Can the nation-wide COVID-19 lockdown help India identify region-specific strategies for air pollution?

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Abstract Air pollution is a serious concern with the developing economics in India and gets more severe when it has major cities ranked among the top 30 polluted cities worldwide. To find a solution, different programs and/or policies have been launched for air quality management country-wide. Unfortunately, no such plan could effectively solve the purpose rather than an unexpected COVID-19 pandemic situation in India. Our study focused on the air pollution status and air quality index (AQI) in 42 cities (that includes 6 metros) representing North, South, East, West, Central, and North-East region of India during the pre-lockdown, four lockdowns and unlock phases. The results depict most of the pollutants except ozone (O₃) were significantly reduced in the lockdown-1, and marginally increased in subsequent lockdown phases. Regarding the average AQI, its value was highest in North Indian cities (227), followed by East India (172), Central

India (141), North-East India (130), West India (124), and South India (83) during the pre-lockdown. Due to COVID-19 induced lockdown, North Indian cities observed the highest dip in average AQI (108), followed by Central India (113), East India (82), West India (73), South India (55), and North-East India (49) in the lockdown and unlock phases. Thus, the study gave a conspicuous vision on mitigation of air pollution under this pandemic; and, if strategic centralized policies are sensibly implemented and by involving the participation of people of India, then there is a feasibility of air pollution issue management.

Keywords COVID-19 pandemic · Nation-wide lockdown · 42 Indian cities · Air Quality Index · Air pollution abatement policies

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1 Introduction

Over the past years, Indian cities were ranked amongst the top air-polluted cities worldwide [1]. Reports on the emission source apportionment of both the gaseous and particulate pollutants demonstrated that vehicular exhausts, industrial operations, burning of crop residues and trash, dust from constructions and roads are the major pollution contributors [2, 3]. Air pollution exerts adverse effect not only on the nature and climate but also on the human health. According to the World Health Organization, approximately 4.1 million deaths have occurred from heart disease and stroke, lung cancer, chronic lung diseases, and respiratory infections between 2010 and 2016 due to the exposure to poor air quality [4]. Different countries have opted for several programs and policies to combat air pollution. Likewise in India, the National Clean Air Program (NCAP) has been launched with a target of 20–30% emission reduction in the pollutant concentrations by the year 2024 [5]. Though, the NCAP has certainly strengthened the air pollution monitoring across India; but it lacks innovation especially needed to tackle the major sources of pollution except for some conventional strategies. Unfortunately, despite all the initiatives, the problem of air pollution is still becoming a more serious issue in India.

During the COVID-19 pandemic enforced lockdown, the air pollution levels plummeted into unusually clean air quality levels which had not been experienced in decades. Researchers from across the world also found an opportunity in the lockdown to analyze the impacts of human activities on the environment and explore the ways to use this information to improve the environment in the post-COVID world. Specifically, in regards to the air pollution, several studies during the lockdowns showed up to a 50% reduction in pollution levels than the pre-COVID situation [6, 7].

In India, the lockdown continued over four phases (25th March to 31st May 2020) with varying levels of activities. The present study mainly focuses on identifying the spatial and temporal patterns of the ambient air quality, and its relationship with the dynamic anthropogenic activities during the pre-lockdown, lockdown, and unlock phases for 42 cities selected from all over the India. The obtained results might help to develop a baseline data or a possible roadmap which could be useful for introducing and/or implementing innovative policies towards the effective control of air pollution throughout India.

2 Method

2.1 COVID-19 lockdown and selection of Indian cities

With only 500 confirmed COVID-19 cases in the country, the Ministry of Home Affairs, Government of India, decided to impose a stringent nationwide lockdown suspending most of the economic activities, services, and movement of people (Table 1). The 67-day historical lockdown had affected the lives of every Indian citizen around the country. Following the demographic and anthropogenic nature, a total of 42 cities, including 06 mega-cities were selected for this study. The Indian states and the union territories were grouped into six regions, i.e. -North, South, East, West, Central, and North-East (Table 2).

2.2 Air quality data and Air Quality Index (AQI)

Following the guidelines of the National Ambient Air Quality Standards (NAAQS), the day-wise data of seven major particulate and gaseous air pollutants, i.e.—particulate matter with aerodynamic size $\leq 2.5 \mu$ and 10μ ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), ammonia (NH_3), sulfur dioxide (SO_2), ozone (O_3), and carbon monoxide (CO) were obtained from the Central Pollution Control Board (CPCB) online portal for air quality data dissemination [8] for the pre-lockdown, lockdown, and unlock phases (Table 1).

An average Air Quality Index (AQI) value was calculated with the phase- and city-wise obtained data for all seven major pollutants [9]. The sub-index of AQI for each pollutant (i) is calculated using the following equation—

$$AQI_i = \frac{IN_{HI} - IN_{LO}}{B_{HI} - B_{LO}} \times (C_i - B_{LO}) + IN_{LO} \quad (1)$$

where C_i = the concentration of pollutant ' i ' B_{HI} = Breakpoint concentration greater or equal to given concentration; B_{LO} = Breakpoint concentration smaller or equal to given concentration; IN_{HI} = AQI value corresponding to B_{HI} ; IN_{LO} = AQI value corresponding to B_{LO} .

Finally the all the sub-indices of AQI_{*i*} were integrated to compute AQI.

2.3 Cartographic analyses

The average AQI values were plotted using the Inverse Distance Weighted (IDW) interpolation method in the ArcGIS 10.5 Spatial Analyst tool.

Table 1 Recommendations of Ministry of Home Affairs, Govt. of India, regarding the permissible and non-permissible activities during the pre-lockdown, lockdown and unlock phases

Anthropogenic activities*	Pre-lockdown (17 January - 24 March 2020)	Lockdown Phases (25 March - 31 May 2020)				Normalization Unlock (1 June - 31 June 2020)
		Lockdown -1 (25 March -14 April)	Lockdown -2 (15 April -3 May)	Lockdown -3 (4 May - 17 May)	Lockdown -4 (18 May - 31 May)	
Central & State Government Offices						
Educational Institutions						
Health & Health Care Services						
Industrial Establishments						
Commercial & Private Establishments						
Religious/Social/Political Gatherings						
Hospitality Services						
Railways Transport						
Roadways Transport						
Services related to Public Utilities						
	Not Allowed		Partially allowed			Allowed

*Adopted from the Ministry of Home Affairs, Government of India (vide Ref. No. – G.O. No. 40-3/2020 DM-I (A) dated 24.03.2020 (for Lockdown- 1); G.O. No. 40-3/2020 DM-I(A), dated 14.04.2020 (for Lockdown- 2); G.O. No. 40-3/2020 DM-I(A), dated 01.5.2020 (for Lockdown-3); G.O. No. 40-3/2020 DM-I(A), dated 17.5.2020 (for Lockdown- 4) and subsequently 01.06.2020 onwards to reopen the prohibited activities outside containment zones in phased manner (vide Ref. No. – G.O. No. 40-3/2020 DM-I(A), dated 30.05.2020)

2.4 Statistical analyses

The phase- and city-wise data obtained from all the available monitoring stations (at least more than one station per city) for the AQI and all 07 pollutants were compared and analyzed using the R- statistical package (version 1.1.3). Box and whisker plots were plotted to visualize the distribution of data in terms of the lower quartile, upper quartile, median, minimum, and maximum value for each region. This was performed to interpret the variation of AQI and air pollutant concentrations for pre-lockdown, lockdown, and unlock phases.

3 Results

The AQI is a single index value obtained from the cumulative calculation of the major criteria pollutants and demonstrates the nature and breathability of the ambient air. In India, the National AQI was introduced in the year 2014. The AQI is divided into five categories- good (0–50), satisfactory (51–100), moderate (101–200), poor (201–300), very poor (301–400), and severe (> 401). During the lockdown, the average AQI value significantly improved to moderate and good from the very poor and poor of the pre-lockdown in all the Indian cities (Fig. 1). In North India, the average AQI values decreased from 227 (poor) of pre-lockdown to 83 and 98 (satisfactory) in lockdown-1 and 2, followed by a slight increase to 127, 124, and 115 (moderate) in lockdown-3, 4, and unlock,

Table 2 List of forty-two cities selected from different states and union territories across six geographical regions in India

Groups	Regions	States/Union territories	Cities
1	North	1. Uttar Pradesh 2. Punjab 3. Haryana 4. Delhi 5. Chandigarh	1. Ghaziabad, 2. Lucknow, 3. Noida, 4. Amritsar, 5. MandiGobindgarh, 6. Faridabad, 7. Gurugram, 8. Delhi*, 9. Chandigarh,
2	South	6. Andhra Pradesh 7. Telangana 8. Tamil Nadu 9. Karnataka 10. Kerala	10. Visakhapatnam, 11. Tirupati, 12. Hyderabad*, 13. Chennai*, 14. Coimbatore, 15. Bengaluru*, 16. Mysuru, 17. Thiruvananthapuram, 18. Kochi,
3	East	11. West Bengal 12. Bihar 13. Jharkhand 14. Odisha	19. Kolkata*, 20. Howrah, 21. Asansol, 22. Patna, 23. Muzaffarpur, 24. Gaya, 25. Joraphokhar, 26. Brajrajnagar, 27. Talcher,
4	West	15. Gujarat 16. Rajasthan 17. Maharashtra	28. Ahmedabad, 29. Gandhinagar, 30. Jaipur, 31. Jodhpur, 32. Mumbai*, 33. NaviMumbai, 34. Thane
5	Central	18. Madhya Pradesh	35. Bhopal, 36. Dewas, 37. Gwalior, 38. Indore, 39. Singrauli,
6	North-East	19. Assam 20. Meghalaya 21. Mizoram	40. Guwahati, 41. Shillong, 42. Aizawl

*The 06 megacities with a population of more than 10 million—Delhi (30 million), Mumbai (20 million), Kolkata (15 million), Bengaluru (12 million), Chennai (11 million), and Hyderabad (10 million)

respectively (Fig. 2). The national capital New Delhi witnessed a steady improvement in the average AQI values from 245 (poor) of pre-lockdown to 79 and 92 (satisfactory) during the lockdown-1 and 2, which again deteriorated to 137, 111, and 115 (moderate) in lockdown-3, 4, and unlock, respectively (Figs. 1 and 3). In this region, the improvement in the average AQI values could be directly correlated to the significant reductions in the concentrations of $PM_{2.5}$, PM_{10} , NO_2 , NH_3 , and CO during the lockdown and unlock, as compared to the pre-lockdown. The SO_2 decreased significantly during the lockdown-1 and 2; but slightly increased in the lockdown-3 and 4, as compared to the pre-lockdown. The $PM_{2.5}$ in New Delhi significantly decreased by 60.61% in lockdown-1, 47.82% in lockdown-4, and 51.2% during unlock phase, as compared to the pre-lockdown; which might indicate the importance of partial restrictions on anthropogenic activities especially related to the $PM_{2.5}$ generation (Table 1).

In general, the air quality in the South Indian region was better as compared to North India. The average AQI values in South Indian cities were significantly reduced to 58–50 in lockdown-1 and unlock phase from 83 (satisfactory) of

pre-lockdown (Fig. 2). With respect to the individual criteria pollutants, the South Indian cities also witnessed similar decreasing trends as of North Indian cities during the lockdown. The concentrations of $PM_{2.5}$ substantially decreased by 34.6–54.6% during lockdown-1 to 4 and unlock phases, as compared to the pre-lockdown, respectively. Like in the general air quality of the South Indian region, the average AQI value of Bengaluru was 86 (satisfactory) during the pre-lockdown; but improved to 43–60 (good-satisfactory) in lockdown and also maintained till unlock (Figs. 1 and 4). On the contrary, the average AQI value of Chennai demonstrated an unusual increase of 35.38% and 16.92% from 65 (satisfactory) of pre-lockdown to 88 and 76 (satisfactory) in the lockdown-4 and unlock phase (Figs. 1 and 5). This unusual trend in Chennai might be correlated with the sudden increase in the concentrations of PM_{10} and O_3 during the later phase of the lockdown and unlock. In Hyderabad too, the decreasing trends in the average AQI value were slightly changed to 96 (satisfactory) in lockdown-4 (3.22% increment) only but again recovered to 45 (good) during the unlock as compared to the average AQI value of 93 (satisfactory) in the

Fig. 1 Spatio-temporal pattern in the Air Quality Index for the forty-two (42) selected Indian cities. **a** Pre-lockdown, **b** Lockdown-1, **c** Lockdown-2, **d** Lockdown-3, **e** Lockdown-4, **f** Unlock. **A** Guwahati, **B** Shillong, **C** Aizawl, **D** Howrah, **E** Kolkata, **F** Asansol, **G** Gaya, **H** Muzaffarpur, **I** Patna, **J** Joraphokhar, **K** Brajrajnagar, **L** Talcher, **M** Mumbai, **N** Navi Mumbai, **O** Thane, **P** Ahmedabad,

Q Gandhinagar, **R** Jaipur, **S** Jodhpur, **T** Bhopal, **U** Dewas, **V** Gwalior, **W** Indore, **X** Singrauli, **Y** Visakhapatnam, **Z** Tirupati, **A1** Thiruvananthapuram, **B1** Kochi, **C1** Bengaluru, **D1** Mysuru, **E1** Chennai, **F1** Coimbatore, **G1** Hyderabad, **H1** Faridabad, **I1** Gurugram, **J1** Ghaziabad, **K1** Lucknow, **L1** Noida, **M1** Delhi, **N1** Amritsar, **O1** Mandi Gobindgarh, **P1** Chandigarh

pre-lockdown (Figs. 1 and 6). Among the criteria pollutants, the O_3 demonstrated unlikely increasing trends in the cities like Chennai and Hyderabad during the later lockdown and unlock phases, as compared to the other South Indian cities; and were the reason behind higher average AQI values.

In the East Indian cities, the average AQI values demonstrated almost similar trends to the North Indian region, and decreased by 42–60.9% during the lockdown and unlock phases, as compared to pre-lockdown, respectively (Fig. 2). This improvement in air quality was mainly because of the significant reduction in all the criteria pollutants, except O_3 , during the lockdown and subsequent phases. Among all 07 pollutants, the $PM_{2.5}$ showed the best

improvements followed by the others during the lockdown. However, the concentrations of O_3 demonstrated unusual increasing trends, especially in Kolkata and Patna, during the lockdown and subsequent phases, as compared to pre-lockdown. Still, the most important city of the East Indian region, Kolkata witnessed an overall reduction in the average AQI values by 45.75–69.93% from 153 (moderate) of pre-lockdown to 83–46 (satisfactory) during the lockdown-1 and unlock, respectively (Figs. 1 and 7). The other important cities, like—Patna and Howrah, too experienced a similar improvement in the average AQI values during the lockdown (Fig. 1). Notably, the Muzaffarpur city in Bihar experienced the highest improvement in the air quality amongst the East Indian cities with an 84.26%

Fig. 2 Spatio-temporal pattern in Air Quality Index in six Indian regions. **I** Pre-lockdown, **II** Lockdown-1, **III** Lockdown-2, **IV** Lockdown-3, **V** Lockdown-4, **VI** Unlock

reduction in the average AQI values from 305 (very poor) of pre-lockdown to 48 (good) in lockdown-4, (Fig. 1).

Similar to the other parts of India, the average AQI values improved to 73 and 53 (satisfactory) during the lockdown and unlock, from 124 (moderate) of pre-lockdown in the West Indian region too (Fig. 2). A significant reduction in all the criteria pollutants contributed to these improved AQI values, except O_3 , in the major West Indian cities. The Indian financial capital-Mumbai, located at the Arabian Sea coast, also recorded a significant improvement in the average AQI values from 132 (moderate) of pre-lockdown to 71–53 (satisfactory) and 34 (good) during the lockdown and unlock phases (Figs. 1 and 8). The concentrations of $PM_{2.5}$ in Mumbai were decreased by 52.3–79.1% during the lockdown and unlock phases, respectively, as compared to its pre-lockdown values. Jaipur and Jodhpur exceptionally observed an enhancement by 15% and 29.6% in the average AQI values from 113 and 125 (moderate) of pre-lockdown to 130 and 162 (moderate)

in lockdown-4 respectively (Fig. 1). This abrupt increase in AQI during lockdown-4 might be due to an elevation in $PM_{2.5}$, PM_{10} , and O_3 levels which were triggered by sudden relaxation in transportation and industrial activities (Table 1).

In the Central Indian cities, the average AQI values followed almost similar trends like the North, South, East, and West Indian region, and decreased by 11.7% to 37.8% during the lockdown and unlock phases, as compared to pre-lockdown, respectively (Fig. 2). The average AQI values recorded an improvement in all the cities except in Singrauli as its average AQI value increased by 15.42% from 175 (moderate) of pre-lockdown to 202 (poor) during lockdown-4 (Fig. 1). With respect to the concentrations of all criteria pollutants, the $PM_{2.5}$ and NO_2 demonstrated the highest reduction. The $PM_{2.5}$ reduced by 21.95% in lockdown-1 and 46.34% in unlock as compared to the pre-lockdown. Except for O_3 and SO_2 , the concentrations of PM_{10} , NO_2 , NH_3 , and, CO also demonstrated the declining

Fig. 3 Spatio-temporal pattern of Air Quality Index in New Delhi. **a** Pre-lockdown, **b** Lockdown-1, **c** Lockdown-2, **d** Lockdown-3, **e** Lockdown-4, **f** Unlock

trends in lockdown-1 and unlock than pre-lockdown. The O_3 and SO_2 demonstrated significant and non-significant increasing trends during lockdown and unlock phases in cities like Singrauli, Dewas, Indore, and Gwalior, as compared to the pre-lockdown period.

In North-East Indian cities, the average AQI values during the lockdown and unlock phases reduced by 20.2–81.84% as compared to the pre-lockdown. Of all the phases, the unlock phase witnessed the highest improvement in air quality as the average AQI value decreased by 81.84% from 130 (moderate) of pre-lockdown to 24 (good) during this phase (Fig. 2). In this region, the most important city Guwahati witnessed a significant improvement in the average AQI values from 264 (poor) of pre-lockdown to 39–49 (good) during lockdown-2, 3, 4, and unlock (Fig. 1). Notably, the average AQI value of Shillong and Aizawl improved to 20–27 and 8–20 (good) during lockdown and unlock from 64 and 60 (satisfactory) of pre-lockdown (Fig. 1). In this region, all the pollutants except SO_2 exhibited a significant decrease during the lockdown and unlock period.

Among all the regions, North India experienced the worst air quality during the pre-lockdown followed by East

India and Central India. In North India, the average AQI values were recorded as 245, 293, 255, and 204 (poor) in four major cities *i.e.* Delhi, Ghaziabad, Noida, and Lucknow; whereas, the other cities, *i.e.* Faridabad, Gurugram, Amritsar, and Mandi Gobindgarh witnessed the average AQI values of 165, 145, 103, and 123 (moderate) during the pre-lockdown. The lockdown have definitely improved the air quality in these North Indian cities, except Gurugram, with slight differences in the pattern of improvement (Fig. 1). Comparatively, the air quality was satisfactory for South India and moderate for West India and North-East Indian cities during pre-lockdown. Therefore, these regions recorded a lesser percent improvement in air quality during lockdown as compared to North, East and Central India.

4 Discussion

4.1 Spatio-temporal pattern of air quality index (AQI) and major air pollutants

Following the results obtained for all the studied cities throughout India, it is evident that the significant

Fig. 4 Spatio-temporal pattern of Air Quality Index in Bengaluru. **a** Pre-lockdown, **b** Lockdown-1, **c** Lockdown-2, **d** Lockdown-3, **e** Lockdown-4, **f** Unlock

improvement in the air quality was mainly due to the government imposed nationwide lockdown, *i.e.* complete restrictions or partially allowed anthropogenic activities. The air quality in most of the Indian cities generally surpasses the NAAQS because of the poor and inconsistent management and policies of the central and state governments, diverse anthropogenic activities, and uncontrolled pollution sources. Studies reported constant higher concentrations of $PM_{2.5}$, PM_{10} , and NO_2 over several Indian cities [10]. The differences in air quality improvement ratio in different cities across six Indian regions during lockdown might result due to various reasons including population density, traffic density, local emission patterns, industrial and power plant emissions, meteorology, and cross-states transport of pollutants. Except power plants, all other sources were closed or partially allowed during lockdown.

A higher pollution level in North India might be due to the presence of many high-density populated cities in the region and located in the same wind sector [11]. Besides, emissions from vehicles, industry, coal-based power plants, brick kilns, and crop residue burning are responsible for poor air quality in this region [12]. During the lockdown, the air pollution reduction and improvement in air quality

in North Indian cities are much higher than other regions. Navinya et al. [13] also reported a similar observation. The East Indian cities also possessed more or less similar emission patterns and hence poor air quality as North India during pre-lockdown. The air quality of Central Indian cities is also poor during the pre-lockdown due to inland location, large power industries and influx of transboundary pollutants. The major part of pollution from North India (particularly Uttar Pradesh, Punjab, Haryana) is transported to Central (Madhya Pradesh); East (Odisha, Jharkhand, and West Bengal) and West region (Rajasthan and Maharashtra). The atmospheric and geographic conditions such as wind directions transport the pollutants to other regions [14]. The West and South Indian coastal cities with higher vehicular exhaust and industrial emissions, possessed relatively better air quality might be due to the presence of land sea breezes. The study reported that the presence of land sea breezes dispersed the industrial and power plants emissions to the sea and their impact is lessened on air quality for Chennai and Vishakhapatnam cities [15]. Singh and Tyagi [16] reported that the pollutants transported to the coastal city Chennai by crossing the states of Andhra Pradesh, Karnataka, Telangana and Maharashtra in 2019. During lockdown this cross-state

Fig. 5 Spatio-temporal pattern of Air Quality Index in Chennai. **a** Pre-lockdown, **b** Lockdown-1, **c** Lockdown-2, **d** Lockdown-3, **e** Lockdown-4, **f** Unlock

transportation pattern changed increasing oceanic sea salt sprays. The geographically isolated mountainous North-East India with sparse population density is well endowed with natural resources (oil, gas, minerals, agro-horticulture, hydro-electric potentials, and forest resources). The region is still lagging behind due to poor basic infrastructure and industrial development contributing less to air pollution (excluding Guwahati).

The present study reported that all the criteria pollutants namely $PM_{2.5}$, PM_{10} , NO_2 , NH_3 , and CO were decreased across the cities during lockdown and unlock period, while, O_3 reflected unlikely behavior in some cities. The finding is in agreement with the previous studies that were focused on the improvement of air quality witnessed due to COVID-19 lockdown in the world's major cities [6, 7, 12, 17].

The $PM_{2.5}$, a globally accepted air quality parameter, principally consists of combustion particles [18] and also contains some crustal particles [19]. A sharp decline in $PM_{2.5}$ and PM_{10} across Indian cities was expected due to

suspended vehicular movements in lockdown-1 and lockdown-2; whereas, a non-significant increase in $PM_{2.5}$ and PM_{10} were observed in subsequent phases with the return of vehicles on the city roads. In spite of the increase in vehicular movements and industrial operations during unlock (Table 1); the concentration of $PM_{2.5}$ and PM_{10} decreased significantly than the pre-lockdown which might be due to rainfall [20]. The rainfall from the South-West monsoon in the unlock period across the Indian cities has significantly washed off $PM_{2.5}$ and PM_{10} . There was a negative correlation between $PM_{2.5}$ and the amount of rainfall that demonstrated the function of the washing process [21].

The NO_2 and NH_3 also showed trends similar to the PM with a decrease in all the regions. This result is in congruence with the previous studies [22, 23]. Vehicles are the major contributor to NO_2 pollution [24]. NO_2 is generated at high temperatures during fossil fuel combustion, biomass burning, thermal power plants, and industrial operations [25]. During lockdown, the concentrations of NO_2

Fig. 6 Spatio-temporal pattern of Air Quality Index in Hyderabad. **a** Pre-lockdown, **b** Lockdown-1, **c** Lockdown-2, **d** Lockdown-3, **e** Lockdown-4, **f** Unlock

Fig. 7 Spatio-temporal pattern of Air Quality Index in Kolkata. **a** Pre-lockdown, **b** Lockdown-1, **c** Lockdown-2, **d** Lockdown-3, **e** Lockdown-4, **f** Unlock

Fig. 8 Spatio-temporal pattern of Air Quality Index in Mumbai. **a** Pre-lockdown, **b** Lockdown-1, **c** Lockdown-2, **d** Lockdown-3, **e** Lockdown-4, **f** Unlock

were reduced across all the cities. Similarly, the concentrations of NH_3 were considerably lower mainly because of lower numbers of petrol vehicles [26].

In India, the SO_2 concentration usually remains low, since major emissions sources like thermal power plants, shipping, and chemical industries are now technologically advanced [7]. During lockdowns, the concentration has declined further. A non-significant increase of SO_2 was noticed in Central India during the lockdown and North India during lockdown-3, Lockdown-4, and unlock phases which could be ascribed to no restrictions on power plants and coal-based energy sources, present in the locality [6]. Kumar and Toshniwal [27] also reported similar observations in their study on Singrauli from 1st March–15th April 2020 (Pre-lockdown and lockdown-1). In North-East India, a significant increase in SO_2 could be attributed to the scattered oil and gas fields which were active during

lockdown [28] and the active functioning of petrochemical industries located in Guwahati.

The CO is largely emitted from incomplete combustion processes from vehicles, biomass burning, and oxidation of hydrocarbons [29]. Vehicular activities accounted for 76.8% of the total CO emissions in urban areas [30]. Its concentration was decreased around 10% in India during the initial lockdown due to restricted anthropogenic activities [6]. Therefore, a significant reduction of CO concentration during lockdown-1 could be attributed to the closure of all types of vehicular movements; thereafter slight increase might be due to relaxations in transportation provided accordingly. This finding is in congruence with a number of studies that reported the decline in CO concentration and resultant AQI improvement [17, 23].

The concentration of O_3 portrays an unusual trend in some cities during the lockdowns. The rising O_3 concentration could be attributed to its complex production

chemistry, predominantly driven by the Volatile Organic Compounds (VOCs) and NO_x precursor's ratio in the presence of sunlight [31], the lower concentrations of CO and NO_x , and also the photochemical titration reaction of CO, NO_x , VOCs, and CH_4 with meteorological conditions [12]. Higher penetration of sunlight due to a lower concentration of PM leads to enhanced photochemical reactions resulting in higher O_3 formation [32]. Besides, reduced NO_2 emission has contributed to enhancement in the O_3 levels [16]. A similar finding was also reported for Indian cities [16, 17, 33].

It may be surmised that the differences in the pollution concentration in different regions instead of the same lockdown periods across the country are basically due to the differences in air quality, geographical features, weather and climatic pattern, properties of aerosols, etc. participate in different atmospheric chemical reactions in presence of photon (hv), hydroxyl radicals and VOCs. Gas to particle formation is also dependent on the regional climatic condition.

4.2 Lessons learnt and the way forward

Of late, COVID-19 induced lockdowns and restricted human activities were a natural compulsion and this, in turn, resulted in a steep decline in air pollution and thus provided a lesson and way out from this curse of modern civilization. Though such lockdowns are unfortunate and also create a severe crisis for modern civilization, especially in the economic activities and mobility; but still provide a unique opportunity to realize our daily mistakes and the importance of such modified activities/lifestyles [34]. Vehicular pollution is an increasingly important issue in urban areas because vehicular activities grow rapidly [35]. In India, on-road vehicular movement is one of the major contributors to urban air pollution [10]. All economic activities and services in urban areas are primarily dependent on the movement of vehicles. Thus the urban air pollution due to emissions from the motor vehicles should be a major consideration for public concern and policy attention. Hence, this study may boost the confidence among the policymakers and regulatory authorities that improving urban air quality is not a daydream if the stringent implementation of pollution control plans is effectively executed.

4.2.1 Act on existing strategies and policies for air pollution abatement

To address the issues of rising air pollution from vehicular activity in urban areas, the policymakers and regulatory authorities should act on a multi-pronged approach. A number of policies have been initiated by the Govt. of India

for air pollution abatement. These are as follows; the Air (Prevention and Control of Pollution) Act-1981, the Environment Pollution (Prevention and Control Authority) (EPCA) was established in 1998 to address air pollution in Delhi-NCR. In 2016, Graded Response Action Plan was established to address air pollution emergencies in Delhi-NCR. After that NCAP has been launched by the Central Government in 2019 with targets to achieve a 20% to 30% reduction in Particulate Matter concentrations by 2024 keeping 2017 as the base year for the comparison of concentration [5]. Therefore, strict implementation of NCAP-India will be a major step towards the improvement of air quality.

4.2.2 Increasing monitoring stations and areal coverage

There is an acute need to increase monitoring stations and their area coverage both in ambient air and at the source. For instance, the national capital Delhi possesses 38 real-time monitoring stations under CPCB, while Kolkata has 7 real-time monitoring stations under CPCB and 16 semi-automatic monitoring stations under West Bengal Pollution Control Board [36]. The wider and judicious use of monitoring data for source apportionment and other scientific purposes is required collaboratively with the regulatory authorities and scientists [37]. Although, during the Commonwealth Games in 2010 in Delhi, the number of monitoring stations were tripled, raised awareness among the public, established some messaging systems, and disseminated data on the web, yet the implemented measures to curb pollution were ineffective [38]. Therefore, more monitoring stations are needed to be installed, air pollution legislation to be amended and the air quality data to be disseminated regularly to aware the general public regarding air quality.

4.2.3 Ensuring high-quality fuel and emissions standards

It is critical to mandate the same quality fuel and emissions standards for all categories of vehicles nationwide and if not done, the manufacturers will have no intention to upgrade the standards of the vehicles. Bharat Stage Emission Standards (BSES) was commenced first in 2000 by the Ministry of Road Transport and Highways (MoRTH), Govt. of India and subsequently upgraded to Bharat Stage (BS) IV nationwide in April, 2017. After skipping BS-V, it was mandated that all new vehicles manufactured on or after April 1, 2020 will have to comply with the regulations after its implementation. BS-VI emission standards are effective for all major on-road vehicle categories [10]. Patil et al. [39] estimated that under the BS-VI emissions regime NO_x levels will decline by 25% for petrol, 68% for diesel engines, and PM emissions by 82% for diesel engines.

Heavy-duty vehicles are major contributors to the gross PM_{2.5}, SO₂, NO_x, and CO emissions. These vehicles are usually driven outside the city limits for most of the year, probably utilize fuel of lower standard and consequently result in higher emissions [10]. Therefore, the regulations under the BS-VI regime should be followed in letter and spirit.

4.2.4 Restructuring environmental laws and regulations

There is an urgent need to restructure the environmental laws and regulations. Severe punishments such as imprisonment or industry closure that are written in India's three fundamental environmental legislations namely the Environmental Protection Act (1986), the Air Act (1981), and the Water Act (1974) are rarely used and preserved in a typical manner for the very atrocious polluters. It would be better to set civil fines; so that, all the industries and other pollution sources have to pay uniform and steady incentives as per pollutant emissions load. For instance, the coal cess started by the Government of India in 2010 of INR 50 per ton was an example of the application of such a principle [37]. However, ill nexus among industries and policy makers can bypass such welfare initiatives.

4.2.5 Improving traffic administering and managing systems

Bigazzi and Rouleau [40] summarized the impacts of traffic management strategies (TMS) on air pollution. Besides TMS, improvement in conventional traffic management, congestion charges [40], introducing car-free days [41], vehicle pollution checking procedures, promoting a clean and efficient mode of public transport [42], arranging arterial roads for walking and cycling [43] are need of the hours to reduce the pollution. The multi-pronged approach is the only solution to address the air quality problem. A concerted, coordinated venture is a sine qua non between individuals, air pollution regulatory bodies, urban development authorities, and transport sectors.

4.2.6 Involving Community in air quality management

The lockdown has established the fact that anthropogenic activities are majorly contributing to air quality deterioration. Government policies may not be able to improve air quality without the active participation of citizens. Citizens need to self-determine their responsibility in improving air quality. The Odd–Even formula [44] and 'Red Light On, Gaadi Off Campaign' [45] are good examples involving the community in the air quality management launched by the present-day Delhi Government. The Government at

different city-scale could do better to promote work from home as one of the strategies to curb vehicular emissions. The community should promote tree plantation drives as trees with a high surface area to volume ratio in the pollution hotspot areas helps in filtering PM pollutants [18].

4.3 Region-specific strategies to control air pollution

Furthermore, region-specific pollution source wise actions should be taken like in the North and East India, transport sector: low Sulphur, BS-VI standard engine, and fuel should be used and replacement of older than 10 years vehicles, use of alternative fuels viz. CNG, LPG, Ethanol-petrol, Bio-diesel, Hydrogen, etc., rail and waterways for freight could be encouraged more. Industries: mixing of low-grade carbonaceous fuel as a fuel source in small-scale industries should be checked, cleaner production by improving technologies in the industry sector. Agriculture: Agri-based residue to energy, business model to manage agriculture residues. Soil and infrastructure Dust: Vacuum cleaning of roads, wall to wall paving, green construction techniques like joint ambient breeze tunnels could be used. Waste: ban open burning, Methane recovery from solid waste dumping sites [46, 47]. Central and Western region, transport sector: low Sulphur, BS-VI standard engine and fuel should be used and replaced vehicles older than 15 years, Industries: cleaner production by improving technologies. Soil Dust: Vacuum cleaning of roads, wall to wall paving. Waste: ban open burning, Methane recovery from solid waste dumping sites [46, 47]. South region, transport sector: low Sulphur, BS-VI standard engine and fuel should be used and replacement of old vehicles, Industries: cleaner production by improving technologies. Soil and infrastructure Dust: Vacuum cleaning of roads, wall to wall paving, and green construction techniques like joint ambient breeze tunnels could be used [46]. The North-eastern region, Agriculture: to check forest fire and biomass burning [48].

5 Conclusion

Indian cities are often in the top slots among the world's most polluted cities. India is a diversified nation with varied climatic and topographic features. Each region is distinct in geographic features. Therefore, region-specific strategies should be formulated to control air pollution. Almost halted anthropogenic activities due to lockdowns have improved the air quality. The concentration of all pollutants declined during lockdowns and unlock across all cities while O₃ reflected heterogeneous behavior. Among the six geographic regions, North Indian cities were most polluted in pre-lockdown. During lockdowns and unlock,

the highest improvement in AQI is recorded in North India followed by Central India, East India, West India, South India, and North-East. But, how do we retain the improved air quality in the post-lockdown? It is a big question now. The phase-wise lockdown with relaxations in human activities has extended a unique opportunity to examine how a possible cut down in emissions from vehicles may improve the air quality in cities. Whenever life in cities will resume in full swing, the air pollution will also undoubtedly rebound. Thus assessing these findings and considering the ground zero situation, the policymakers should have to formulate centralized policies to improve ambient air quality. However, the lockdown can never be the measures to curtail pollution, because the COVID-19 lockdown has affected the livelihood of citizens, and eventually human health, and the global economy negatively. All the sources contributing to urban air pollution are interlinked. Among all sources, vehicles are a major contributor and most critical in this context. Therefore, it is required to formulate policies to address the issue of keeping vehicular pollution at the forefront.

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Declaration

Conflict of interest The authors declare no conflicts of interest.

References

1. IQAir. (2019). World Air Quality Report. Retrieved July 9, 2020, from <https://www.iqair.com/us/world-most-polluted-cities>.
2. Hama, S. M., Kumar, P., Harrison, R. M., Bloss, W. J., Khare, M., Mishra, S., Namdeo, A., Sokhi, R., Goodman, P., & Sharma, C. (2020). Four-year assessment of ambient particulate matter and trace gases in the Delhi-NCR region of India. *Sustainable Cities and Society*, 54, 102003–102021. <https://doi.org/10.1016/j.scs.2019.102003>
3. Rizwan, S. A., Nongkynrih, B., & Gupta, S. K. (2013). Air pollution in Delhi: Its magnitude and effects on health. *Indian Journal of Community Medicine*, 38(1), 4. <https://doi.org/10.4103/0970-0218.106617>
4. World Health Organization. (2018). Global Health Risks. Mortality and burden of diseases attributable to selected major risks. Retrieved August 12, 2020, from https://www.who.int/healthinfo/global_burden_disease/GlobalHealthRisks_report_full.pdf.
5. Ganguly, T., Selvaraj, K. L., & Guttikunda, S. K. (2020). National Clean Air Programme (NCAP) for Indian cities: Review and outlook of clean air action plans. *Atmospheric Environment*, X, 100096. <https://doi.org/10.1016/j.aeaoa.2020.100096>
6. Sharma, S., Zhang, M., Gao, J., Zhang, H., & Kota, S. H. (2020). Effect of restricted emissions during COVID-19 on air quality in India. *Science of the Total Environment*, 728, 138878. <https://doi.org/10.1016/j.scitotenv.2020.138878>
7. Mahato, S., Pal, S., & Ghosh, K. G. (2020). Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. *Science of the Total Environment*, 730, 139086–139109. <https://doi.org/10.1016/j.scitotenv.2020.139086>
8. Central Pollution Control Board. (2020). Central control room for air quality management- All India. Retrieved July 17, 2020, from <https://app.cpcbcr.com/ccr/#/caaqm-dashboard-all/caaqm-landing>.
9. Central Pollution Control Board. (2014). *National Air Quality Index Report*. Central Pollution Control Board, New Delhi, India. Retrieved July 17, 2020, from <https://cpcb.nic.in/national-air-quality-index/>.
10. Guttikunda, S. K., Goel, R., & Pant, P. (2014). Nature of air pollution, emission sources, and management in the Indian cities. *Atmospheric Environment*, 95, 501–510. <https://doi.org/10.1016/j.atmosenv.2014.07.006>
11. Beig, G., Sahu, S. K., Singh, V., Tikle, S., Sobhana, S. B., Gargava, P., Ramakrishna, K., Rathod, A., & Murthy, B. S. (2020). Objective evaluation of stubble emission of North India and quantifying its impact on air quality of Delhi. *Science of The Total Environment*, 709, 136126. <https://doi.org/10.1016/j.scitotenv.2019.136126>
12. Singh, R. P., & Chauhan, A. (2020). Impact of lockdown on air quality in India during COVID-19 pandemic. *Air Quality, Atmosphere & Health*, 13(8), 921–928. <https://doi.org/10.1007/s11869-020-00863-1>
13. Navinya, C., Patidar, G., & Phuleria, H. C. (2020). Examining effects of the COVID-19 national lockdown on ambient air quality across urban India. *Aerosol and Air Quality Research*, 20(8), 1759–1771. <https://doi.org/10.4209/aaqr.2020.05.0256>
14. Du, X., Guo, H., Zhang, H., Peng, W., & Urpelainen, J. (2020). Cross-state air pollution transport calls for more centralization in India's environmental federalism. *Atmospheric Pollution Research*, 11(10), 1797–1804. <https://doi.org/10.1016/j.apr.2020.07.012>
15. Guttikunda, S. K., Goel, R., Mohan, D., Tiwari, G., & Gadepalli, R. (2015). Particulate and gaseous emissions in two coastal cities—Chennai and Vishakhapatnam, India. *Air Quality, Atmosphere & Health*, 8(6), 559–572. <https://doi.org/10.1007/s11869-014-0303-6>
16. Singh, J., & Tyagi, B. (2021). Transformation of air quality over a coastal tropical station Chennai during COVID-19 lockdown in India. *Aerosol and Air Quality Research*. <https://doi.org/10.4209/aaqr.200490>
17. Rahaman, S., Jahangir, S., Chen, R., Kumar, P., & Thakur, S. (2021). COVID-19's lockdown effect on air quality in Indian cities using air quality zonal modeling. *Urban Climate*, 36, 100802. <https://doi.org/10.1016/j.uclim.2021.100802>
18. Tucker, W. G. (2000). An overview of PM_{2.5} sources and control strategies. *Fuel Processing Technology*, 65, 379–392. [https://doi.org/10.1016/S0378-3820\(99\)00105-8](https://doi.org/10.1016/S0378-3820(99)00105-8)
19. Laden, F., Neas, L. M., Dockery, D. W., & Schwartz, J. (2000). Association of fine particulate matter from different sources with daily mortality in six US cities. *Environmental Health Perspectives*, 108(10), 941–947. <https://doi.org/10.1289/ehp.00108941>
20. Sahoo, P. K., Mangla, S., Pathak, A. K., Salamao, G. N., & Sarkar, D. (2021). Pre-to-post lockdown impact on air quality and the role of environmental factors in spreading the COVID-19 cases-a study from a worst-hit state of India. *International Journal of Biometeorology*, 65(2), 205–222. <https://doi.org/10.1007/s00484-020-02019-3>

21. Ouyang, W., Guo, B., Cai, G., Li, Q., Han, S., Liu, B., & Liu, X. (2015). The washing effect of precipitation on particulate matter and the pollution dynamics of rainwater in downtown Beijing. *Science of the Total Environment*, 505, 306–314. <https://doi.org/10.1016/j.scitotenv.2014.09.062>
22. Ashwini, K., Saw, G. K., & Singh, A. (2021). Phase wise spatial and temporal variations of nitrogen dioxide during and pre COVID-19 lockdown period in tier-1 cities of India. *Spatial Information Research*. <https://doi.org/10.1007/s41324-021-00400-x>
23. Eregowda, T., Chatterjee, P., & Pawar, D. S. (2021). Impact of lockdown associated with COVID19 on air quality and emissions from transportation sector: Case study in selected Indian metropolitan cities. *Environment Systems and Decisions*. <https://doi.org/10.1007/s10669-021-09804-4>
24. He, L., Zhang, S., Hu, J., Li, Z., Zheng, X., Cao, Y., Xu, G., Yan, M., & Wu, Y. (2020). On-road emission measurements of reactive nitrogen compounds from heavy-duty diesel trucks in China. *Environmental Pollution*, 262, 114. <https://doi.org/10.1016/j.envpol.2020.114280>
25. Sharma, S. K., Datta, A., Saud, T., Saxena, M., Mandal, T. K., Ahammed, Y. N., & Arya, B. C. (2010). Seasonal variability of ambient NH₃, NO, NO₂ and SO₂ over Delhi. *Journal of Environmental Sciences*, 22(7), 1023–1028. [https://doi.org/10.1016/S1001-0742\(09\)60213-8](https://doi.org/10.1016/S1001-0742(09)60213-8)
26. Kean, A. J., Harley, R. A., Littlejohn, D., & Kendall, G. R. (2000). On-road measurement of ammonia and other motor vehicle exhaust emissions. *Environmental Science & Technology*, 34(17), 3535–3539. <https://doi.org/10.1021/es991451q>
27. Kumari, P., & Toshniwal, D. (2020). Impact of lockdown measures during COVID-19 on air quality—A case study of India. *International Journal of Environmental Health Research*. <https://doi.org/10.1080/09603123.2020.1778646>
28. Pathak, B., Bhuyan, P. K., Saikia, A., Bhuyan, K., Ajay, P., Nath, S. J., & Bora, S. L. (2021). Impact of lockdown due to COVID-19 outbreak on O₃ and its precursor gases, PM and BC over Northeast India. *Current Science*, 120(2), 322.
29. Saxena, A., & Raj, S. (2021). Impact of lockdown during COVID-19 pandemic on the air quality of North Indian cities. *Urban Climate*, 35, 100754. <https://doi.org/10.1016/j.uclim.2020.100754>
30. Hao, J., Wu, Y., Fu, L., He, D., & He, K. (2001). Source contributions to ambient concentrations of CO and NO_x in the urban area of Beijing. *Journal of Environmental Science and Health, Part A*, 36(2), 215–228. <https://doi.org/10.1081/ESE-100102619>
31. Jeon, W. B., Lee, S. H., Lee, H., Park, C., Kim, D. H., & Park, S. Y. (2014). A study on high ozone formation mechanism associated with change of NO_x/VOCs ratio at a rural area in the Korean Peninsula. *Atmospheric Environment*, 89, 10–21. <https://doi.org/10.1016/j.atmosenv.2014.02.005>
32. Marr, L. C., & Harley, R. A. (2002). Modeling the effect of weekday—Weekend differences in motor vehicle emissions on photochemical air pollution in central California. *Environmental Science & Technology*, 36(19), 4099–4106. <https://doi.org/10.1021/es020629x>
33. Chauhan, A., & Singh, R. P. (2021). Effect of lockdown on HCHO and trace gases over India during March 2020. *Aerosol and Air Quality Research*, 21, 200445. <https://doi.org/10.4209/aaqr.2020.07.0445>
34. Hadzipetrova, E., Mitrikeska, M., Maksimovski, B., & Kamcheva, A. (2020). Lessons we will learn from this pandemic. Retrieved July 29, 2021, from <https://www.unicef.org/eca/stories/lessons-we-will-learn-pandemic>.
35. Badami, M. G. (2005). Transport and urban air pollution in India. *Environmental Management*, 36(2), 195–204. <https://doi.org/10.1007/s00267-004-0106-x>
36. West Bengal Pollution Control Board. (2019). *Ambient air quality monitoring in West Bengal*. Retrieved August 20, 2021, from <https://www.wbpcb.gov.in/ambient-air-quality-monitoring-in-west-bengal>.
37. Greenstone, M., Nilekani, J., Pande, R., Ryan, N., Sudarshan, A., & Sugathan, A. (2015). Lower pollution, longer lives: Life expectancy gains if India reduced particulate matter pollution. *Economic and Political Weekly*, 40–46. <https://www.jstor.org/stable/24481424>.
38. Beig, G., Chate, D. M., Ghude, S. D., Mahajan, A. S., Srinivas, R., Ali, K., Sahu, S. K., Parkhi, N., Surendran, D., & Trimbake, H. R. (2013). Quantifying the effect of air quality control measures during the 2010 Commonwealth Games at Delhi, India. *Atmospheric Environment*, 80, 455–463. <https://doi.org/10.1016/j.atmosenv.2013.08.012>
39. Patil, A. A., Joshi, R. R., Dhavale, A. J., & Balwan, K. S. (2019). Review of Bharat Stage 6 emission norms. *International Research Journal of Engineering and Technology*, 6, 1359–1361.
40. Bigazzi, A. Y., & Rouleau, M. (2017). Can traffic management strategies improve urban air quality? A review of the evidence. *Journal of Transport & Health*, 7, 111–124. <https://doi.org/10.1016/j.jth.2017.08.001>
41. Nieuwenhuijsen, M. J., & Khreis, H. (2016). Car free cities: Pathway to healthy urban living. *Environment International*, 94, 251–262. <https://doi.org/10.1016/j.envint.2016.05.032>
42. He, K., Huo, H., & Zhang, Q. (2002). Urban air pollution in China: Current status, characteristics, and progress. *Annual Review of Energy and the Environment*, 27(1), 397–431. <https://doi.org/10.1146/annurev.energy.27.122001.083421>
43. Rojas-Rueda, D., De Nazelle, A., Andersen, Z. J., Braun-Fahrlander, C., Bruha, J., Bruhova-Foltynova, H., Desqueyroux, H., Praznocy, C., Ragetti, M. S., Tainio, M., & Nieuwenhuijsen, M. J. (2016). Health impacts of active transportation in Europe. *PLoS ONE*, 11(3), e0149990. <https://doi.org/10.1371/journal.pone.0149990>
44. Rafiqi, F. A., & Pandith, N. (2016). Prevention of pollution through public restraint: A critical appraisal of odd-even formula in the national capital Delhi. *IUP Law Review*, 6(4).
45. Gujral, A. (2020). Steps being taken to control the major rise in pollution in Delhi again. Retrieved July 25, 2021, from <https://www.whatshot.in/delhi-ncr/steps-government-is-taking-to-control-pollution-in-delhi-c-25962>.
46. Sharma, V. S., et al. (2016). Breathing cleaner air: Ten scalable solutions for Indian Cities. The Energy and Resources Institute. A self-organized task force report for the World Sustainable Development Summit, New Delhi.
47. Central Pollution Control Board. (2012). Alternative transport fuels an overview. A news letter from ENVIS Centre. Retrieved July 14, 2021, from <http://www.cpcbenviis.nic.in/newsletter/alternatefuel/intro0403.htm>.
48. Chakraborty, K., Sivasankar, T., Lone, J. M., Sarma, K. K., & Raju, P. L. N. (2020). Status and opportunities for forest resources management using geospatial technologies in northeast India. In *Spatial Information Science for Natural Resource Management* (pp. 206–224). IGI Global.

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