is the pollutant concentration during the lockdown, C_{2019}

is the pollutant concentration during 2019 (exact dates as 2020), and C_{2020} is the pollutant concentration during 2020 (lockdown dates).

Result and discussion

Hourly pollutant concentrations have been plotted from 1 February to 31 May for 2019 and 2020 (Figures S1-S5 of supplementary material). A trend discernible in most cities, the pollutant concentration in 2019 has reduced steadily as months proceed due to increased mixing height rendered by rising temperatures with the onset of summer (Mor et al. 2021). Contrastingly in 2020, a sharp, more conspicuous drop is visible as the line chart enters the lockdown period (Figure S1-S5). A trend of gradually increasing concentrations can also be observed as the lockdown phases progressed, except in Kolkata, which received heavy rainfall during the lockdown, leading to a further decrease in pollutant concentration..

Particulate matter

PM_{10}

Average hourly PM_{10} concentrations in Delhi decreased by 41%, 22%, 15%, and -10% in phases 1, 2, 3, and 4, respectively, with respect to before lockdown PM_{10} concentrations (Table 1). It indicates that the maximum decrease in pollutant concentrations was observed during phase 1 when anthropogenic activities stopped immediately due to the sudden imposition of a lockdown. However, as new phases were introduced with vantage on restrictions for anthropogenic activities, the pollutant concentrations started increasing gradually until the 4th phase. A similar trend was noted in Bangalore, wherein PM_{10} concentrations decreased by 46%, 44%, 31%, and 39%, respectively (Table 1).

The maximum decrease in average 24-h concentration across all phases was observed in Kolkata, followed by Bangalore, Delhi, and Mumbai. In Mumbai, PM_{10} concentrations during lockdown were consistently more significant than

Table 1 Percentage decrease in PM_{10} concentrations with respect to before lockdown

Phase	Bangalore	Delhi	Kolkata	Mumbai
1	46	41	38	-36
2	44	22	68	-56
3	31	15	62	-49
4	39	-10	63	-58
Average drop	40	17	58	-50

Due to unavailability of PM_{10} data of Chennai for the study period, the present study doesn't include any discussion for the same

before lockdown concentrations by 36%, 56%, 49%, and 58% in the 4 phases, respectively (Table 1). The average decrease in hourly PM₁₀ concentrations in all phases has also been presented for all the cities in Table 1.

As seen in Fig. S1–S5, it can be deduced that the majority of 2019 PM₁₀ peak hour concentrations lie above the 24-h National Ambient Air Quality Standards (NAAQS) limits contrary to 2020 peak hour concentrations. It can also be seen that 2020 PM₁₀ concentrations are above the NAAQS limits majorly before lockdown; as the lockdown begins, the drop is evident. While PM₁₀ (2020) in Delhi has frequently crossed the standard, it remains considerably lower than in 2019 (Fig. 2). Moreover, Delhi's higher PM₁₀ concentrations can be witnessed during the later phases when restrictions were lower. Phase 3 allowed offices and workplaces to function at 33% capacity while also allowing vehicles with two passengers and 2-wheelers with a single rider. Phase 4 further lifted restrictions on public transport, vehicle passenger limits, and workplace limits. Apart from Mumbai, the difference between 2019 and 2020 is more significant during the initial phases. Still, the difference becomes smaller as the final phases are approached, i.e., restrictions on outdoor activities are eased in pollution with commercial activity.

During both peak and off-peak durations, the maximum decrease, averaged across all phases in PM₁₀ concentrations, was observed in Kolkata (52%, 55%), followed by Delhi (46%, 46%), Bangalore (44%, 41%), and Mumbai (Fig. 2). Although, in phase 1, Kolkata witnessed a 20–30% decrease in PM₁₀ concentrations, intermittent heavy rainfall days between 20 April and 6 May (phase 2) further abated PM₁₀ concentrations, leading to 60–70% year on year (y-o-y) reduction. On comparing the y-o-y

reduction in PM₁₀ across all phases, it can be noted from Fig. 2 that coastal cities, i.e. Mumbai and Kolkata, showed a more significant reduction in off-peak durations than peak durations, whereas in inland cities, i.e. Delhi and Bangalore, peak-hour PM₁₀ values showed a more significant y-o-y decrease compared to off-peak hours. Moreover, the y-o-y percentage decrease in 24-h PM₁₀ concentrations indicates that the farther away from the sea the city was, the more significant was the decrease in PM concentrations. However, it must be noted that the neutralising effect of the ocean can only be tangible up to a certain distance, after which the oceans exert little-to-no influence on pollution dispersion.

The more pronounced decline during peak hours in Bangalore and Delhi can also be explained by the fact that these two cities have maximum registered vehicles in India. Due to a more extensive fleet of vehicles rendered stationary due to the lockdown, the peak hours have witnessed a more significant decline in PM₁₀ levels, as seen in Fig. 2. Since accurate data on traffic reduction due to the lockdown was not available, to compare the drop in PM₁₀ levels during peak hours with traffic, a regression analysis was plotted between percentage decrease in PM₁₀ evening and morning peak hour concentration with vehicle count of the cities. The R^2 value of 0.7447 and 0.6329 was obtained, respectively, relating decline during peak hours to the number of vehicles in the city (Fig. 3). The correlation between percentage decrease in average 24-h PM₁₀ concentration during phase 1 with vehicle count displays an overwhelming R^2 value of 0.9711 (Fig. 3), therefore emphasising that reduced traffic on roads due to the lockdown was a significant cause of the decline in PM₁₀ levels.

Fig. 2 Phase-wise year-on-year percentage drop in PM₁₀—peak vs off-peak hours

Fig. 3 Vehicle count correlation with year-on-year PM₁₀ percentage drop—evening peak, morning peak, and 24-h average (clockwise from top-left)

Thermal power plants (TPPs) are also significant contributors to particulate pollution; however, even during the lockdown, the TPPs were functioning at an equal capacity, therefore not contributing to the decrease in particulate pollution. Apart from power plants and traffic, there are two critical PM₁₀ emitters. Road dust and construction are the top two contributors to PM₁₀ in Delhi at 24 kt/year and 14.2 kt/year, respectively (Sharma and Saraf 2018). In Delhi and the other four selected cities, construction and road dust are significant inter-linked contributors to PM₁₀ (CPCB 2010; Guttikunda et al. 2019; NEERI 2010). On regression analysis of the contribution of road dust and construction to PM₁₀ and year-on-year phase 1 PM₁₀ decline for each city, the R^2 value of 0.8032 was obtained (Fig. 4), signifying an essential role of halt in construction activity in decreasing PM₁₀ concentration.

Another trend observed in inland cities is that y-o-y PM₁₀ concentration levels increase with every successive phase, i.e. as commercial activity increases with the introduction of a new phase, the difference between the PM₁₀ levels of 2019 and 2020 also becomes narrower. Morning peak and off-peak hours during phase 3 in Delhi show an anomaly due to the capital's heavy rainfall during this phase. In week 11, after lockdown imposition (17 to 24 May 2020), 2020 PM₁₀ concentrations have regularly crossed the 2019 levels due to heavy rainfall in 2019 during this week. This anomaly can also be attributed to Rajasthan's high surface winds this week, which also contributed to greater PM₁₀ concentration in 2020.

Barring these days, on almost every other occasion, 2020 PM₁₀ concentrations are lower in Delhi. Mumbai was the only city wherein an increase in PM₁₀ concentrations was observed. During morning peak durations, Mumbai witnessed a decline in PM₁₀ only during the second phase (Kumari and Toshniwal 2020; Mahato et al. 2020). In contrast, increases of 4%, 23%, and 4% were observed during the 1st, 3rd, and 4th phase, respectively. However, in evening peak and off-peak timings, Mumbai witnessed a y-o-y increase in PM₁₀ only during the third phase of lockdown. The abnormal increase witnessed in Mumbai with respect to 2019 is attributable to the increase in average wind speeds from 0.13 to 1.28 m/s. In

Fig. 4 Year-on-year PM₁₀ percentage drop correlation with construction and road dust contribution to PM₁₀

Mumbai being a coastal city, increased wind speed subsequently increases sea-salt concentrations, which are further transported to the air above land (Nair et al. 2005).

PM_{2.5}

The maximum decrease in PM_{2.5} with respect to before lockdown averaged across all phases was observed in Kolkata (60%), followed by Bangalore (44%), Chennai (42%), Delhi (23%), and Mumbai (−46%) (Table 2). Similar to PM₁₀, Mumbai witnessed an increase in PM_{2.5} in all the phases. It is hypothesised that the increase in wind speeds wrt. before lockdown is an attributable reason for Mumbai's abnormal PM concentration rise. Figure 5 shows a high positive correlation ($R^2 = 0.8706$) between the increase in wind speed and PM_{2.5} concentrations. Wind speeds directly influence the concentration of particulate matter. It can be seen in Table 2 that while PM has consistently increased wrt. Before Lockdown (BL) in Mumbai, there has been a simultaneous decrease in gaseous pollutants such as NO₂ and CO. If the reason behind PM rise was source-related, a similar increase in gaseous pollutants would be expected, which is not the case. Moreover, since the wind direction during the lockdown period was majorly from West to East, i.e. from the sea towards the coast, it can be deduced that sea salt aerosols from the sea may be a contributing factor towards the increased particulate concentration in Mumbai.

For peak and off-peak hours' analysis, a percentage decrease has been calculated concerning 2019 than before lockdown. This is primarily due to the fact that even before lockdown imposition, traffic was lower than usual due to public awareness about the contagious virus. Minimum year-on-year decrease in PM_{2.5} concentrations has been observed in Mumbai, followed by Delhi in peak and off-peak hours across all phases (Table 3). Like PM₁₀ trends of inland cities, Delhi and Bangalore experienced more significant PM_{2.5} reductions during peak hours due to a more extensive vehicle fleet. Vehicles being an essential source of PM_{2.5}, on regression analysis of y-o-y percentage decrease in 24-h PM_{2.5} concentrations with vehicle count in the five cities, an R^2 value of 0.7163 was obtained (Fig. 6), indicating that the reduction in

PM_{2.5} was more significant in cities with a more extensive vehicle fleet.

Coastal cities being surrounded by the ocean are subject to enormous ventilation potentials, which enhance the pollutant assimilation due to breeze exchange. The ocean's neutralising effect on particulate pollution helps coastal cities maintain their air pollution levels compared to landlocked cities. The absence of pollutant assimilation due to being landlocked prevents the dispersion of air pollutants in cities like Delhi and Bangalore. Therefore, landlocked cities like Delhi have much higher baseline levels of particulate pollution. The high 'before lockdown' levels due to lack of pollutant dispersion in landlocked cities imply that when lockdown is imposed and emissions are drastically minimised, the percentage drop is much more significant than coastal cities with already low baseline particulate pollution (Kumar et al. 2015).

After transport, road dust is the second most significant contributor to PM_{2.5} concentration levels. However, road dust is directly related to traffic on roads, so lesser traffic can be conferred as the most crucial cause of better air quality. While establishing a correlation, no concrete relation was discerned between PM_{2.5} and construction activity and industrial activities. This may be because construction activities tend to influence PM₁₀ concentrations more than PM_{2.5} (Azarmi et al. 2016). In line with anomalous PM₁₀ trends observed in Mumbai, the city observed increasing PM_{2.5} concentrations on several occasions. During off-peak hours, PM_{2.5} concentrations in Mumbai increased only during the third phase (Fig. 7). However, in evening and morning peak hours, three phases recorded increasing PM_{2.5} (Table 3). This trend, however, is specific to Mumbai. In all the other megacities, PM_{2.5} declined consistently wrt. 2019. Averaging the y-o-y percentage change in all the cities across four phases, it can be observed that the most significant decrease in PM_{2.5} occurred during off-peak hours (40%) compared to 32% and 34% decline during evening and morning peak hours, respectively. In Bangalore, Chennai, and Delhi, the smallest drop in year-on-year PM_{2.5} concentrations was observed during the final lockdown phase when there were minimum restrictions on public activity. In Kolkata, lower PM_{2.5} concentrations in the 4th phase of the lockdown were primarily because of the city's rainfall in May.

Gaseous pollutants

In addition to the significant PM drop in Indian urban cities, the lockdown also significantly contributed to reducing the concentration of gaseous pollutants.

NO₂

Among all the pollutants, NO₂ showed the most significant drop across all the cities. Across all the five selected cities,

Table 2 Percentage decrease in PM_{2.5} concentrations with respect to before lockdown

Phase	Bangalore	Chennai	Delhi	Kolkata	Mumbai
1	34	26	37	31	−24
2	42	66	30	71	−46
3	47	60	15	67	−52
4	53	18	10	73	−62
Average drop	44	42	23	60	−46

Fig. 5 Correlation between the percentage increase in PM_{2.5} and percentage increase in WS (Mumbai) w.r.t Before Lockdown

there was an average 51% drop in concentration levels of NO₂ wrt. Before Lockdown (BL) and 46% drop wrt. 2019. Furthermore, wrt. BL, Mumbai recorded the most significant drop (69%) in concentration levels of NO₂, and in contrast, Chennai recorded the lowest drop (18%) in concentration levels of NO₂. The slight drop recorded in Chennai is primarily due to low (10.50 µg/m³) NO₂ concentration levels even before lockdown, whereas other cities had much higher NO₂ concentration levels than Chennai (Fig. S1–S5). Even wrt. 2019, Chennai recorded the slightest drop in NO₂ (31%). The significant reduction in concentration levels of NO₂ in the selected cities is chiefly attributed to minimal vehicle transportation in the cities; only emergency vehicular

transportation was allowed in the first phase of the lockdown (Singh and Chauhan 2020). This supports the research that vehicular traffic is a significant contributor to NO₂ concentration levels, especially in megacities. Also, Fig. S1–S5 shows that with ease in lockdown, the concentration levels in NO₂ rose in all the cities except Kolkata. The abnormal conditions in concentration levels of NO₂ in Kolkata are due to an increase in ambient temperature and wind speed of 7% and 18%, respectively, from phase 1 to phase 4. An increase in temperature reduces the atmosphere's stability and increases the mixing height, thereby increasing the vertical mixing of pollutants (Mor et al. 2021). In contrast, Kolkata recorded an average increase of 30% in concentration levels of NO₂ from phase 1 to phase 4. Across all the study locations, the lowest decrease wrt. 2019 was observed in the final phase of lockdown when restrictions on the general public were least. Among the peak and off-peak hours, the five selected cities recorded the largest drop in NO₂ concentration levels in evening peak hours (57%), followed by morning peak (51%) and off-peak hours (46%). From Fig. 8, it can be observed that NO₂ showed a sharper decrease in peak hours over off-peak hours throughout the study locations. This more significant

Table 3 Year-on-year percentage decrease in PM_{2.5} during morning, evening and off-peak hours

Peak	Phase	Bangalore	Chennai	Delhi	Kolkata	Mumbai
Morning peak	1	41	25	45	22	−4
	2	43	57	36	60	9
	3	42	62	43	76	−11
	4	38	17	23	63	−7
Evening peak	1	60	45	46	16	−35
	2	57	58	24	63	−1
	3	59	69	26	63	−56
	4	42	29	4	64	2
Off-peak	1	45	41	47	25	18
	2	43	62	34	61	33
	3	43	79	44	65	−12
	4	43	40	14	63	9
Peak average	1	50	35	46	19	−19
	2	50	58	30	61	4
	3	50	66	35	70	−34
	4	40	46	13	64	−1

Fig. 6 PM_{2.5} percentage drop correlation with vehicle population

Fig. 7 Phase-wise year-on-year percentage drop in $PM_{2.5}$ —peak vs off-peak hours

decrease during peak durations suggests the role of traffic in NO_2 reduction.

O_3

Interestingly, apart from all the gaseous pollutants, which observed a drop in their respective concentration levels, O_3 concentration levels increased by 12% in Chennai, Delhi, and Kolkata; Bangalore and Mumbai recorded a slight decrease (7%) in O_3 concentration levels (Fig. S1–S5). This phenomenon is closely related to the concentration levels of NO_2 . NO_x helps in the conversion/breakdown of O_3 into O_2 . For a long time, it has been

debated whether the Indian urban cities are VOC or NO_x limited. The trend of O_3 , as depicted in Fig. S1–S5, shows how the O_3 levels increase in most of the cities and, at the same time, decrease in NO_2 concentration levels. Through these trends and previously conducted studies by Chen et al. (2021), it is precedent that the O_3 production in Indian urban cities is VOC-limited. These results indicate that there is a need to control VOC production alongside PM and NO_2 . If VOC production is not limited, the O_3 concentration levels could reach alarming levels, crossing the NAAQS for O_3 ($100 \mu g/m^3$). It can be seen from Fig. 9 that O_3 concentration had increased consistently during peak hours across all the cities. However, during off-peak

Fig. 8 Phase-wise year-on-year percentage decrease in NO_2 —peak vs non-peak hours

Fig. 9 Phase-wise year-on-year percentage decrease in O₃—evening peak vs non-peak hours

hours, O₃ has somewhat decreased in Delhi and Mumbai. It further adds to the hypothesis that ozone concentrations are inversely related to NO₂ concentrations. NO₂ shows a more significant decrease during peak hour durations, while ozone concentration increases during peak hours.

Another reason for O₃ increases across all cities is attributed to a smaller decrease in CO. Data showed that ozone concentrations increased whenever the percentage decrease in CO was lower than 20%. Since CO is involved in O₃ formation, the more significant the reduction in CO, the greater decrease should be in O₃ (NRC 1999). The correlation between the percentage decrease in CO and O₃ in all cities and all phases indicates a positive correlation ($R^2 = 0.5638$), which suggests the possibility that the ozone increase can be attributable to slowly declining CO (Fig. 10).

Fig. 10 Percentage decrease in ozone correlation with percentage decrease in CO

CO

In the concentration levels of CO across all the five selected cities, there was an average 29% drop between before lockdown and phase 1. The year-on-year average decrease for all the cities except Mumbai due to lack of available data was 23%. The lowest year-on-year decrease was observed in Kolkata (16%), while the highest drop was observed in Delhi (46%) (Fig. S1–S5). Across phase 1 and phase 4, the cities of Delhi and Chennai observed an increase in CO concentration levels by 50% and 75%, respectively, resulting from the reduction in restrictions across phases. However, Mumbai and Kolkata saw a further decrease in CO concentrations by 39% and 29%, respectively. At the same time, Bangalore has a minor reduction of only 4% (Fig. S1–S5).

From Fig. 11, in Bangalore and Kolkata, CO has consistently increased with respect to 2019 during off-peak hours. This increase can be attributed to the fact that in 2019, Bangalore and Kolkata already had the lowest CO concentrations, 0.76 mg/m³ and 0.52 mg/m³, respectively, compared to 1.08 mg/m³, 1.67 mg/m³, and 0.82 mg/m³ for Delhi, Mumbai, and Chennai, respectively. However, unlike off-peak durations, peak hours presented a consistent decline in CO concentrations compared to 2019, which can be owed majorly to reducing traffic volume due to the lockdown since vehicles are the single largest source of CO in Delhi.

SO₂

The SO₂ concentration in the selected five cities observed an average decline of 23% in phase 1 with respect to Before

Fig. 11 Phase-wise year-on-year percentage decrease in CO—peak vs non-peak hours

Lockdown (BL) in 2020. The slightest drop was recorded in Delhi (7%) (Fig. S1). Delhi's low decline can be attributed to the early launch of BS-VI fuel in India's National Capital Territory. India shifted from BS-IV fuel to directly BS-VI fuel, which implies five times decrease in the fuel's sulphur content. Earlier, the fuel used to have 50 ppm sulphur, whereas the new BS-VI fuel contains just 10 ppm sulphur. In Delhi, the BS-VI fuel was launched in April 2019; however, it was launched in April 2020 in the rest of the nation (BCMT 2020). Every city observed an increase in concentration levels of SO_2 as the phases progressed and lockdown restrictions started to ease, except Kolkata.

In contrast, Kolkata recorded a further decrease of 47% in phase 4 with respect to phase 1 in 2020 (Fig. S3). The further drop in Kolkata is mainly due to meteorological conditions attributed to Kolkata, especially wind speed and atmospheric temperature. Progressive increase in temperature across phases increased mixing height. The wind speeds in Kolkata rose by 57% from phase 1 to phase 4 in 2020 (Tasić et al. 2013). However, from Fig. 12, it can be seen that in terms of year on year change, in Kolkata and Bangalore, SO_2 concentration increased during peak hours. This anomaly is mainly because SO_2 concentrations were already low in 2019 in these two cities during these dates.

Fig. 12 Phase-wise year-on-year percentage decrease in SO_2 —peak vs off-peak hours

Conclusion

A comparison of five megacities has been studied to discern the role of reduced traffic, halt in construction, meteorological parameters, and other anthropogenic factors in ameliorating air quality due to the imposition of a lockdown. For peak hours and off-peak hours analyses, a comparison was made with 2019 rather than before lockdown. The holistic analysis of pollutant concentrations of PM₁₀, PM_{2.5}, NO₂, SO₂, CO, and O₃ resulting from this study lends several conclusive outcomes. PM₁₀ and PM_{2.5} recorded a maximum overall drop in Kolkata (58%, 60%) and an overall increase in Mumbai (50%, 46%) mainly due to a consistent rise in wind speed in the respective cities. High positive correlations of 24-h average drop percentages have been recorded with vehicle populations for PM₁₀ ($R^2 = 0.97$) and PM_{2.5} ($R^2 = 0.72$), relating drop in particulate pollution to reduced road traffic. PM₁₀ drop percentages also showed a significant correlation ($R^2 = 0.80$) with dust contribution to total particulate emissions. Among gaseous pollutants, maximum drop averaged across wrt. Before Lockdown (BL) in all studies, locations were recorded in NO₂ (51%), followed by CO (29%) and SO₂ (23%), while ozone recorded an overall increase (4%). Among all pollutants, wrt. 2019, the maximum drop was observed in NO₂ (46%), followed by PM_{2.5} (40%), PM₁₀ (37%), and CO (19%), suggesting that vehicle-dominated pollutants declined by the greatest during the lockdown. The more significant decrease in NO₂ and CO in peak hours over off-peak hours further suggests the role of reduced traffic volume. The lowest drop wrt. before lockdown was observed in the case of SO₂ (23%), primarily due to SO₂ not being a primary vehicular pollutant. Instead, SO₂ is linked with power plants that were running at equal capacity during the lockdown. The increase in ozone concentrations can be attributed to low NO₂ conditions rendered by reduced traffic since NO₂ is involved in ozone decomposition, and a lower decrease in CO, which is involved in tropospheric ozone formation. The reduction in ozone concentrations showed a positive correlation with the decline in CO ($R^2 = 0.5638$). The present study will help policymakers identify the factors that led to the changes in concentration levels of criteria pollutants and enable them to draft a response plan for high air pollution incidents in metro cities.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12517-021-07777-x>.

Acknowledgements The authors are very much thankful to Advance Air and Acoustics Research Lab, Delhi Technological University, for providing necessary facilities to conduct this study.

Availability of data and material The data used in the current study have been taken from CPCB and is available in the public domain.

Code availability Not applicable

Declarations

Conflict of interest The authors declare no competing interests.

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