Correlating the trends of COVID-19 spread and air quality during lockdowns in Tier-I and Tier-II cities of India—lessons learnt and futuristic strategies

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Abstract

The present study focuses on the impact of early imposed lockdowns and following unlocking phases on the status of air quality in six Tier-I and nine Tier-II cities of India as compared to the pre-lockdown measures. Furthermore, the study highlights the possible correlation of air quality index (AQI) with the initial trend of COVID-19 issues including the vaccination cases. Based on the statistical data analysis, we observed that the long-term averages for representing the short-term pre-lockdown conditions can impose a healing effect to the observed anomalies in air pollution data. However, the reduction in air pollution during the imposed lockdown series was only a phenomenal consequence, and the trends started reversing during the later phases of partial unlocking, where the correlation showed reversing trends. Being a yearly averaged parameter, the marginal reductions in the exceedance factor (EF) alone could not dictate air quality compared to the AQI. As there is incoherent variability in the pollutant distributions among the cities during various phases of the study, the trend analysis served as a preferable criterion to choose the preferred sources of variations. Based on the results, the correlation analysis revealed that air quality expressed in terms of AQI can act as an important precursor to estimate the critical phase of COVID-19 spread and the effectiveness of various control measures taken during each phase. Based on our proposed ranking, Kolkata and Patna are ranked first in the Tier-I and Tier-II cities respectively according to their responsiveness to the various institutionalized restrictions in terms of air quality parameters.

Keywords Air quality · AQI · COVID-19 pandemic · Exceedance factor · Lockdown

Introduction

The COVID-19 pandemic situation due to the uncontrolled spread and attack of novel coronavirus (SARS-CoV-2) during 2020–2021 has created a totally unprecedented global crisis especially in the people's lives, interactions, businesses and economics (Dutheil et al. 2020; Gautam 2020). The deadly impact of this virus on human health has been reported as an acute respiratory disease affecting the lungs causing

pneumonia and also triggering further damages to the kidney and heart. The high mortality rate of this infection has been associated with cardiac diseases, cancers and immunodeficiency (Chen et al. 2020; Wang et al. 2020). As on July 25, 2021, the coronavirus has attacked more than 194.5 million people with more than 13.78 million active cases and snatched the lives of 4.17 million people worldwide. The rapid spreading rate and its associated fatal mortality rate make it challenging to restrain the deadly impacts even after introducing specific vaccines at a later stage (Link 1 (2021)). As a precautionary and temporary arrangement, many countries have imposed nationwide lockdowns in order to restrict people's movement and thereby reduce the chances of possible infections through interactions. Though impacting the state economics adversely, such restrictions without interrupting services such as food, medical and other emergency systems are often interpreted to be the best possible interventions to regularize the necessary follow-up actions (Bao and Zhang 2020; Sharma et al. 2021).

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However, some of the early-affected countries have implemented lockdown only after realising the extent of disaster with increasing death tolls, owing to peer financial pressure, over-dependency on economic strategies and lack of preparedness with sufficient infrastructure to enforce mass restrictions. Inevitably, by virtue of restricted human interventions, such institutional restrictions have long-term impacts not only on the socio-economic scenario but also on the total environmental quality and performance of natural recovery and remediation systems.

Air pollution has been an acute problem that is inflicting the lives of people every year, especially in all the metropolitan cities (Louati et al. 2018). It is particularly important for India as 35% of the deaths in 2015 reported were due to air pollution (Sharma et al. 2019) and 9 out of the 10 most polluted cities listed released by the World Health Organization (WHO) are from the Indian sub-continent (Yuda 2019). Being a country that imposed national lockdowns much before the major hit, India has faced many challenges and advantages in the fight against COVID-19 during the year 2020. The major boon, however, was the remarkable improvements in air and water quality of major cities during and after the periods of lockdowns. Hypothetically, any significant improvement in the major air quality parameters of the atmosphere can possibly contribute towards better environment and public health. Therefore, it is important to observe the spatiotemporal trends of various air quality parameters under the prevailing situations in order to derive any plausible correlations that can significantly mark conclusive remarks and futuristic predictions.

Most of the literature dealing with air quality assessment would typically include trend analysis based on long-term monitoring data in order to check the consistency of the results. Sharma et al. (2020) demonstrated the changing trends in air pollution over varying geographical locations in India by analysing the annual growth rate of sulphur dioxide (SO_2), NO_2 and $\text{PM}_{2.5}$ from 2015 to 2018. Markandeya et al. (2021) investigated the seasonal variations in the air pollution levels in Lucknow and also assessed the ambient air quality of the city with emphasis on the impacts of PM_{10} , $\text{PM}_{2.5}$, SO_2 , NO_2 , Pb, Ni and aerosols on the health of the people from 2010 to 2019.

However, in the case of the COVID-19 pandemic, the response time has been quite short to realize the apparent changes in air quality (in terms of concentration of air pollutants) during the imposed lockdown due to drastic change in social activities. This necessitates evolution of short-term trend analysis to capture the nature and trend of changing atmospheric behaviour during different periods of locking and unlocking events. The waning in the air pollution was reported in various parts of the globe as caused by the constrained social and economic activities during the periods of lockdown (Saadat et al. 2020; Zambrano-Monserrate et al. 2020). In India, the

prominent features of the lockdowns during March–May 2020 were observed like almost complete ban on all modes of transport, closure of public places of crowding (tourism spots, shopping malls, restaurants, theatres, marriage halls and religious centres) and restricted operation of factories. However, the essential commodities were supplied in a conservative manner with various initiatives from local vendors. During this period, several studies have been conducted focusing on the air pollution status in different cities across the Indian sub-continent under various lockdown phases (Table 1). Being the national capital territory (NCT) and ill-famed city for air pollution, Delhi has been a point of attraction for almost all early lockdown studies. Mahato et al. (2020) was one of the early studies highlighting on the impact of short-period lockdown on the air quality in Delhi. Sharma et al. (2020) reported significant improvement in air quality based on the short periods of analysis, before lockdown (10 days, March 11–20, 2020) and during lockdown period (54 days, March 25 to May 17, 2020) in seven selected cities of Rajasthan, India.

There is an increasing pile of research articles reporting the immediate responses of lockdown events on the local environmental quality, especially on the air quality (Agarwal et al. 2020; Menut et al. 2020; Ropkins and Tate 2021; Vali et al. 2021). Gautam (2020) has reported the significant reduction in the levels of nitrogen dioxide (NO_2) in the Asian and European countries during the pandemic lockdowns. Ambade et al. (2021) compared the levels of black carbon, polycyclic aromatic hydrocarbons and particulate matter ($\text{PM}_{2.5}$) concentrations and the associated health risk assessment during the normal days, lockdown period and unlock 1.0 at Sakchi, Jamshedpur city. Gautam et al. (2021) have reported that there is a positive correlation between the level of air pollution of a region and the lethality of COVID-19 that may aggravate the death rate in the future. They also reported that high level of $\text{PM}_{2.5}$ has a significant correlation with COVID-19 mortality compared with PM_{10} . Apart from this, there are many studies focused on individual states and cities of India such as Bangalore (Ramasamy and Jayakumar 2020), West Bengal (Roy and Singha 2020) and Bhubaneswar (Panda et al. 2021).

In addition to the individual trend analysis studies, investigations on the comparative status of multiple cities are also being studied widely. Agarwal et al. (2020) conducted a comparative study on the air quality status in six Indian and six Chinese cities before and during the COVID-19 lockdown period based on real-time monitoring data in terms of the concentration of particulate matter ($\text{PM}_{2.5}$) and nitrogen dioxide (NO_2). Ravindra et al. (2021) studied the impact of restrictions during various phases of COVID-19 lockdown and unlocking phases on daily mean $\text{PM}_{2.5}$ concentrations in five Indian megacities (New Delhi, Chennai, Kolkata, Mumbai and Hyderabad). They observed maximum reduction in

Table 1 Recent studies highlighting the variations in air quality in view of the pandemic restrictions

Location	Air quality parameters	Key observations	Reference
Mumbai and Delhi	NO ₂	Substantial decrease in NO ₂ (40–50%) during January to April 2020 lockdown period.	Shehzad et al. (2020)
Bangalore	NO, NO ₂ , NO _x , PM _{2.5} , O ₃ , SO ₂	Faded track of NO ₂ seen in the maritime route of the Indian ocean. Reduced air pollutants between the pre-lockdown (01–23 March 2020) and lockdown (24 March–12 May 2020) resulting in improved air quality.	Gouda et al. (2021)
Delhi, Kolkata, Chennai	PM ₁₀ , PM _{2.5} , NO ₂ , SO ₂ , AQI	Delhi and Kolkata are most affected by air pollution during 2017–2020. Higher concentration of pollution found during the winter season.	Dutta et al. (2021)
Chandigarh	PM ₁₀ , PM _{2.5} , NO ₂ , NO, NO _x , SO ₂ , O ₃ , NH ₃ , CO, BTEX	Reduced air pollutants during the first and second phases of the lockdown and increment in the third phase. Increasing concentrations of SO ₂ , O ₃ and m,p-xylene except for benzene.	Mor et al. (2021)
Delhi	PM _{2.5}	Unusually delayed withdrawal in monsoon resulted in extreme levels of PM _{2.5} particles (~760 µg/m ³) after the monsoon retreat during 2016 and 2017.	Beig et al. (2021)
Delhi, Dhaka, Kathmandu, Colombo, Islamabad and Kabul	AQI, CO ₂ , SO ₂ , NO ₂	The concentration of the gaseous pollutants decreased the AQI in the South Asian megacities by about 50%.	Mishra and Kulshrestha (2021)
Mumbai, Bengaluru and Kolkata	NO ₂ , PM _{2.5} , AOD, NO ₂ , PM ₁₀ , O ₃ , CO, SO ₂	A lockdown-based reassessment of large-scale transport and industrial operations Substantial reduction in NO ₂ , PM _{2.5} , AOD, NO ₂ , PM ₁₀ , O ₃ levels Moderate reduction in CO level No significant reduction in SO ₂ level	Sathe et al. (2021)
134 sites in India	PM _{2.5} , PM ₁₀ , NO ₂ , O ₃ , CO, SO ₂	Highest reduction in hourly averaged concentrations for PM ₁₀ and PM _{2.5} in north-west, Indo-Gangetic plains, South and Central regions. Reduction in NO ₂ and CO in the central region. Enhancement in O ₃ proportional to the population density. Significant reduction in all pollutants except O ₃ during 2020 lockdown.	Singh et al. (2020a)
Kolkata	PM ₁₀ , PM _{2.5} , O ₃ , SO ₂ , NO ₂ , CO		Bera et al. (2021)
Kolkata, Bengaluru, Chennai, Mumbai, New Delhi	AQI, PM _{2.5} , PM ₁₀ , CO, O ₃	Significant correlation between PM _{2.5} , PM ₁₀ , CO, O ₃ , AQI and meteorological parameters with confirmed cases and deaths during the lockdown period. Temperature and ozone explained the highest variability. Decreased air pollution during the 2020 lockdown. Five stations (Panipat, Ghaziabad, Delhi, Gurugram and Varanasi) showed consistent pollution loading	Kolluru et al. (2021)
Northern, Western, Central, Southern, Eastern and North-Eastern India	PM _{2.5} , PM ₁₀ , SO ₂ , NO ₂ and O ₃	Mann-Kendall trend analysis for AOD, NO ₂ , SO ₂ Higher air pollution in coal-fired power plant clusters NO ₂ reduction occurred in New Delhi, Delhi (old), Bangalore, Ahmedabad, Nagpur, Gandhinagar and Mumbai.	Tyagi et al. (2021)
Eastern, Central and Western India	AOD, NO ₂ , SO ₂		Vadrevu et al. (2020)
41 cities in India	NO ₂ and AOD	Increase in NO ₂ in the cities of Northeast India during 2020 lockdown period. The correlations were poor for NO ₂ temporal patterns with the AOD signals.	

PM_{2.5} concentrations in Kolkata, followed by Mumbai, Chennai and New Delhi during the lockdown period. A more detailed study was reported by Pant et al. (2020) on air quality in four major metropolitan cities in India (Delhi, Mumbai, Kolkata and Chennai) from January 1, 2020, to May 31, 2020, by analysing the particulate matter PM_{2.5} and PM₁₀, NO₂, NH₃, SO₂, CO and ozone levels. Gautam et al. (2021) also studied the variations in five air pollutants, (PM₁₀, PM_{2.5}, SO₂, NO₂ and CO) during the pandemic over eight most polluted cities across India. In another study, the diurnal variations in six major air pollutants across the six geographical regions of India during March–May 2020 were reported by Singh et al. (2020a). However, their study was focused only on the margin of reduction with limited discussion on the scope of correlation analysis.

Apart from the direct measurements of the pollutant concentrations, there were also reports on variation in air quality in terms air quality index (AQI), a non-dimensional parameter. Mahato et al. (2020) highlighted the drastic reduction in national air quality index (NAQI) in various parts of Delhi in response to the early lockdowns. Selvi et al. (2020) analysed the daily and monthly variations of AQI of sixteen cities located in India. They reported that the improvement in the overall air quality after 21 days of lockdown in all the selected cities necessitates the study of variations in specific to socio-cultural backgrounds. Gautam et al. (2020) reported notable differences in the AQI of Delhi, Haryana and Uttar Pradesh from 17th February 2020 to 4th May 2020. Similarly, Ramasamy and Jayakumar (2020) have reported sharp declining trends in AQI values during the initial phase of lockdown in the city of Bangalore. Roy and Singha (2020) addressed the impact of common air pollutants in the city of Siliguri in West Bengal, India, and reported the criticality of dust particles in the atmosphere (PM₁₀ and PM_{2.5}) using exceedance factor (EF) and AQI based on the trend in the average annual concentrations. Singh et al. (2020b) used kernel density estimation (KDE) and spatial inter-correlation between the diurnal variations of pollutants across the six geographical regions of India during March–May 2020. Results from the satellite-based studies about 41 cities of India by Vadrevu et al. (2020) reported that the variations in NO₂ can better provide the characteristic trend of air pollution in major Indian cities in comparison with the aerosol optical depth (AOD). This is based on an extensive data analysis such as paired *t*-test and autoregressive moving average (ARMA) analysis of the QGIS-based data for a period of 3 months (March–May 2020) where reductions up to 13% were caused by the short-term imposed lockdown. In a similar study, the responses of climate on the COVID-19 restrictions were studied by Ranjan et al. (2020) in terms of reduction in AOD indicating reduced human activities in the Indian metropolitan cities. They also reported that continued industrial operations may cause positive anomalies in AOD even during the imposed

lockdown periods. As evident from these studies, one can certainly infer that the lockdown was a blessing in disguise at least to the air and water environments (Kumari and Toshniwal 2020; Mandal and Pal 2020; Bherwani et al. 2020; Girdhar et al. 2021).

As the second wave of COVID-19 has been continuing the destruction in a massive way, there are many upcoming studies showcasing the enhanced dimensions of COVID-19 impacts on a global scale. As evident from numerous medical and economic reports, the impact of air pollution incidents on public health has been a critical topic of concern for many populated cities of India. However, deriving a generic relationship between air pollution and COVID-19 cases has been an emerging scope of study to arrive at strategic conclusions pertaining to the dynamic colloidal (or aerosol) characteristics of the coronavirus and to check the effectiveness of the standard operating protocols (SOP) set forth during various phases of the pandemic. Only a few studies have attempted so far to relate COVID-19 spread to the atmospheric quality and meteorological conditions. Sharma et al. (2021) examined the relationship between the COVID-19 confirmed cases, deaths and meteorological factors including air pollution for the top 10 infected countries using advanced econometric methods. Wiśniewski et al. (2021) analysed the impact of weather factors such as temperature, relative humidity, wind speed and ground-level ozone concentration on the number of COVID-19 cases in Warsaw, Poland, using the Spearman rank correlation test. Interestingly, they observed an inverse correlation between ground-level ozone concentration and the daily number of COVID-19 cases. In a similar study, Bilal et al. (2020) have analysed the relationship between climate, pollution and COVID-19 cases in Germany using wavelet transform coherence (WTC). They suggested that PM₁₀ and O₃ are the main determinants associated with the outbreak of COVID-19. Kuttralam-Muniasamy et al. (2021) performed statistical correlation tests to investigate the impacts of two short-term lockdown events on air pollution and mortality trends in Mexico City. They recommended enforcing new air pollution regulations based on the rise in concentration of some pollutants with increase in mortality rate. However, generalization of such statistical interpretations is likely limited as these studies are spatiotemporally constrained and therefore advocates unique economic and medical policy strategies.

The air pollution in growing cities is likely to be increasing due to the increase in human activities resulting in higher emissions from vehicles, industries, power plants, etc. To worsen the scenario, statistics says that the largest number of COVID-19 cases is reported from the cities having more population, thus pointing towards the higher risk of community spread. However, a mere comparison of major cities of India based on population into Tier-I and Tier-II categories may not illustrate the real scenario because the nature of pandemic spread and the extent of preventive and supportive

mechanisms may not be similar in many cities. Most of the early reports about air quality variations during the lockdown phases were highly abstract and limited in scope with only focus on representing the notable variations in trends, rather than investigating on the possible correlations, consequences and combating measures.

While the lockdown phases in 2020 are featured with restrictions on social activities and public transport by anticipating some deadly impacts, the unlock phases in late 2020 are implemented with gradual release of restrictions for public gathering and commercial/industrial activities based on projected declining spread of COVID-19. In addition, the unlock phases in early 2021 are associated with the introduction of precautionary vaccines throughout the country as a massive drive. However, there are still ambiguities in accounting for the impacts of imposed lockdowns as well as vaccinations towards mitigating the COVID-19 spread as witnessed by the unexpected rise of positive confirmed cases while vaccination drive was expanding in India. Since the cities are considered air pollution hotspots, the present study focuses on analysing the trend and correlation of air quality and COVID-19 spread in all major Indian cities (six cities under Tier-I and nine cities under Tier-II categories) over the various phases of pre-locking, locking and unlocking events in 2020. In this study, we also aim to investigate on the correlation between the COVID-19 risk parameters and air quality indices using various statistical measures such as the exceedance factor, the *t*-test, the ANOVA test and the Pearson product moment correlation analysis for the available dataset.

Materials and methods

Study area

The geographical details of the 15 selected Indian cities are provided in Table 2 and the geographical location of the same is provided in Fig. 1. We follow the generic classification of Indian cities as Tier-I and Tier-II which is based on population and infrastructural development. The six Tier-I cities are Chennai, Mumbai, Delhi, Kolkata, Bengaluru and Hyderabad, while the nine Tier-II cities are Ahmedabad, Bhopal, Chandigarh, Guwahati, Jaipur, Lucknow, Patna, Thiruvananthapuram and Visakhapatnam. As observed from Fig. 1, by virtue of the strategic location, analysis of these cities can substantially provide an overview of the national status of air pollution in the midst of COVID-19 (Link 2 (n.d.)). It is to be noted that during the early hit of COVID-19, most of these cities were involved in identifying the local epicentres of the spread by identifying most infected locations under the red zone category, even before the lockdowns were officially announced (Link 3 (n.d.)). In addition, numerous containment zones were declared to minimize the social

interaction with strict police patrolling and taxing fine for the offenders (Link 4 (n.d.); Link 5 (n.d.)). Details of the containment zone status during the peak of the first COVID-19 wave are mentioned in Table 2.

Various lockdown and unlocking phases in India

As an unconventional strategy by the central government of India to combat against the virus spread, there were four national-level imposed lockdown events (LD1–LD4) between March and May 2020 (Table 3). To make the statistical analysis more coherent and unbiased, we have defined the pre-lockdown period in three terms (BLD1, BLD2 and BLD3) based on the extent of time period considered for calculating the average values of concentration and other indices. The prominent socio-economic features of the lockdowns during this period were observed as complete ban on all modes of transport, closure of public places of crowding (tourism spots, shopping malls, restaurants, theatres, marriage halls and religious centres) and restricted operation of factories. However, a conservative supply of the essential commodities to the people was ensured with the help of various non-government organizations and self-help groups. Following the lockdown, about ten progressive unlocking periods (UL1–UL10) were identified for the period from June 2020 to April 2021 in order to capture the recent trends in air quality as well as COVID-19 spread, especially during the vaccination drive.

Data collection

The present study utilized an extensive database of 12 major air pollutants (PM_{2.5}, PM₁₀, NO, NO₂, NO_x, NH₃, CO, SO₂, O₃, benzene, toluene and xylene) which are regularly included in the air quality monitoring networks established by the Central Pollution Control Board (CPCB) covering 703 air quality stations across 307 cities of India (Sharma et al. 2020). The required database of daily averaged (24 h) concentrations is availed from their online portal (Link 6 (2021)) for the entire study duration. After downloading the spread sheets, the dataset is primarily filtered for eliminating rows with missing data and rearranged as per the priority considerations. Similarly, the daily databases of air quality index (AQI) for the selected cities were also collected from the online portal (Link 7 (2021)) as separate customized spread sheets. The daily reported counts of COVID-19 positive cases, recovery cases, mortality cases and vaccination details were accessed from the website (Link 8 (2021)) which is regularly updating based state bulletins and official handles.

Table 2 City-wise description of the geographical specifications and COVID-19 initial strategic actions of major Indian cities

S. no.	City name	Latitude (°N)	Longitude (°E)	State	City class	Population as per census 2011	CPCB remarks	COVID-19 strategic actions		
								State share of red zone [£]	No. of red zone districts [£]	
Tier-I cities										
1	Chennai	13.08	80.27	Tamil Nadu	Tier-I	4,328,063	Coastal city - PM ₁₀ exceeding NAAQS	6.25% No. of containment zones - 15	12	
2	Mumbai	19.07	72.87	Maharashtra	Tier-I	12,691,836	Non-attainment city - PM ₁₀ exceeding NAAQS	8.33%	14	
3	Delhi	28.70	77.10	Union territory	Tier-I	10,927,986	Non-attainment city - PM ₁₀ and NO ₂ exceeding NAAQS	27.27%	11	
4	Bengaluru	12.97	77.59	Karnataka	Tier-I	5,104,047	Non-attainment city - PM ₁₀ exceeding NAAQS	-	3	
5	Kolkata	22.57	88.36	West Bengal	Tier-I	4,631,392	Non-attainment city - PM ₁₀ and NO ₂ exceeding NAAQS	4.35%	10	
6	Hyderabad	17.38	78.48	Telangana	Tier-I	3,597,816	Non-attainment city - PM ₁₀ and NO ₂ exceeding NAAQS	3.23%	6	
Tier-II cities										
1	Ahmedabad	23.02	72.51	Gujarat	Tier-II	3,719,710	Non-attainment city - PM ₁₀ exceeding NAAQS	6.06%	9	
2	Bhopal	23.25	77.41	Madhya Pradesh	Tier-II	1,599,914	Non-attainment city - PM ₁₀ exceeding NAAQS	3.92%	9	
3	Chandigarh	30.73	76.77	Haryana	Tier-II	960,787	Non-attainment city - PM ₁₀ and NO ₂ - exceeding NAAQS	-	2	
4	Guwahati	26.14	91.73	Assam	Tier-II	899,094	Non-attainment city - PM ₁₀ exceeding NAAQS	-	2	
5	Jaipur	26.91	75.78	Rajasthan	Tier-II	2,711,758	Non-attainment city - PM ₁₀ exceeding NAAQS	6.06%	8	
6	Lucknow	26.84	80.94	Uttar Pradesh	Tier-II	2,472,011	Non-attainment city - PM ₁₀ exceeding NAAQS	1.33%	19	
7	Patna	25.59	85.13	Bihar	Tier-II	1,599,920	Non-attainment city - PM ₁₀ and NO ₂ - exceeding NAAQS	-	5	
8	Thiruvananthapuram	8.52	76.93	Kerala	Tier-II	784,153	Coastal city - pollution within NAAQS	7.14%	2	
9	Visakhapatnam	17.68	83.21	Andhra Pradesh	Tier-II	1,063,178	Non-attainment city - PM ₁₀ exceeding NAAQS	15.38%	5	

CPCB, Central Pollution Control Board (India); NAAQS, national ambient air quality standard. £Data as on April 19, 2020; £Data as on May 1, 2020

Fig. 1 Geographical location of the chosen cities (marked in black box)

Data analysis

Air quality index

The national ambient air quality index (AQI) has been conceived as an effective tool for depicting the real-time generic nature of air quality in terms of the corresponding ambient concentrations of the identified pollutants (CPCB 2016). The daily reported AQI values for all the 15 cities were initially analysed for spatiotemporal variations in terms of standard

deviations from their arithmetic average values. This is particularly emphasized to capture the reliability of long-term monitored data during the pre-lockdown phase in terms of three timelines (BLD1, BLD2 and BLD3). Furthermore, the AQI values were averaged to the corresponding periods of lockdowns and unlocking phases to elucidate their dependencies on specific pollutants. The recommended AQI categories were accepted as the direct indicators of the severity of various air pollutants with their associated likely health impacts such as AQI: 0–50 (good), 51–100 (satisfactory), 101–200

Table 3 Details of the various lockdown and unlock phases in India

Phase	Start date	End date	No. of days	Notation	Major remarks
1	01 January 2019	24 March 2020	449	BLD1	Period considered for long-term average
2	01 January 2020	24 March 2020	84	BLD2	Period considered for short-term average
3	01 March 2020	24 March 2020	24	BLD3	Period considered for very short-term average
4	25 March 2020	14 April 2020	21	LD1	Complete curfew – COVID-positive cases increased from 600 to 10,000; a few hotspots located with a test positivity ratio of 4.7%
5	15 April 2020	3 May 2020	19	LD2	More hotspots in Maharashtra, Gujarat, Delhi, Rajasthan, Madhya Pradesh, Tamil Nadu and Uttar Pradesh; partial relaxation to selected shops
6	4 May 2020	17 May 2020	14	LD3	More red zones in Delhi, Mumbai, Bengaluru, Chennai and Ahmedabad; cases increased from 42,533 to 85,940
7	18 May 2020	31 May 2020	14	LD4	Reported 5,000 fatalities; administered 1,00,000 tests; cases tolled to 1,94,504
8	01 June 2020	30 June 2020	30	UL1	Lockdown only in containment zones; highest backlog fatalities in Delhi and Maharashtra; new 4,00,000 cases in 38 days
9	01 July 2020	31 July 2020	31	UL2	Announced with more ease in restrictions; lockdown only in containment zones; crosses 6,00,00 cases
10	01 August 2020	31 August 2020	31	UL3	Relaxed night curfews; administered 1,000,000 tests; Maharashtra and Tamil Nadu imposed lockdown for a month
11	01 September 2020	30 September 2020	30	UL4	Lockdown only in containment zones; reached 1,017,000 cases; limited public gatherings
12	01 October 2020	31 October 2020	31	UL5	Lockdown only in containment zones; declined rate of cases; permitted inter-state movement
13	01 November 2020	30 November 2020	30	UL6	No new guidelines; active cases reduced to 4,94,000; limited public gatherings
14	01 December 2020	15 January 2021	46	UL7	Vaccination plan announced; active cases declined to 2,14,000; new coronavirus variant detected
15	16 January 2021	15 February 2021	31	UL8	COVID-19 vaccine rollout; active cases declined to 1,68,000; public transport and gathering restored; administered 7 million vaccinations
16	16 February 2021	15 March 2021	28	UL9	Total cases 2,19,262; more cases in Maharashtra, Punjab, Karnataka, Gujarat and Tamil Nadu; Tamil Nadu extended lockdown; administered 30 million vaccinations; total of 158,725 deaths
17	16 March 2021	15 April 2021	31	UL10	Surge in daily cases; enforced the Test-Track-Treat protocol for the second wave; more cases in Maharashtra, Kerala, Karnataka, Tamil Nadu and Andhra Pradesh; administered 100 million vaccinations

(moderate); 201–300 (poor), 301–400 (very poor) and 401–500 (severe).

Exceedance factor

The annual average levels of the air quality parameters were calculated for the chosen cities for the years 2019 and 2020. According to the standards and classes prescribed by the CPCB, the intensity of persistence of the pollutants can be

calculated using the exceedance factor (EF), as stated below (CPCB 2016):

$$EF = \frac{\text{Pollutant annual mean concentration}}{\text{Annual standard for pollution}} \quad (1)$$

The above expression was used to measure the level of pollution for the 12 air quality parameters for the chosen 15 cities. Furthermore, the air pollution status was analysed using

the following criterion: low pollution (L), $EF < 0.5$; moderate pollution (M), $EF = 0.5$ to 1.0 ; high pollution (H), $EF = 1.0$ to 1.5 ; and critical pollution, $EF > 1.5$.

Correlations and trends

The inter-dependencies and similarities in the observed concentration of air pollutants from the 15 cities invariably proclaimed the existence of complex interactions. In order to evaluate the cross-similarities among the pollutants as well as the locations, various hypotheses were tested using the statistical analysis tool pack available in Microsoft Excel spread sheet. Anticipating the variation of the phase-wise averaged air quality parameters within the sample domain (study period), a null hypothesis is defined for a particular function to ascertain its validity based on the permissible level of significance (invariably taken as 5% for all cases). Initially, the significance of differing the sampling locations (Tier-I cities and Tier-II cities) versus period of study (phases) for a single pollutant was analysed using two-factor ANOVA without replication. This is performed by defining the hypotheses as follows:

$$\text{Null hypothesis, } H_0 : \mu_{\text{city-1}} = \mu_{\text{city-2}} = \dots \mu_{\text{city-n}} \quad (2)$$

$$\text{Alternate hypothesis, } H_1 : \mu_{\text{city-1}} \neq \mu_{\text{city-2}} \neq \dots \mu_{\text{city-n}} \quad (3)$$

where μ_{city} indicates the mean value of the pollutant in all the cities (6 Tier-I cities and 9 Tier-II cities) during the selected phase period. This is repeatedly performed for all the remaining pollutants.

In a similar way, the resemblance of having significant variation for different pollutants for a particular city was tested using the principles of ANOVA as follows:

$$\text{Null hypothesis, } H_0 : \mu_{\text{pollutant-1}} = \mu_{\text{pollutant-2}} = \dots \mu_{\text{pollutant-n}} \quad (4)$$

$$\text{Alternate hypothesis, } H_1 : \mu_{\text{pollutant-1}} \neq \mu_{\text{pollutant-2}} \neq \dots \mu_{\text{pollutant-n}} \quad (5)$$

where $\mu_{\text{pollutant}}$ indicates the mean value of the pollutants in a particular city during the selected phase period. This is also performed repeatedly for all the remaining cities.

The significance of considering AQI as a unique parameter for the air pollution based on the same standard limits in both Tier-I and Tier-II cities is evaluated by employing t -tests. The hypotheses are defined as follows:

$$\text{Null hypothesis, } H_0 : \mu_{\text{pollutant-1}} = \mu_{\text{AQI}} \quad (6)$$

$$\text{Alternate hypothesis, } H_1 : \mu_{\text{pollutant-1}} \neq \mu_{\text{AQI}} \quad (7)$$

where $\mu_{\text{pollutant-1}}$ indicates the true mean of a pollutant for a city and μ_{AQI} indicates the comparison value of the corresponding AQI.

As mentioned earlier, in order to compare the significance of availing different durations while defining the BDL phase, another set of t -tests was performed by keeping the average value obtained for BDL-1 as the reference for pre-lockdown period. This test also serves as a comparison of pollution trends during different lockdown and unlocking phases compared to the pre-lockdown scenario.

Finally, the correlation between air pollution and the prevailing spread of COVID-19 pandemic was evaluated by considering the AQI as the sole representative of air pollution scenario and by configuring the COVID-19 infection levels into four classes, namely confirmed cases, active cases, deceased cases and recovered cases. The correlation analysis particularly included the entire history of COVID-19 spread and its after-effects in India, starting from the onset, spike, drop and also the symptoms of the next phase onset. In addition, this correlation is included with the early-stage history of administered vaccinations during the last 3 months of the study (January 16, 2021, to April 15, 2021). The required daily distribution datasets were prepared by converting the cumulative dataset for COVID-19 (mass curve) in order to highlight the transformations that happened during each phase of the study period. Furthermore, in order to normalize the data among each cities of unique gesture, three additional parameters were defined to effectively represent the statistical impacts of COVID-19 on public health.

Active ratio

$$= \frac{\text{no. of active cases during selected time period}}{\text{no. of confirmed cases during same period}} \times 100 \quad (8)$$

Recovery ratio

$$= \frac{\text{no. of recovered cases during selected time period}}{\text{no. of confirmed cases during same period}} \times 100 \quad (9)$$

Case fatality ratio

$$= \frac{\text{no. of deceased cases during selected time period}}{\text{no. of confirmed cases during same period}} \times 100 \quad (10)$$

Results and discussion

Status of air pollution responses

Apart from many isolated case studies of air quality variations, the results of the present study unveil a

comprehensive overview of the spatiotemporal variations of 12 major air pollutants across the 15 Indian cities including Tier-I and Tier-II cities. The details of the phase-wise averaged distributions of the air pollutants are provided in Table 6. It can be inferred that there is a common trend of declining concentrations for all major air pollutants during various phases in 2020 compared to 2019; nonetheless, a mere generalization would be incomplete without referring to the specific attributes of the location. For example, based on the results for Tier-I cities, the highest percentage of reduction in Chennai city was observed for PM_{10} , followed by $PM_{2.5}$ and toluene, while the reduction in the city of Delhi was highest for NO_x followed by $PM_{2.5}$ (Fig. 2a–e). Despite clear deviation from the historic trends, the highest reduction was observed during the middle stages of lockdown (LD2 and LD3). The highest degree of reduction in Mumbai city was reported for CO followed by NO_x and PM_{10} which is similar to Bengaluru. Similarly, Kolkata and Hyderabad have the highest reduction in $PM_{2.5}$ and PM_{10} . In a similar way, significant variations in air quality were observed for Tier-II cities also. One can observe a striking similarity in the concentration trends for the coastal cities despite being classified under different tiers. It is also observed that the concentrations of a few gaseous pollutants such as O_3 , NH_3 and petroleum hydrocarbons were increasing during the lockdown phases, especially for the south Indian cities. As reported in a few previous studies (Pant et al. 2020; Gautam et al. 2020), such anomalies can be more preferably related to the human activities than to the local weather conditions.

As evident from the graphs (Fig. 2a–e), some pollutants take a longer time to decrease from their higher values during BLD3 as indicated by the negative values of reduction (which means increase). This is partially due to the impact of considering BLD3 as the reference for estimating reduction in concentration as compared to 2019, which is an averaged value over 449 days prior to the first lockdown. Therefore, the results may substantiate the healing effect of long-term averaging studies despite the necessity to identify the extent of anomalies, which is useful in making futuristic predictions (Ropkins and Tate 2021). However, it is also anticipated that the existence of already released emissions in the atmosphere may be experienced for a longer period even after imposing the sudden lockdowns and may be reduced eventually if such restrictions are continually followed.

Based on the results, it may seem to revisit the assumption that the reduction in air pollution was only a phenomenal consequence during the lockdowns, as the trends started reversing while the government of India

announced partial unlocking phases during the later period. Except for Hyderabad and Bengaluru, almost all cities have regained increased emissions of pollutants during the unlocking phases, primarily due to the increased transportation activities. Phenomenal increase or decrease in pollutant concentrations during these phases can also be attributed to the regulatory infrastructure followed by the individual state governments as ordained by the central government. Since this particular study is focused on the early impacts of lockdown and unlocking phases, and is also based on a long-term averaged reference, the results safely provide strong evidence for further analysis of air quality during the later unlocking periods to extrapolate the anticipated trend.

Variation in exceedance factor and AQI

As mentioned above, the AQI is a summative figure of the prevalence of all major air pollutants for a given location and period. In order to capture the similarity of the means, the distributions of AQI as well as each pollutant need to be compared between 2019 and 2020. It is observed that the occurrence of anomalies in pollutant concentrations on a yearly basis can be effectively described using the exceedance factor (EF). The results from the current study show that there is a clear relationship between the percentage variation in AQI (during 2019–2020) and the observed range of EF values (Fig. 3). When compared to the previous graphs, there is a significant reduction in pollutant concentrations as depicted by the EF scores during 2019–2020 for all Indian cities despite the fact that the range of EF is closely associated with the pollution history. This may be due to the fact that EF is calculated based on the yearly average value for a particular pollutant whereas the AQI is calculated based on the worst case scenario within the selected timeframe of analysis (Roy and Singha 2020). It is evident from the fact that though there are reductions in EF scores, majority of the cities are exhibiting increased pollution deviating from the national ambient air quality standards (NAAQS) set in force by the CPCB especially during the early unlock phases. This is clearly observed in the case of $PM_{2.5}$, PM_{10} and CO (Fig. 3) indicating the lack of adequate enforcement infrastructure to improve the urban air quality in many Indian cities which can cause terrific disasters while handling any airborne pandemic as we see in the following sections. The variation in annual AQI thus serves as a reference to identify the cities whose variations are quite significant based on the short-term averaging techniques.

Fig. 2 Trend of air quality parameters and AQI for Tier I and Tier II cities during pre-lockdown, lockdown and unlock phases

Fig. 2 (continued)

Spatiotemporal trend analysis of AQI with its core elements

In addition to the bulk analysis, the specific trends of individual parameters were also evaluated to understand their variability among the locations (cities) and the time periods (phases). The key results from the two-factor ANOVA (without replication) were expressed in terms of F value and p value. Based on the validity of the null hypothesis to justify the test statistic, only pollutant-wise ANOVA tests were satisfactorily performed for both Tier-I and Tier-II cities independently (Table 4). The F critical values (F_{crit}) were obtained for each of the tests when the level of significance (α) was set to be 0.05. The null hypothesis was rejected when the resulting p value is less than the α value, as well as the resulting F value is greater than the obtained F_{crit} values. The F_{crit} values for Tier-I cities are found to be 2.285 and

2.485 while testing the variability among the time periods and cities respectively.

The phase-averaged AQI values have shown significant variations for both Tier-I and Tier-II cities when the time period and location of cities were considered the preferred sources of variation. Out of the 12 parameters, a statistically significant similarity in the average values of pollutant concentrations was observed for SO₂, O₃, benzene and xylene during different phases of the study while all other pollutants showed significant variations. However, there was no case of p value exceeding the α value for various cities, thus ensuring the distinct distribution of air pollutants in Tier-I cities. The results are further confirmed with the higher F values exceeding the F_{crit} values. In the case of Tier-II cities, majority of the pollutants exhibited significantly differing average concentrations over the selected time periods, except for CO, SO₂, O₃, benzene and xylene.

Fig. 3 Percentage variation in AQI and Exceedance factor values for Tier I and Tier II cities during 2019 and 2020

This indicates some kind of delay in pollutant abatement from the atmosphere in response to the imposed lockdown schedule which is in coherence with the observation mentioned above regarding the selection of short-term averaging techniques. Apart from the meteorological and geographical contributions, it is also to be understood from the public media that the enforced strict COVID-19 protocols were not uniform among the various Indian states despite the official

announcements (Table 3). This is confirmed from the *p* values and *F* values for the pollutants among the nine Tier-II cities. Hence, the trend analysis serves as a preferable technique to obtain the level of significance of pollutant concentrations in the atmosphere under multiple sources of variations.

In order to understand the significance of variation in the selected air pollutants due to the difference in time scale of reference, two-tailed *t*-tests were performed by

Table 4 Trend analysis for various air quality parameters based on the ANOVA tests

Air Quality Parameter	Variability	Tier-I cities		Tier-II cities	
		F value	p-value	F value	p-value
AQI	Time periods	6.9583 ^{\$}	3.28E-05 [*]	5.9454 [¥]	3.38E-05 [*]
	Cities	12.7572 [#]	4.31E-07	7.3491 [€]	1.25E-06
PM _{2.5}	Time periods	11.2645	2.25E-07	12.0757	2.80E-09
	Cities	14.6850	9.01E-08	8.9936	7.77E-08
PM ₁₀	Time periods	3.9523	0.0028	5.31048	0.0001
	Cities	6.6195	0.0002	14.1976	4.78E-11
NO	Time periods	5.6833	0.0002	2.3265	0.03715
	Cities	8.6366	2.08E-05	22.7064	5.49E-15
NO ₂	Time periods	12.1791	9.10E-08	8.0715	9.30E-07
	Cities	10.0612	4.95E-06	7.3132	1.33E-06
NO _x	Time periods	8.4660	4.90E-06	6.4216	1.46E-05
	Cities	5.3783	0.0009	8.7744	1.11E-07
NH ₃	Time periods	8.4262	5.14E-06	2.2532	0.0430
	Cities	118.4700	6.53E-21	17.7179	7.86E-13
CO	Time periods	5.6522	0.0002	1.4289	0.2122
	Cities	11.6691	1.11E-06	3.9135	0.0010
SO ₂	Time periods	0.8898	0.5249	1.9054	0.0858
	Cities	13.2505	2.85E-07	5.9351	1.68E-05
O ₃	Time periods	0.7255	0.6514	1.1075	0.3714
	Cities	5.6978	0.0006	19.6397	1.05E-13
Benzene	Time periods	1.6227	0.1615	0.6747	0.6925
	Cities	4.5886	0.0025	14.9410	1.91E-11
Toluene	Time periods	2.4884	0.0348	2.4580	0.0285
	Cities	25.9983	7.17E-11	36.7694	1.39E-19
Xylene	Time periods	2.1694	0.0615	1.9389	0.0804
	Cities	9.0741	1.32E-05	5.5764	3.35E-05

\$: F value corresponding to the F-critical value (Fcrit = 2.285); #: F value corresponding to the F-critical value (Fcrit = 2.485); *: p-value corresponding to the level of significance ($\alpha = 0.05$); ¥: F value corresponding to the F-critical value (Fcrit = 2.178); €: F value corresponding to the F-critical value (Fcrit = 2.108)

comparing the true means for the various phases of lockdown series (LDS) while considering BLD1 as the comparison mean (representative of pre-lockdown period from January 01, 2019). For the preferred α value of 5%, the observed levels of significance (p values) were quite low for majority of the pollutants in Tier-I cities. The highest impact of lockdown was observed in the concentrations of NO_x and PM_{2.5} in majority of the Tier-I cities. Two distinguishing features of the Tier-I cities to cause this deviation are ascertained to be the reduced vehicular emissions caused by the decrease in public transport and climatic modifications in the coastal cities during the study period. On the other hand, majority of the Tier-II cities did not exhibit any significant difference for the averaged pollutant concentrations as a consequence of restrictions imposed during the LDS except in the case of

PM_{2.5} and CO concentrations. One reason for this phenomenon may be attributed to the lesser impact of reduced vehicular emissions compared to the partially continued industrial activities. Based on the trend analysis, it is observed that consideration of long-term averaging techniques as the reference for measuring the impacts of short-term LDS can give significant insights to the cause of pollution incidents and the effectiveness of their control strategies.

Was air pollution a precursor in extending COVID-19 impacts?

Being the second most populated country in the world, India has been valiantly fighting against the COVID-19 spread, in spite of the projected historical ambiguities

persisting while pursuing the environmental quality norms. Considering the infrastructural limitations in handling the serious consequences of pandemic situations, India had exhibited strong political strategies during the onset period of COVID-19 by announcing the country's longest-ever lockdown series during March–May 2020. In order to keep the population safe and moving, individual states have taken various preparatory steps including uninterrupted emergency services to get the maximum benefits of complete lockdown. Therefore, it is important to investigate the correlations and trends of COVID-19 issues and the prevailing air quality while implementing such massive institutional restrictions. In order to make the comparison more generic and informative, the phase-averaged AQI values were computed for the entire period of COVID-19 pandemic (including 4 lockdown events and 10 unlock events until April 2021). Similarly, the COVID-19 database is represented with five critical parameters, namely positive confirmed cases, deceased cases, active cases, recovered cases and vaccination cases (expressed as actual count).

The results from the two-way ANOVA studies among these counts and the corresponding AQI values revealed that air quality can be an important precursor to estimate the critical phase of COVID-19 spread and the effectiveness of control measures taken during that period. The prepared databases of the phase-averaged counts and AQI values are presented in Table 7. It is observed that each phase of the study period was characterized by certain temporary activities including establishment of containment zones and red zones in various parts of the cities (Table 2). The results indicate that gradual relaxations of the restrictions during the later stages have enabled increased pollution activities and have worsened the air quality in many cities.

Another important activity to curtail the pandemic spread was the introduction of vaccine from January 16, 2021. Thereafter, the country has witnessed massive spikes in the vaccination doses through large-scale vaccination drives. As evident from the trend analysis results, the later stages of unlocking were illustrating a reversal of earlier trends of disease spread, an indication of the popular phrase “COVID wave.” This is associated with a combination of mutually exclusive events such as administration of massive vaccination drives while granting permission to hold local gatherings. As a result, the correlation analysis showed that there is no significant trend and correlation between AQI and COVID-19 database for Tier-I cities except for the vaccination cases and recovery cases (Fig. 4a–c).

In addition, it also observed that the COVID-19 impact parameters such as active ratio, recovery ratio and case fatality ratio do not hold the same relationship with

the AQI values as compared to their parent components (actual counts). The correlation between AQI and recovery ratio was found to be positive and significant (between 0.35 and 0.55) for all Tier-I cities except for Chennai (Fig. 5a). It is to be noted that Chennai, Bengaluru and Hyderabad are the cities with better air quality (i.e. lower AQI values) compared to the other three cities in the same group, and have experienced drastic variations in AQI during the lockdown and unlocking periods. This variability has caused these cities to limit almost all their correlations with COVID-19 parameters to be something less than 50%. Another remarkable observation is that three biggest metropolitan cities—Delhi, Mumbai and Kolkata—showed highest correlation for AQI with vaccine data but in the negative direction. This can be attributed to the onset of second wave, showing further rapid increase in the positive confirmed cases, despite increase in the vaccination cases (Link 8 (2021)).

The results also facilitate another discussion on the consequence of imposing initial lockdown series as against administering vaccinations, as both were introduced at a critical juncture to curtail the possibility of community spread. In the present study, both these trials have the same duration of 3 months, thus making it more comparable. As evident from the study, the lockdown phases were crucial in limiting the active ratio and recovery ratio by enabling institutionalized implementation of public health precautions such as social distancing and wearing masks. The results also indicate that case fatality ratio has drastically reduced during the initial 3 months of vaccination dosage. However, this is not sufficient to declare that vaccination alone can stop spreading the pandemic despite seeing the current evidences of the next phase spread.

Comparing the results of correlation analysis for the Tier-II cities, it is observed that the confirmed cases, recovery cases and vaccination cases bear significant correlation with AQI (always greater than 30%) except for Patna and Lucknow (Fig. 5b, c). Highest negative correlation was observed for vaccination cases (always greater than 40%) except for Patna and Jaipur. The low correlation between AQI and COVID-19 data in those cities may be attributed to the exceptionally high records of AQI values as a remark of their pollution history. This is verified based on the pre-lockdown data analysed presented in Table 3. It is also important to note that the correlation of AQI with active cases remains very poor in almost all cities with negative values for Pearson's product moment correlation coefficient. This is due to the rapid variations in the number of daily active cases causing irregular increases and decreases compared to the previous phase values.

Based on the available medical records, the variations in the case fatality ratio may be mainly caused by the infection by the novel coronavirus instigating other prominent health issues like cardiac attack, pneumonia and other types of lung infections (Balakrishnan et al. 2014; Gorbalenya et al. 2020). However, the correlation analysis strongly substantiates the necessity to investigate the possibility of associated air pollution history to worsen the scenario causing such high casualty records. This can be further enlightened by including the meteorological, social and institutional factors also into consideration. Actually, most of the present results are mainly aimed to provide a feasibility analysis to correlate these factors; and therefore, we feel that the linear correlations may not fit well to predict the cyclic (or wave-type) nature of the daily record of COVID-19 database for Indian scenario. We therefore strongly recommend using multi-criteria non-linear correlation analysis to reveal more about the hidden interactions in our understanding about the atmospheric reach of coronavirus and its associated health risks.

Proposed classification based on significance of responsiveness

Considering the outreach of the COVID-19 pandemic in redefining the global socio-economic margins, it is necessary to have city-specific strategic plans to combat the widespread impacts and associated public health risks. In this regard, the current study postulates a proposal to classify the Indian cities according to their resilience and susceptibility to incorporate sudden impacts of institutionalized massive restrictions in terms of atmospheric quality within their premises. We have observed that quite a few cities are highly responsive and can reflect the significant variations in the concentrations of many air pollutants as a result of the imposed lockdown series, compared to their past historical records.

Based on the results, it is clear that some of the primary air pollutants are widely present in all cities and have minimum diurnal variations across the seasons due to the continuous presence of the interactive sources. However, the lockdown series have clearly

Fig. 4 Correlation between AQI and COVID-19 cases (Confirmed, Deceased, Active, Recovered)

Fig. 4 (continued)

posed a check on them; and as a result, many cities have shown dramatic changes in their concentrations. Considering these aspects of responsiveness (or in other words, absence of resilience), we have ranked the Indian cities within the Tier-I and Tier-II classifications (Table 5). Among the Tier-I cities, Kolkata stands first followed by Mumbai, Bengaluru and Chennai. This indicates that these cities have experienced a sudden

change in the concentrations of the primary air pollutants during the LDS. It is not surprising to see that Delhi comes in the fifth rank because of the persisting air pollution incidents in the city which could not recognize any significant improvements to the short-term activities based on the previous year observations. This is more specifically depicted by the less significant change in AQI compared to BDL1 as the reference.

Fig. 5 Correlation between AQI, confirmed cases, deceased cases, active cases, recovered cases, vaccinated cases, active ratio, recovery ration and case fatality ratio

Fig. 5 (continued)

Among the Tier-II cities, the top three ranks are allocated to Patna, Chandigarh and Visakhapatnam, followed by Thiruvananthapuram, Ahmedabad and Bhopal. It is invariably anticipated that curtailing the industrial activities in the Tier-II Indian cities may provide significant improvement in the total environment, which are to be implemented along with reduced public movement. This also points out towards the success of local enforcement activities towards bringing a significant change in the air quality as seen in the modifications in the AQI values. However, caution should be

taken while interpreting the reasons for lesser significant changes in air pollutants in Lucknow, Jaipur and Guwahati as they typically represent varying topographical, industrial and climatic conditions. As we observed for Delhi, the cities of Lucknow and Jaipur have shown significant variations for NO and NO_x concentrations alone, while Guwahati has shown increase in O₃ concentration. Based on the analysis, we have also prioritized the pollutants according to their significance of variability among the Indian cities. It is observed that among the Tier-I cities, NO_x has shown the highest variability in maximum number of cities, followed by PM_{2.5}, NO₂ and NH₃. Among the Tier-II cities, CO and PM (both PM_{2.5} and PM₁₀) have shown significant variability in maximum number of cities, followed by NO_x and O₃ concentrations. As mentioned above, the variations in CO and PM can be thought to be effected by reduced industrial emissions, while the variation in O₃ has shown increasing trend in many cities owing to the favourable situations for secondary photochemical emissions in the lower atmosphere.

Conclusions and recommendations

The present study addresses the status of air quality in major Indian cities during various lockdown and unlocking phases during the COVID-19 pandemic spread compared to the pre-lockdown measures. The significance of considering long-term averaged values as references for evaluating the short-term impacts of lockdown series was evaluated using statistical tests. The observed variability in air quality in terms of AQI and its core elements were evaluated among the Tier-I and Tier-II cities as well as during regular phases of lockdown events. Furthermore, the study highlights the

Table 5 Classification of Tier-I and Tier-II Indian cities according to the significance of their responsiveness to the lockdown events

Location	Significantly varied pollutants	Rank
Tier-I cities		
Kolkata	PM _{2.5} , PM ₁₀ , NO ₂ , NO _x , NH ₃ , CO	1
Mumbai	PM ₁₀ , NO, NO ₂ , NO _x , NH ₃ , O ₃	2
Bengaluru	PM _{2.5} , PM ₁₀ , NO ₂ , NH ₃ , CO	3
Chennai	PM _{2.5} , NO, NO _x , O ₃	4
Delhi	NO, NO _x , benzene, toluene	5
Hyderabad	PM _{2.5} , CO	6
Tier-II cities		
Patna	PM _{2.5} , PM ₁₀ , NO ₂ , NH ₃ , CO, benzene	1
Chandigarh	NO, NO _x , CO, O ₃ , benzene	2
Visakhapatnam	PM _{2.5} , NH ₃ , CO, benzene, toluene	3
Thiruvananthapuram	PM _{2.5} , PM ₁₀ , CO, O ₃	4
Ahmedabad	PM _{2.5} , PM ₁₀ , SO ₂ , toluene	5
Bhopal	PM ₁₀ , NO ₂	6
Lucknow	NO, NO _x	7
Jaipur	NO ₂ , NH ₃	8
Guwahati	O ₃	9

possibility of correlating the AQI with the initial trend of COVID-19 issues including the vaccination cases. The major conclusions drawn from the study are as follows:

1. The imposition of lockdown has caused invariably declining trend of concentrations for major air pollutants during various phases in 2020 compared to 2019. The highest reduction in concentration was observed during the middle stages of lockdown followed by a reversed trend during the unlocking phases. The results indicate that the current nature of trend cannot be generalized without referring to the specific attributes of the location. Statistical analysis infers that long-term averaging technique for representing the impacts of short-term pre-lockdown conditions can impose a healing effect to the observed anomalies despite the necessity to identify their extent.
2. The statistical significance analysis showed evidence for the reversing trends in air pollution for the partial unlocking phases, indicating that the earlier reductions in air pollution during the imposed lockdown series were only a phenomenal consequence. The variations in significant levels (p values) thus represent the influence of local administrative decisions to provide sufficient enforcement infrastructure during the complete lockdown period (March–May 2020). Remarkably, an oscillating trend of active COVID-19 cases was visible in those cities.
3. The results suggest the existence of a strong relationship between the percentage variation in AQI (for 2019–2020) and the observed range of EF scores. However, the marginal reductions in EF during the study period alone cannot dictate any improvement in air quality as the concentrations of major air pollutants in many of the cities may be well beyond the national ambient air quality standards (NAAQS) being measured with respect to the worse scenario.
4. The trend analysis serves to be a preferable criterion to choose the preferred sources of variations despite the fact that there is incoherent variability in the pollutant distributions among the cities for various phases of the study. The results highlighted that consideration of long-term average as the reference for measuring the impacts of short-term LDS can give significant insights to the cause of pollution incidents and the effectiveness of their control strategies.
5. The correlation analysis revealed that air quality expressed in terms of AQI can act as an important precursor to estimate the critical phase of COVID-19 spread and the effectiveness of various control measures taken during each phase. However, the study failed to identify any significant correlation between AQI and COVID-19 database for Tier-I cities except for the vaccination cases and recovery cases due to the variability introduced by a sequence of mutually exclusive events such as administration of massive vaccination drives and permission to hold local gatherings. The latest trends in vaccination drive amidst the onset of second wave of the pandemic have shown negative correlation with AQI for Delhi, Mumbai and Kolkata having large number of positive confirmed cases.
6. The 3 months of lockdown (during March–May 2020) and the following partial unlocking events were able to limit the active ratio and recovery ratio by enforcing strict precautions such as social distancing and wearing masks. Similarly, the first 3 months of onset of vaccination drive (January–April 2021) has resulted in reduced case fatality ratio despite the advancement in number of daily positive confirmed cases in major Indian cities. The correlation analysis suggests that the case fatality ratio may be modified by including the prominent diseases associated with air pollution to realize the actual impact of coronavirus on public health surveillance system, thereby incorporating a much wider aspect of air quality in COVID-19 impact studies.
7. As the COVID-19 impacts demarcate highly dynamic oscillatory trends, the linear correlation analysis proves insufficient to capture the original nature of observed deviations. A multi-criteria non-linear correlation model could realise the hidden interactions of coronavirus in the social atmosphere and its associated health risks.
8. Based on the results, a ranking is proposed for the Indian cities according to their responsiveness to various institutionalized restrictions in terms of air quality parameters. Among the Tier-I cities, Kolkata stands first, followed by Mumbai, Bengaluru and Chennai, signifying their resilience in reflecting the sudden changes in primary air pollutants during the LDS. The top three-ranked cities among the Tier-II category consist of Patna, Chandigarh and Visakhapatnam, followed by Thiruvananthapuram, Ahmedabad and Bhopal, indicating the influence of reduced industrial activities along with restricted public movement. However, caution must be exercised while interpreting the causes for the observed variations in view of the prevailing climatic, topographical, social and industrial conditions of the cities.

Appendix

Table 6 Phase-averaged concentrations of various air pollutants and the corresponding AQI values for the selected Indian cities

City	Phase	PM _{2.5}	PM ₁₀	NO	NO ₂	NO _x	NH ₃	CO	SO ₂	O ₃	Benzene	Toluene	Xylene	AQI
Tier-I cities Chennai	BLD1	43.94±25.28	58.51±38.2	8.65±5.35	16.21±5.48	22.72±7.31	40.16±34.1	0.86±0.19	8.17±4	35.2±14.63	0.39±1.09	1.42±2.02	0±0	102.94 ±41.67
	BLD2	38.44±13.69	57.53±30.39	8.92±2.78	13.52±4.35	21.48±6.27	51.67±17.01	0.81±0.14	12.07±5.43	29.71±6.77	1.37±2.41	0.06±0.17	0±0	80.58 ±24.75
	BLD3	32.67±7.55	35.59±30.74	8.95±1.63	10.36±3.25	18.38±4.21	49.55±16.83	0.75±0.14	8.46±4.57	31.59±9.79	0.85±0.41	0.1±0.16	0±0	74.58±11.1
	LD1	23.73±8.24	127.15±98.99	6.67±1.31	8.73±2.45	13.58±2.2	50±4.83	0.58±0.04	5.79±1.62	34.56±5.01	2.97±6.72	0.02±0.06	0±0	61.57±8.18
	LD2	10.96±3.13	0±0	6.05±1.06	7.38±2.77	12.25±2.62	36.77±9.49	0.65±0.07	4.89±0.69	39±5.02	0.25±0.05	0±0.01	0±0	63.84±5.19
	LD3	12.92±6.08	0±0	5.51±2.17	5.8±1.65	10.79±3.72	36.24±5.88	0.73±0.05	4.46±0.83	43.81±3.15	0.2±0.03	0.01±0.01	0±0	72±5.78
	LD4	26.16±5.91	177.03±121.7	7.86±1.03	10.8±2.22	17.88±2.8	42.19±2.38	1.01±0.08	5.9±1.05	49.27±7.57	0.13±0.02	0.05±0.14	0±0	87.07 ±11.71
	UL1	29.01±19.07	52.32±60.62	8.99±1.44	11.8±2.37	19.68±3.11	37.73±5.02	1.08±0.1	6.34±1.41	58.6±9.18	0.1±0.03	0.03±0.04	0±0	102.71 ±21.07
	BLD1	108.5±85.55	215.05 ±119.56	32.11±24.32	45.24±14.64	53.25±28.56	36.4±9.59	1.37±0.51	14.03±5.03	38.94±11.68	3.8±1.94	28.94±12.8	1.14±1.17	232.1 ±17.6
	BLD2	118.41±61.59	204.14±81.63	38.47±25.88	45.45±9.63	59.74±27.56	39.05±6.55	1.3±0.52	13.56±3.22	33.85±7.76	3.86±1.58	26.43±11.45	1.13±1.31	248.14 ±90.39
	BLD3	64.71±20.22	140.71±47.64	25.57±13.98	38.52±7.4	44.58±16.04	32.97±2.82	0.97±0.2	14.72±2.36	39.23±5.17	2.68±0.8	23.94±8.27	1.43±1.71	153.33 ±41.31
Delhi	LD1	40.09±12.17	83.07±29.1	9.27±1.53	20.33±3.4	19.19±2.68	26.29±3.31	0.67±0.12	13.76±2.7	40.1±6.96	1.35±0.38	9.78±1.91	0.72±0.81	93.9±21.87
	LD2	45.48±13.8	112.96±36.13	10.57±1.68	19.68±3.99	21.07±2.93	30.46±2.49	0.83±0.11	15.74±2.35	49.58±7.81	1.76±0.55	10.48±3.23	0.01±0.01	122.42 ±19.54
	LD3	54.73±18.52	121.94±34.97	8.64±3.34	21.43±4.25	19.81±3.72	29.18±1.82	0.84±0.1	14.41±2.21	60.8±9.14	1.63±0.28	12.54±2.06	0.36±0.57	137±27.02
	LD4	58.88±27.98	159.06±61.59	10.32±5.07	30.29±9.79	25.59±9.9	29.3±3.21	1±0.18	16.71±5.13	53.03±8.24	1.9±0.69	16.55±6.85	1.4±3.02	165.21 ±46.29
	UL1	46.93±11.2	121.45±48.98	8.39±2.68	23.64±4.92	20.99±5.08	32.65±3.58	0.92±0.08	12.36±1.83	39.3±10.33	1.84±0.34	19.15±4.61	0.76±0.55	124.94 ±32.3
	BLD1	34.74±27.39	95.93±57.46	31.81±16.78	23.59±14.66	54.97±26.02	14.06±4.31	1.27±0.76	14.18±6.62	28.87±21.15	2.56±2.31	0±0	0±0	107.95 ±48.3
	BLD2	59.9±25.25	144.56±38.01	30.45±14.87	38.72±12.53	68.04±24.15	19.9±3.39	0.93±0.31	10.39±3.06	37.55±9.08	5.49±3.01	0±0	0±0	149.46 ±45.77
	BLD3	34.59±15.44	117.86±38.51	24.99±15.55	27.45±11.73	52±25.27	18.56±3.64	0.65±0.3	12.07±3.37	29.46±7.84	5.96±3.2	0±0	0±0	112.92 ±30.69
	LD1	25.98±2.78	75.03±11.01	10.83±2.54	8.67±1.65	18.95±2.3	9.05±1.72	0.42±0.05	7.47±0.91	27.41±9.06	3.95±0.78	0±0	0±0	78.95±9.41
	LD2	19.19±3.53	52.83±10.22	15.65±2.02	7.29±1.52	22.44±2.1	6.77±1.42	0.45±0.16	10.7±3.28	19.91±2.97	6.65±4.16	0±0	0±0	67±9.57
Bengaluru	LD3	16.43±6.07	60.76±22.06	23.13±4.65	6.79±1.87	27.61±5.06	4.25±0.95	0.31±0.03	23.03±9.02	18.6±2.59	2.72±0.36	0±0	0±0	70.93 ±16.79
	LD4	13.16±3.47	49.74±11.16	16.08±2.81	9.26±1.99	24.31±3.16	3.85±0.74	0.26±0.03	10.02±3.12	19.01±2.49	1.13±0.61	0±0	0±0	58.71 ±10.22
	UL1	11±4.07	34.41±12.32	19.08±4.82	11.49±2.92	30.42±3.85	12.28±6.05	0.37±0.05	10.35±2.44	12.12±5.77	1.59±0.59	0±0	0±0	53.29±5.48
	BLD1	35.42±16.15	75.61±27.19	9.93±4.86	28.38±8.09	29.99±9.12	15.06±3.53	0.9±0.16	5.35±1.16	40.34±15.22	0.88±0.64	5.64±9.63	0±0	91.6±27.04
	BLD2	40.73±9.7	88.08±16.27	7.13±3	30.77±7.5	32.16±7.88	13.58±1.46	1.05±0.12	7.3±1.28	42.04±8.05	0.56±0.35	5.37±8.88	0±0	96.33 ±13.74
	BLD3	41.49±11.25	88.82±19.43	5.36±1.93	24.59±4.85	26.37±5.77	12.99±1.63	0.98±0.12	7.01±0.54	46.96±7.53	0.39±0.11	1.75±0.78	0±0	97.46 ±14.65
	LD1	26.15±4.72	46.56±13.45	2.82±0.47	11.29±1.97	12.57±1.86	11.99±1.86	0.77±0.07	5.98±0.76	43.15±4.88	0.25±0.16	4.54±5.04	0±0	69.24±5.24
	LD2	23.83±6.43	49.66±7.88	2.99±0.43	12.56±1.73	13.9±1.63	9.31±1.14	0.72±0.07	6.19±0.64	36.57±4.39	0.29±0.12	3.37±2.75	0±0	68.05±8.53
	LD3	21.83±4.4	61.45±12.14	3.25±0.49	15.93±2.1	15.73±1.58	8.83±1.05	0.82±0.07	6.91±0.58	33.65±4.48	0.3±0.14	1.6±0.93	0±0	76.57±7.05
	LD4	20.59±3.35	58.86±9.5	4.28±1.16	14.99±2.05	15.46±2.36	9.22±1.11	0.75±0.08	6.1±0.39	29.67±4.88	0.31±0.15	1.7±0.31	0±0	69.93±4.57

Table 6 (continued)

City	Phase	PM _{2.5}	PM ₁₀	NO	NO ₂	NO _x	NH ₃	CO	SO ₂	O ₃	Benzene	Toluene	Xylene	AQI
Kolkata	UL1	18.02±4.7	40.72±13.15	4.86±1.55	13.71±2.23	15.11±2.45	6.3±0.75	0.63±0.05	7.09±0.37	16.22±2.34	0.56±0.29	1.88±0.67	0±0	54.77±7.6
	BLD1	68.32±58.17	123.55±91.91	27.37±36.12	43.38±32.54	66.58±57.18	20.21±13.34	0.77±0.43	8.14±5.83	29.15±9.07	15.26±10.47	18.52±14.04	3.32±1.84	143.91
	BLD2	79.11±29.28	155.79±55.44	42.76±32.96	50.69±16.68	91±43.93	27.29±4.71	0.96±0.37	13.71±3.74	39.41±11.46	20.04±13.16	27.6±14.02	3.03±1.7	185.14
	BLD3	53.43±21.87	101.77±40.1	15.76±12.09	33.41±10.68	48.97±21.81	23.7±2.48	0.73±0.19	11.85±2.79	47.58±11.48	7.24±3	13.63±4	1.8±0.82	128.88
	LD1	37.71±12.45	65.39±16.13	5.06±0.66	12.64±3.26	17.74±3.66	17.06±1.85	0.47±0.1	9.38±2.19	57.13±10.96	2.71±0.91	6.8±0.89	0.56±0.21	93.71±19.6
	LD2	15.78±5.32	33.43±10.74	3.98±0.17	9.22±1.28	13.24±1.41	12.65±0.42	0.34±0.03	6.82±1.14	37.75±6.73	1.61±0.45	6.05±0.6	0.37±0.09	53.42±7.9
	LD3	17.83±5.29	39.26±9.09	3.53±0.33	7.74±1.85	11.32±2.11	9.18±2.23	0.33±0.04	6.3±1.47	39.8±12.77	1.55±0.38	5.46±0.76	0.32±0.09	60.93
	LD4	14.59±3.97	38.19±9.9	3.37±0.39	6.59±1.49	10.01±1.6	9.16±1.44	0.34±0.04	4.97±0.81	26.67±5.6	1.15±0.35	7.97±1.65	0.52±0.13	45.57±6.94
	UL1	13.54±4.18	34.66±7.93	4.97±1.59	10.36±2.23	14.64±2.31	9.76±1.44	0.36±0.03	6.44±2.32	25.66±6.48	2.28±1.03	12.11±2.49	0.83±0.35	46.42±8.57
	BLD1	41.55±21.23	91.3±41.83	5.05±3.08	29.67±12.73	19.07±8.51	13.99±4.34	0.57±0.17	7.11±3.43	28.98±10.6	1.43±1.28	9.69±9.57	1.91±3.01	93.98
	BLD2	44.72±13.73	96.35±26.1	10.83±4.14	32.09±8.61	24.39±7	18.03±5.12	0.52±0.1	7.13±3.26	27.2±4.91	1.13±1.08	6.55±6.58	0.57±1.08	94.85
	BLD3	36.06±8.48	84.39±17.62	9.04±2.21	26.16±5.67	20.08±3.6	15.03±3.7	0.51±0.07	5.77±1.67	24.71±4.09	2.31±0.92	11.43±5.42	1.48±1.63	82.17
Tier-II cities Ahmedabad	LD1	33.11±8.43	63.14±13.24	7.77±5.72	19.53±4.99	15.03±4.86	12.6±3.01	0.48±0.11	6.82±1.92	31.33±4.52	1.35±0.41	6.4±2.96	0.26±0.13	67.9±9.02
	LD2	28.02±5.99	59±11.11	6.89±0.92	23.34±2.91	16.89±1.93	14.47±2.84	0.47±0.07	4.76±0.84	26.89±4.17	1.2±0.51	6.97±3.74	0.19±0.11	62.32±8.45
	LD3	28.63±3.99	63.11±9.39	6±0.77	24.5±2.91	17.02±1.9	11.9±1.16	0.44±0.06	5.24±0.84	28.95±2.85	1.31±0.65	9.61±5.48	0.5±0.37	68.36±6.92
	LD4	32.32±7.88	101.84±28.89	5.86±1.31	28.31±5.04	18.53±3.18	15.18±7.11	0.46±0.1	7.31±2.08	33.91±4.83	2.02±1.18	14.55±10.13	2.15±1.39	93.71
	UL1	18.9±5.3	45.79±16.25	5.95±1.27	21.9±2.98	15.26±1.72	14.76±5.27	0.32±0.05	6.51±1.51	18.33±4.6	0.81±0.36	5.87±3.5	0.96±0.92	47.1±11.56
	BLD1	62.12±27.74	120.15±38.47	26.13±17.55	91.09±48.61	62.85±35.39	0±0	26.13±17.55	72.79±42.09	46.59±22.57	5.23±8.27	44.05±33.69	5.28±8.03	516.35
	BLD2	59.64±20.81	125.2±34.86	17.81±19.89	39±22.9	31.55±21.89	0±0	17.81±19.89	52±23.79	39.33±15.58	2.18±1.18	36.01±8.39	1.34±1.03	392.08
	BLD3	49.42±16.11	116.41±21.78	9.38±6.32	35.4±12.38	23.82±10.6	0±0	9.38±6.32	48.03±21.84	45.2±16.15	2.99±1.09	42.55±11.33	1.47±1.45	310.87
	LD1	32.48±8.11	82.39±14.59	4.14±1.02	28.22±7.98	16.78±3.82	0±0	3.48±1.93	26.57±9.7	43.55±8.05	6.12±2.33	27.6±11.46	3.26±1.57	149.52
	LD2	28.49±4.16	78.08±11.38	3.68±0.67	18.25±4.35	11.26±1.74	0±0	0.44±0.1	25.23±8.32	46.86±6.83	2.91±1.39	20.75±8.88	1.5±0.77	107.16
	LD3	25.82±4.75	77.07±20.2	3.46±1.07	18.27±3.65	11.22±1.49	0±0	0.56±0.11	11.23±12.46	56.4±3	3.41±1.36	20.16±5.5	1.18±0.39	130.71
	LD4	27.07±3.81	77.62±12.44	3.33±0.64	21.23±5.3	12.81±2.78	0±0	0.61±0.12	0±0	55.36±5.12	4.64±2.1	18.68±6.31	1.66±0.67	127.07
Bhopal	UL1	30.5±21.35	123.8±104.48	6.29±3.6	29.69±10.75	17.97±4.78	0±0	0.68±0.18	14.36±3.82	42.06±16.67	5.39±4.07	41.28±12.29	3.81±2.66	98.1±16.19
	BLD1	67.29±33.29	143.37±62.13	10.96±6.29	44.75±13.98	32.71±10.31	23.73±10.23	1.18±0.27	12.53±5.88	57.16±17.4	0±0	0±0	0±0	162.61
	BLD2	54.44±21.73	134.96±28.1	7.38±5.58	37.35±10.99	25.95±9.79	17.9±4.87	0.92±0.26	14.79±8.2	59.5±14.16	0±0	0±0	0±0	136.96
	BLD3	34.82±9.23	120.48±24.56	3.35±1.71	25.44±6.69	16.34±4.66	14±3.67	0.69±0.17	12.79±3.6	71.04±5.75	0±0	0±0	0±0	116.63
	LD1	29.85±8.88	84.56±30.92	2.9±1.1	10.35±2.5	7.57±1.17	17.37±3.59	0.48±0.16	12.27±2.34	56.02±13.84	0±0	0±0	0±0	88.82
	LD2	44.59±14.9	109.45±19.42	3.02±1.25	11.01±2.19	8.39±1.63	15±2.19	0.6±0.15	12.9±2.89	70.78±12.07	0±0	0±0	0±0	115.79
	LD3	22.16±6.89	72.98±21.83	1.19±0.23	10.38±2.15	6.56±1.23	14.01±2.56	0.41±0.07	11.22±3.94	83.71±7.66	0±0	0±0	0±0	108.43
														±8.76

Table 6 (continued)

City	Phase	PM _{2.5}	PM ₁₀	NO	NO ₂	NO _x	NH ₃	CO	SO ₂	O ₃	Benzene	Toluene	Xylene	AQI
Chandigarh	LD4	20.57±3.84	93.2±33.92	1.23±0.48	6.81±2.17	4.68±1.35	10.01±2.05	0.35±0.06	11.61±3.59	67.75±18.01	0±0	0±0	0±0	102.36 ±23.47
	UL1	16.36±3.52	46.95±15.04	2.04±1.01	10.38±3.07	7.26±2.34	15.86±3.64	0.53±0.13	12.12±3.43	50.45±13.09	0±0	0±0	0±0	71.58 ±13.83
	BLD1	64.32±30.82	113.51±40.75	15.3±12.2	10.51±8.59	18.93±13.58	13.86±14.74	0.75±0.21	10.08±2.58	16.34±0.35	6.23±6.38	2.29±2.25	3.72±9.32	135.55 ±69.08
	BLD2	37.38±15.43	84.09±29.65	13.58±10.89	14.98±3.76	18.48±9.4	49.81±16.32	0.68±0.17	8.78±1.75	11.82±3.37	5.64±1.62	0.57±0.81	3.05	84.52 ±26.92
	BLD3	21.11±7.02	58.97±22.17	8.71±7.54	14.49±4.59	14.53±7.57	66.65±12.56	0.57±0.12	9.89±1.82	13.44±2.62	4.53±0.99	1.21±1.19	7.78	61.5±19.47 ±25.04
	LD1	14.26±3.52	35.87±9.46	1.88±0.61	10.68±1.24	6.96±0.83	38.36±5.76	0.46±0.07	10.02±1.17	19.14±5.3	3.22±0.33	0.41±0.36	1.07±0.15	37.81±6.57
	LD2	15.42±4.72	43.98±17.87	2.4±0.84	11.61±1.28	7.98±1.24	32.11±7.36	0.52±0.07	11.44±1.78	26.53±6.5	3.03±0.48	0.66±0.58	1.09±0.14	51.72±12.9
	LD3	19.82±6.65	55.44±15.3	2.33±1.09	12.99±1.24	8.53±0.98	32.44±6.27	0.57±0.09	11.73±1.87	31.87±7.34	2.17±0.81	1.03±1.79	0.87±0.49	65.79 ±11.58
Guwahati	LD4	22.76±7.49	79.87±33.13	3.43±0.59	6.32±3.58	10.05±0.96	27.85±8.29	0.51±0.1	12.79±2.4	40.86±11.51	3.57±0.63	0.88±0.51	0.82±0.33	84.79 ±25.61
	UL1	23.86±6.97	56.74±16.49	1.74±1.09	9.04±2.33	6.21±1.7	34.41±8.99	0.3±0.05	11.62±2.45	38.72±9.63	3.43±0.58	1.66±4.75	0.76±0.2	66.48±12.6
	BLD1	57.8±63.06	110.69	18.11±18.09	13.07±5	43.68±32.43	10.31±8.56	0.71±0.33	14.71±5.03	24.41±14.92	5.01±14.1	0±0	0±0	127.56 ±108.99
	BLD2	118.56±49.48	198.86±68.42	45.89±24.44	19.22±7.31	89.15±46.51	17.75±3.58	1.14±0.59	13.5±0.71	19.23±1.55	2.08±6.55	0±0	0±0	252.79 ±86.7
	BLD3	83.65±21.99	161.06±42.69	28.45±15.01	24.82±8.07	49.58±29.25	15.54±2.26	0.61±0.21	13.75±0.54	19.56±1.29	0.36±0.19	0±0	0±0	185.88 ±62.76
	LD1	87.3±32.09	168.72±43.23	9.04±7.77	15.41±7.27	14.25±8.67	15.49±8.62	0.58±0.27	16.46±1.63	38.59±14.37	2.45±7.22	0±0	0±0	206.33 ±62.78
	LD2	26.5±17.41	40.82±21.5	3.15±3.29	7.27±2.2	5.88±3.21	12.28±11.21	0.39±0.12	15.17±1.87	32.31±6.3	0.68±2.29	0±0	0±0	62.89±48.6
	LD3	26.98±9.66	45.56±17.87	3.24±2.77	11.46±4.97	8.4±1.7	5.73±2.17	0.42±0.08	14.7±0.34	35.41±6.06	14.45±45.44	0±0	0±0	54.5±15.52
Jaipur	LD4	20.37±13.17	36.87±21.87	3.11±4.05	10.19±4.64	7.28±5.16	3.12±2.36	0.47±0.24	14.86±0.24	32.54±7.02	0±0	0±0	0±0	51.86 ±16.57
	UL1	20.21±7.87	33.87±13.44	2.86±2.63	8.46±3.03	6.25±3.22	3.01±1.28	0.45±0.09	15.73±0.23	26.07±5.95	0±0	0±0	0±0	42.1±11.68
	BLD1	48.93±21.06	114.18±53.07	13.64±9.43	33.05±11.95	38.98±15.92	31.36±12.58	0.9±0.25	12.08±2.68	44.87±14.55	1.44±1.39	7.02±4.85	0±0	120.51 ±49.04
	BLD2	47.82±11.52	109.39±30.7	13.02±13.38	42.75±12.21	47.1±21.24	37.07±11.92	0.95±0.23	13.09±1.94	55.36±13.14	3.22±1.53	13.65±9.06	0±0	116.49 ±22.58
	BLD3	39.83±11.82	96.03±41.17	7.37±4.38	33.8±9.15	33.96±10.63	36.35±10.11	0.86±0.27	13.5±1.56	68.99±11.47	1.89±0.77	21.66±8.66	0±0	111.13 ±25.18
	LD1	22.88±8.21	58.76±24.79	3.21±0.63	13.42±3.12	13.98±3.04	19.99±3.82	0.54±0.08	12.7±2.23	47.94±5.68	0.64±0.4	18.41±6.53	0±0	75.86 ±11.64
	LD2	31.72±10.09	84.21±41.24	3.49±0.42	13.79±2.22	14.72±2.11	20.35±2.32	0.58±0.07	12.24±1.07	51.31±7.43	0.64±0.33	3.44±4.12	0±0	93.74 ±20.08
	LD3	35.21±12.45	95.54±54.86	3.82±0.8	15.77±2.47	16.93±2.59	22.14±3.17	0.66±0.12	10.52±1.12	60.48±11.25	0.91±0.45	1.2±0.84	0±0	102±18.48
Lucknow	LD4	47.53±8.4	130.07±37.2	4.78±1.49	19.36±4.69	20.17±4.25	28.68±5.18	0.67±0.11	11.07±1.56	61.31±14.87	1.65±0.58	2.67±2.24	0±0	125.5 ±17.45
	UL1	36.08±10.33	85.46±31.35	5.55±0.85	16.67±2.45	19.4±2.43	25.89±3.82	0.64±0.08	9.9±1.17	59.05±12.89	0.67±0.41	1.21±0.64	0±0	93.32 ±19.87
	BLD1	98.09±61.42	0±0	14.96±14.02	35.22±17.78	30.14±18.04	22.8±13.15	1.23±0.32	7.68±3.47	32.23±10.5	1.3±1.3	6.79±13.26	0±0	202.56 ±100.54
	BLD2	105.57±47.02	0±0	20.6±15.92	48.22±21.83	40.45±20.84	18.33±11.43	1.42±0.44	9.19±4.51	30.97±8.4	6.62±8.76	13.18±11.2	0±0	216.38 ±83.35
	BLD3	69.12±22.07	0±0	13.56±10.66	27.83±8.67	24.88±9.31	18.61±4.77	1.1±0.05	6.31±1.18	37.05±4.12	16.59±10.68	18.24±12.48	0±0	143.38 ±46.04
	LD1	51.18±14.53	0±0	6.42±2.93	13.54±4.94	11.57±2.25	34.38±4.92	0.99±0.03	6.48±0.85	31.12±5.81	16.72±8.64	5.19±3.09	0±0	101.24 ±40.18

Table 6 (continued)

City	Phase	PM _{2.5}	PM ₁₀	NO	NO ₂	NO _x	NH ₃	CO	SO ₂	O ₃	Benzene	Toluene	Xylene	AQI
Patna	LD2	54.1±14.67	0±0	2.89±1.04	16.03±4.3	10.81±3.28	31.44±12.05	1±0.05	7.44±1.46	24.29±3.74	20.04±8.08	7.16±4.2	0±0	105.32 ±39.5
	LD3	53.41±12.38	0±0	5.05±2	15.05±3.49	11.57±3.05	10.89±6.43	0.88±0.07	7.09±1.09	29.54±8.18	24.53±9.1	10.42±5.57	0±0	105.93 ±28.78
	LD4	65.37±20.85	0±0	6.97±1.54	15±4.78	13.31±3.41	11.51±2.45	1.05±0.17	6.6±1.75	33.17±4.63	19.13±12.32	10.94±7.12	0±0	142.64 ±40.34
	UL1	46.22±16.62	0±0	7.61±2.03	14.36±5.13	13.68±3.9	14.83±4.8	1.06±0.14	5.5±1.04	44.68±6.46	10.96±7.18	8.01±5.7	0±0	95.84±35.2
	BLD1	104.37±88.83	197.36±33.29	20.93±17.79	42.3±32.79	26.3±20.61	37.41±10.13	1.56±0.63	41.44±13.36	61.17±26.12	3.3±3.96	16.94±13.76	11.55	218.26 ±15.63
	BLD2	95.47±38.07	164.89±48.62	60.51±23.1	45.67±12.22	92.21±29.36	27.62±6.97	1.47±0.7	9.5±1.73	17.88±5.42	2.58±1.3	6.19±3.31	2.54±1.5	214.5 ±119.87
	BLD3	69.02±20.97	152.27±49.53	57.37±18.55	52.66±9.11	73.91±15.14	22.46±5.59	1.25±0.3	10.54±1.5	22.08±6.14	2.67±1.11	6.11±1.9	1.15±1.1	168.13 ±61.64
	LD1	51.81±10.85	118.57±24.42	46.97±14.69	42.11±12.55	54.88±13.2	13.24±1.36	1.49±0.34	11.75±1.01	24.25±8.49	0.91±0.77	4.34±0.62	0.89±0.97	135.62 ±34.68
	LD2	26.02±9.86	71.76±27.85	75.55±19.54	15.44±2.38	57.51±14.83	11.59±1.73	0.79±0.44	10.11±0.8	32.62±8.21	0.68±0.37	3.06±0.92	0.43±0.57	125.21 ±20.35
	LD3	33.97±12.33	118.62±64.06	72.65±25.29	22.23±9.12	63.83±12.95	9.07±1.57	0.58±0.14	9.61±3.27	44.3±6.63	2.37±0.9	5.13±4.63	2.42±0.96	162.21 ±15.89
Thiruvananthapuram	LD4	31.49±12.26	95.72±30.93	38.01±19.38	16.38±5.37	36.11±22.9	6.78±1.88	0.51±0.12	6.32±1.83	40.22±8.54	1.85±0.59	5.88±2.78	1.59±0.35	114.79 ±41.16
	UL1	22.7±8.17	62.08±22.71	40.95±23.34	22.74±7.56	34.22±12.15	5.46±3.59	0.71±0.15	3.74±1.26	24.36±8.18	1.81±0.55	3.94±1.89	1±0.55	82.87 ±18.77
	BLD1	25.37±15.83	51.71±25.05	2.35±3.72	7.05±6.1	6.07±6.26	3.99±3.06	0.88±0.51	4.7±5.35	39.85±18.71	0±0	0±0	0±0	76.24 ±19.78
	BLD2	36.21±10.81	64.34±14.88	8.88±2.04	21.18±4.79	20.97±5.66	11.14±2.85	1.01±0.22	7.65±1.69	45.17±8.35	0±0	0±0	0±0	81.44±20 ±26.46
	BLD3	30.27±4.88	57.76±8.8	7.73±2.42	16.62±4.77	18.56±7.29	8.58±2.42	1.09±0.33	6.4±1.28	40.46±7.16	0±0	0±0	0±0	76.88 ±15.37
	LD1	22.31±4.25	47.5±6.62	5.38±1.48	8.1±0.97	10.8±1.21	5.29±1.32	0.62±0.18	5.76±0.9	41±6	0±0	0±0	0±0	62.29±6.89
	LD2	17.23±3.61	36.47±10.17	5.32±1.04	7.71±1.35	11.21±1.67	5.74±0.53	0.46±0.04	5.49±0.28	36.14±5.01	0±0	0±0	0±0	54.89±4.61
	LD3	17.51±4.18	41.18±7.45	17.57±9.95	10.14±1.67	24.78±10.36	17.22±9.65	0.51±0.06	5.72±0.36	32.84±7.76	0±0	0±0	0±0	59.86±5.36
	LD4	15.12±3.57	35.37±7.4	7.1±1.02	10.71±2.19	14.6±2.4	5.87±0.67	0.53±0.06	5.71±0.74	30.66±6.77	0±0	0±0	0±0	52.14±6.62
	UL1	19.98±7.11	40.69±11.25	8.17±2.51	10.88±2.92	15.01±4.51	6.62±1.01	0.5±0.11	6.31±1.32	21.16±5.51	0±0	0±0	0±0	45.26±8.13
Visakhapatnam	BLD1	47.38±31.11	115.2±55.38	13.96±11.3	37.73±16.9	31.37±15.71	10.18±7.02	0.86±0.22	12.96±8.01	33.01±28.58	4.14±1.98	9.11±5.44	2.52±2.09	123.44 ±63.43
	BLD2	46.26±23.84	100.58±46.99	7.23±8.45	33.89±13.49	23.71±12.74	12.05±1.99	1±0.23	8.35±2.8	33.31±19.69	4.15±1.52	10.23±5.02	2.31±1.58	103.86 ±43.42
	BLD3	30.61±14.39	79.62±31.68	5.17±5.2	31.38±10.97	20.55±8.64	12.38±2.35	0.85±0.19	9.19±2.91	17.77±8.25	3.66±1.34	11.01±4.08	2.41±1.36	84.39±25.4
	LD1	21.88±6.08	60.08±14.98	11.27±3.48	28.51±3.6	24.38±4.18	6.72±1.16	0.16±0.17	7.85±2.14	21.86±15.29	3.06±0.89	8.75±3.93	1.18±0.3	67.19 ±20.04
	LD2	13.72±5.16	53.28±15.63	8.22±6.21	24.98±6.5	19.65±8.38	7.81±0.92	0.11±0	6.65±1.35	18.01±9.01	2.53±0.7	6.48±1.76	1.39±0.6	54.71 ±15.98
	LD3	10.4±4.08	44.89±13.49	1.93±0.74	14.87±3.83	9.32±2.11	9.17±1.63	0.11±0	8.02±1.36	15.99±3.85	2.08±0.82	6.26±2.77	1.08±0.76	47.21 ±10.67
	LD4	25.15±14.92	93.25±41.53	3.44±2.93	29.97±13.55	18.04±8.85	10.74±3.02	0.3±0.27	8.85±2.7	26.19±6.95	2.54±1.02	6.04±4.12	1.12±0.65	81.64 ±34.98
Visakhapatnam	UL1	23.15±7.97	80.54±20.54	4.5±9.243	35.37±9.22	22.18±6.1	10.05±2.54	0.64±0.15	8.62±2.77	28.48±6.73	2.81±1.28	8.14±4.35	1.44±0.74	81.16 ±18.22

Table 7 Phase-averaged COVID-19 database with the corresponding AQI values for the selected Indian cities

City	Phase	No. of days	Average AQI	COVID-19 database					COVID-19 impacts		
				Positive confirmed cases	Deceased cases	Active cases	Recovered cases	Vaccination cases	Activity ratio	Recovery ratio	Case fatality ratio
Tier-I cities											
Chennai	LD1	21	61.6	0	0	0	0				
	LD2	19	63.8	1463	17	1196	250		81.75	17.09	1.16
	LD3	14	72.0	5298	37	4035	1226		76.16	23.14	0.70
	LD4	14	87.1	8038	78	1545	6415		19.22	79.81	0.97
	UL1	30	102.7	43528	753	15838	26937		36.39	61.88	1.73
	UL2	31	75.0	41467	1225	−9846	50088		−23.74	120.79	2.95
	UL3	31	68.0	35803	634	459	34710		1.28	96.95	1.77
	UL4	30	51.8	31779	463	−1904	33220		−5.99	104.53	1.46
	UL5	31	80.8	32540	441	−4129	36228		−12.69	111.33	1.36
	UL6	30	82.9	15444	199	−3442	18301		−22.29	118.50	1.29
Delhi	UL7	46	80.8	13551	212	−1803	15341		−13.31	113.21	1.56
	UL8	31	86.3	4571	63	−378	5073	28807	−8.27	110.98	1.38
	UL9	28	61.5	5649	54	455	5140	225197	8.05	90.99	0.96
	UL10	31	71.5	35603	174	19368	16061	774558	54.40	45.11	0.49
	LD1	21	93.9	1531	30	1470	31		96.02	2.02	1.96
	LD2	19	122.4	2988	34	1623	1331		54.32	44.54	1.14
	LD3	14	137.0	5206	84	2282	2840		43.83	54.55	1.61
	LD4	14	165.2	10089	325	5488	4276		54.40	42.38	3.22
	UL1	30	124.9	67516	2269	15377	49870		22.78	73.86	3.36
	UL2	31	68.6	48238	1221	−15565	62582		−32.27	129.74	2.53
Mumbai	UL3	31	98.0	39150	481	3921	34748		10.02	88.76	1.23
	UL4	30	135.4	104967	917	12282	91768		11.70	87.43	0.87
	UL5	31	323.7	106991	1150	5811	100030		5.43	93.49	1.07
	UL6	30	369.0	183668	2663	166	180839		0.09	98.46	1.45
	UL7	46	450.0	61809	1564	−30194	90042		−48.85	145.68	2.53
	UL8	31	322.2	4904	155	−1655	6801	206172	−33.75	138.68	3.16
	UL9	28	243.8	6977	51	1285	5641	740756	18.42	80.85	0.73
	UL10	31	215.5	140073	708	51988	87377	1508037	37.11	62.38	0.51
	LD1	21	79.0	0	0	0	0				
	LD2	19	67.0	8800	326	213	130		2.42	1.48	3.70
Bengaluru	LD3	14	70.9	11350	408	424	3368		3.74	29.67	3.59
	LD4	14	58.7	19536	545	−187	13293		−0.96	68.04	2.79
	UL1	30	53.3	37972	3277	2273	27379		5.99	72.10	8.63
	UL2	31	47.0	36626	1797	2441	42904		6.66	117.14	4.91
	UL3	31	37.7	31521	1305	−342	30194		−1.08	95.79	4.14
	UL4	30	58.7	59463	1271	4899	52000		8.24	87.45	2.14
	UL5	31	82.7	52229	1364	−8609	58422		−16.48	111.86	2.61
	UL6	30	123.4	25970	591	−49	28613		−0.19	110.18	2.28
	UL7	46	244.6	18188	345	−383	26130		−2.11	143.67	1.90
	UL8	31	191.0	12914	193	−48	15737	119576	−0.37	121.86	1.49
Kolkata	UL9	28	144.7	29393	117	7267	21757	314584	24.72	74.02	0.40
	UL10	31	130.9	209442	658	76854	135366	1434179	36.69	64.63	0.31
	LD1	21	69.2	0	0	0	0				
	LD2	19	68.1	149	6	70	72		46.98	48.32	4.03
	LD3	14	76.6	67	1	16	50		23.88	74.63	1.49
	LD4	14	69.9	143	3	31	109		21.68	76.22	2.10
	UL1	30	54.8	4196	85	3798	313		90.51	7.46	2.03
	UL2	31	35.0	50989	934	33703	16352		66.10	32.07	1.83
	UL3	31	24.1	73581	936	−502	73147		−0.68	99.41	1.27
	UL4	30	44.4	103538	971	10029	92538		9.69	89.38	0.94
Kolkata	UL5	31	74.8	103806	928	−16547	115564		−15.94	111.33	0.89
	UL6	30	86.4	33265	273	−13350	50203		−40.13	150.92	0.82
	UL7	46	101.6	24479	220	−11538	35797		−47.13	146.24	0.90
	UL8	31	89.3	7999	73	−1812	9688	108784	−22.65	121.12	0.91
	UL9	28	73.3	9777	94	2556	7177	251552	26.14	73.41	0.96
	UL10	31	92.5	100532	439	65373	34720	1009878	65.03	34.54	0.44
	LD1	21	93.7	0	0	0	0				
	LD2	19	53.4	635	0	453	95		71.34	14.96	0.00
	LD3	14	60.9	736	216	220	383		29.89	52.04	29.35
	LD4	14	45.6	754	626	341	424		45.23	56.23	83.02

Table 7 (continued)

City	Phase	No. of days	Average AQI	COVID-19 database					COVID-19 impacts		
				Positive confirmed cases	Deceased cases	Active cases	Recovered cases	Vaccination cases	Activity ratio	Recovery ratio	Case fatality ratio
Hyderabad	UL1	30	46.4	3859	599	838	2851		21.72	73.88	15.52
	UL2	31	42.0	15655	156	4521	10753		28.88	68.69	1.00
	UL3	31	41.0	18518	118	−1664	19652		−8.99	106.12	0.64
	UL4	30	40.0	16255	97	564	15271		3.47	93.95	0.60
	UL5	31	40.6	24876	90	1666	22714		6.70	91.31	0.36
	UL6	30	159.4	25445	158	−502	25545		−1.97	100.39	0.62
	UL7	46	272.5	19688	980	−5017	24273		−25.48	123.29	4.98
	UL8	31	258.7	2210	50	−340	2451	84837	−15.38	110.90	2.26
	UL9	28	174.7	1959	19	202	1787	205654	10.31	91.22	0.97
	UL10	31	141.4	16368	73	9053	7242	592260	55.31	44.24	0.45
Hyderabad	LD1	21	67.9	605	0	477	110		78.84	18.18	0.00
	LD2	19	62.3	438	29	−8	435		−1.83	99.32	6.62
	LD3	14	68.4	469	5	17	447		3.62	95.31	1.07
	LD4	14	93.7	1147	48	663	436		57.80	38.01	4.18
	UL1	30	47.1	13641	178	7597	5866		55.69	43.00	1.30
	UL2	31	54.0	46364	259	8011	38094		17.28	82.16	0.56
	UL3	31	45.0	62260	308	14503	47449		23.29	76.21	0.49
	UL4	30	37.7	66423	300	−1973	68096		−2.97	102.52	0.45
	UL5	31	98.4	45801	209	−10917	57954		−23.84	126.53	0.46
	UL6	30	145.3	31999	122	−8387	39449		−26.21	123.28	0.38
Tier-II cities Ahmedabad	UL7	46	187.2	21932	116	−5580	26766		−25.44	122.04	0.53
	UL8	31	122.4	5555	44	−2766	8277	293442	−49.79	149.00	0.79
	UL9	28	112.8	4645	36	307	4302	401369	6.61	92.62	0.78
	UL10	31	122.5	36727	134	25878	10715	1927705	70.46	29.17	0.36
	LD1	21	149.5	0	0	0	0				
	LD2	19	107.2	3817	0	3076	533		80.59	13.96	0.00
	LD3	14	130.7	4603	216	2160	2127		46.93	46.21	4.69
	LD4	14	127.1	3760	626	−816	4258		−21.70	113.24	16.65
	UL1	30	98.1	8733	599	−916	9050		−10.49	103.63	6.86
	UL2	31	84.0	5604	156	−52	5500		−0.93	98.14	2.78
Bhopal	UL3	31	82.0	5002	118	−19	4987		−0.38	99.70	2.36
	UL4	30	81.0	5329	97	755	4393		14.17	82.44	1.82
	UL5	31	135.0	5666	90	−910	6486		−16.06	114.47	1.59
	UL6	30	151.0	7563	158	−100	7505		−1.32	99.23	2.09
	UL7	46	193.0	9562	216	−626	9972		−6.55	104.29	2.26
	UL8	31	167.9	2197	29	−2008	4176	109936	−91.40	190.08	1.32
	UL9	28	160.3	3009	18	365	2626	188026	12.13	87.27	0.60
	UL10	31	170.2	27467	219	12243	15005	923822	44.57	54.63	0.80
	LD1	21	88.8	0	0	0	0				
	LD2	19	115.8	532	15	280	237		52.63	44.55	2.82
Bhopal	LD3	14	108.4	460	23	110	327		23.91	71.09	5.00
	LD4	14	102.4	475	19	57	399		12.00	84.00	4.00
	UL1	30	71.6	1322	40	51	1231		3.86	93.12	3.03
	UL2	31	57.3	3524	79	1676	1769		47.56	50.20	2.24
	UL3	31	38.9	4183	109	−604	4678		−14.44	111.83	2.61
	UL4	30	122.0	6912	107	533	6272		7.71	90.74	1.55
	UL5	31	163.0	7218	88	−579	7709		−8.02	106.80	1.22
	UL6	30	204.0	7348	38	1370	5940		18.64	80.84	0.52
	UL7	46	282.0	9419	77	−888	10230		−9.43	108.61	0.82
	UL8	31	148.7	1903	22	−1450	3331	43954	−76.20	175.04	1.16
Chandigarh	UL9	28	130.5	2239	5	422	1812	71378	18.85	80.93	0.22
	UL10	31	156.3	18006	44	6336	11626	339929	35.19	64.57	0.24
	LD1	21	37.8	14	0	7	7		50.00	50.00	0.00
	LD2	19	51.7	76	1	63	12		82.89	15.79	1.32
	LD3	14	65.8	94	3	60	32		63.83	34.04	3.19
	LD4	14	84.8	102	0	−47	148		−46.08	145.10	0.00
	UL1	30	66.5	147	2	−20	165		−13.61	112.24	1.36
	UL2	31	34.0	611	9	299	303		48.94	49.59	1.47
	UL3	31	65.5	3295	41	1488	1764		45.16	53.54	1.24
	UL4	30	97.0	7592	106	106	7382		1.40	97.23	1.40

Table 7 (continued)

City	Phase	No. of days	Average AQI	COVID-19 database					COVID-19 impacts		
				Positive confirmed cases	Deceased cases	Active cases	Recovered cases	Vaccination cases	Activity ratio	Recovery ratio	Case fatality ratio
Guwahati	UL5	31	121.4	2480	64	−1322	3738		−53.31	150.73	2.58
	UL6	30	142.5	2991	51	421	2519		14.08	84.22	1.71
	UL7	46	239.0	3055	53	−796	3798		−26.06	124.32	1.73
	UL8	31	128.0	800	16	−137	945	9356	−17.13	118.13	2.00
	UL9	28	109.9	1980	12	1037	907	44422	52.37	45.81	0.61
	UL10	31	113.6	9153	49	2205	6899	80785	24.09	75.37	0.54
	LD1	21	206.3	33	0	32	0		96.97	0.00	0.00
	LD2	19	62.9	10	1	−23	33		−230.00	330.00	10.00
	LD3	14	54.5	58	1	48	9		82.76	15.52	1.72
	LD4	14	51.9	1239	2	1090	144		87.97	11.62	0.16
Jaipur	UL1	30	42.1	7068	8	1598	5462		22.61	77.28	0.11
	UL2	31	37.0	31862	86	7066	24710		22.18	77.55	0.27
	UL3	31	31.0	68771	208	13462	55101		19.58	80.12	0.30
	UL4	30	54.0	71770	391	11223	60156		15.64	83.82	0.54
	UL5	31	94.0	25540	233	−25129	50436		−98.39	197.48	0.91
	UL6	30	126.0	6425	51	−5968	12342		−92.89	192.09	0.79
	UL7	46	276.0	4001	85	−1783	4352		−44.56	108.77	2.12
	UL8	31	255.7	527	23	−1349	1870	132475	−255.98	354.84	4.36
	UL9	28	199.2	513	10	−2	491	412430	−0.39	95.71	1.95
	UL10	31	210.6	4550	24	3348	1178	1010556	73.58	25.89	0.53
Lucknow	LD1	21	75.9	0	0	0	0				
	LD2	19	93.7	993	40	553	400		55.69	40.28	4.03
	LD3	14	102.0	583	26	41	516		7.03	88.51	4.46
	LD4	14	125.5	415	25	−309	699		−74.46	168.43	6.02
	UL1	30	93.3	1327	69	290	968		21.85	72.95	5.20
	UL2	31	87.0	2100	28	652	1420		31.05	67.62	1.33
	UL3	31	93.0	5373	87	2566	2649		47.76	49.30	1.62
	UL4	30	100.0	10697	46	3976	6746		37.17	63.06	0.43
	UL5	31	142.3	11880	52	−3674	15502		−30.93	130.49	0.44
	UL6	30	144.3	14403	62	5230	9111		36.31	63.26	0.43
Patna	UL7	46	140.5	10618	74	−8152	18668		−76.78	175.81	0.70
	UL8	31	141.6	831	8	−893	1744	64211	−107.46	209.87	0.96
	UL9	28	117.8	827	2	230	595	179315	27.81	71.95	0.24
	UL10	31	136.1	11044	28	8694	2322	654105	78.72	21.02	0.25
	LD1	21	101.2	0	0	0	0				
	LD2	19	105.3	226	1	156	69		69.03	30.53	0.44
	LD3	14	105.9	69	0	−93	162		−134.78	234.78	0.00
	LD4	14	142.6	91	2	20	69		21.98	75.82	2.20
	UL1	30	95.8	752	16	347	388		46.14	51.60	2.13
	UL2	31	87.0	7040	76	3851	3114		54.70	44.23	1.08
Patna	UL3	31	112.0	19250	266	2893	16091		15.03	83.59	1.38
	UL4	30	160.5	25341	342	−387	25386		−1.53	100.18	1.35
	UL5	31	248.8	10493	175	−3637	13955		−34.66	132.99	1.67
	UL6	30	351.9	8507	117	498	7892		5.85	92.77	1.38
	UL7	46	381.9	8707	156	−1515	10066		−17.40	115.61	1.79
	UL8	31	291.2	1221	36	−1755	2940	0	−143.73	240.79	2.95
	UL9	28	207.5	470	2	−116	584	134971	−24.68	124.26	0.43
	UL10	31	198.1	45128	221	35603	9304	321292	78.89	20.62	0.49
	LD1	21	135.6	0	0	0	0				
	LD2	19	125.2	44	0	31	13		70.45	29.55	0.00
Patna	LD3	14	162.2	120	2	89	29		74.17	24.17	1.67
	LD4	14	114.8	87	0	27	60		31.03	68.97	0.00
	UL1	30	82.9	484	5	255	224		52.69	46.28	1.03
	UL2	31	63.0	8029	34	3024	4971		37.66	61.91	0.42
	UL3	31	68.0	12281	121	−1276	13436		−10.39	109.40	0.99
	UL4	30	88.8	6839	50	−206	6995		−3.01	102.28	0.73
	UL5	31	180.0	11045	56	309	7680		2.80	69.53	0.51
	UL6	30	239.0	3242	58	−323	6507		−9.96	200.71	1.79
	UL7	46	297.4	9114	75	−243	9282		−2.67	101.84	0.82
	UL8	31	254.0	1325	33	−1421	2713	50479	−107.25	204.75	2.49
Patna	UL9	28	209.4	429	12	−87	504	114978	−20.28	117.48	2.80

Table 7 (continued)

City	Phase	No. of days	Average AQI	COVID-19 database					COVID-19 impacts		
				Positive confirmed cases	Deceased cases	Active cases	Recovered cases	Vaccination cases	Activity ratio	Recovery ratio	Case fatality ratio
Thiruvananthapuram	UL10	31	229.0	13874	40	10139	3695	308152	73.08	26.63	0.29
	LD1	21	62.3	0	0	0	0				
	LD2	19	54.9	17	1	2	14		11.76	82.35	5.88
	LD3	14	59.9	0	0	−2	2				
	LD4	14	52.1	44	1	41	2		93.18	4.55	2.27
	UL1	30	45.3	150	3	42	105		28.00	70.00	2.00
	UL2	31	30.0	4281	7	2965	1305		69.26	30.48	0.16
	UL3	31	42.0	11055	79	2177	8778		19.69	79.40	0.71
	UL4	30	49.0	18933	135	5683	13105		30.02	69.22	0.71
	UL5	31	70.5	24240	178	−2275	26326		−9.39	108.61	0.73
Visakhapatnam	UL6	30	85.5	13297	141	−4629	17509		−34.81	131.68	1.06
	UL7	46	58.5	14648	148	−741	15486		−5.06	105.72	1.01
	UL8	31	78.0	12144	100	633	11402	45484	5.21	93.89	0.82
	UL9	28	60.3	6008	62	−2338	8279	137285	−38.91	137.80	1.03
	UL10	31	59.6	8953	49	3287	5104	494791	36.71	57.01	0.55
	LD1	21	67.2	0	0	0	0				
	LD2	19	54.7	29	0	9	20		31.03	68.97	0.00
	LD3	14	47.2	46	1	32	13		69.57	28.26	2.17
	LD4	14	81.6	26	0	−11	37		−42.31	142.31	0.00
	UL1	30	81.2	441	2	255	184		57.82	41.72	0.45
	UL2	31	50.0	9240	102	7789	2332		84.30	25.24	1.10
	UL3	31	49.0	26912	184	−747	26492		−2.78	98.44	0.68
	UL4	30	64.0	13334	143	−3571	16762		−26.78	125.71	1.07
	UL5	31	153.0	5785	77	−1833	7541		−31.69	130.35	1.33
	UL6	30	167.0	2350	32	−1135	3453		−48.30	146.94	1.36
	UL7	46	278.0	1334	16	−617	1935		−46.25	145.05	1.20
	UL8	31	172.4	429	7	−143	565	31066	−33.33	131.70	1.63
	UL9	28	115.2	370	4	71	256	80829	19.19	69.19	1.08
	UL10	31	129.0	6129	24	3534	2809	316674	57.66	45.83	0.39

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Data Availability Not applicable

Declarations

Ethics approval and consent to participate Not applicable

Consent for publication Not applicable

Competing interests The authors declare no competing interests.

Abbreviations ANOVA, Analysis of variance; AOD, Aerosol optical depth; AQI, Air quality index; ARMA, Autoregressive moving average; BLD 1, Pre-lockdown phase 1; BLD 2, Pre-lockdown phase 2; BLD 3, Pre-lockdown phase 3; CO, Carbon monoxide; CPCB, Central Pollution Control Board; EF, Exceedance factor; KDE, Kernel density estimation; LD 1, Lockdown period phase 1; LD 2, Lockdown period phase 2; LD 3, Lockdown period phase 3; LD 4, Lockdown period phase 4; NAAQS, National ambient air quality standards; NAQI, National air quality index; NCT, National capital territory; Ni, Nickel; NH₃, Ammonia; NO₂, Nitrogen dioxide; O₃, Ozone; Pb, Lead; PM_{2.5}, Particulate matter 2.5 µm; PM₁₀, Particulate matter 10 µm; SO₂, Sulphur dioxide; SOP, Standard operating protocols; WHO, World Health Organization; WTC, Wavelet transform coherence

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