



Assessment of Air Quality Before and During COVID-19-Induced Lockdown in Jaipur, India

R. Dangayach¹, M. Pandey² , D. Gusain³ , A. L. Srivastav⁴ , R. Jain¹ , B. M. Bairwa¹ and A. K. Pandey^{1*}

¹School of Earth Sciences, Banasthali Vidyapith, P.O. Banasthali, Tonk, Rajasthan 304022, India

²Department of Environmental Studies, P.G.D.A.V. College (Evening), University of Delhi, Ring Road, Nehru Nagar, New Delhi, Delhi 110065, India

³Department of Environmental Studies, Ramanujan College, University of Delhi, New Delhi, India

⁴Chitkara University School of Engineering and Technology, Chitkara University, Solan, Himachal Pradesh 174103, India

Received: 24 May 2022 / Accepted: 21 December 2022 / Published online: 13 January 2023

© Metrology Society of India 2023

Abstract: Air pollution is increasing at a frightening pace due to emissions from industrial plants and manufacturing activities and other anthropogenic activities affecting living beings, property, and environment. This study aims to monitor the impact of COVID-19-induced lockdown and unlock down phases on the air quality of Jaipur city, Rajasthan, India by assessing the change in ambient air quality during pre-COVID-19 (January 2018–December 2019) and COVID-19 (January 2020–December 2021) phases by evaluating air quality parameters (PM₁₀, PM_{2.5}, NO₂, O₃, Benzene and o-Xylene) using ground station data. Outcome of the study revealed that the ambient air quality improved significantly during lockdown phases (March–May 2020) as the percentage change in concentration of studied parameters declined by more than 100% at different sites. However, the concentrations tend to escalate with the introduction of unlock down phases (June–December 2020) and the onset of winter season (October–December 2020) aggravated the conditions. The AQI touched moderate and poor category many times during study period. Student's *t*-test was conducted on the dataset. Results revealed significant difference in the concentration of air pollutants between pre-covid and covid period.

Keywords: Air pollution; Particulate matter; Nitrogen dioxide; Student's *t*-test; COVID-19 lockdown

1. Introduction

The first case of novel Corona Virus Disease (COVID-19) came in December 2019 and the World Health Organization (WHO) declared the disease as a global pandemic on March 11, 2020. Due to the outbreak of COVID-19 pandemic, the world was put on hold in terms of temporary closure of industries and transportation activities and various nations of the world announced complete lockdown resulting in the improvement of air quality, especially in urban areas. The impact of lockdown was clearly observed in various regions and megacities like Beijing, Shanghai, Zaragoza, New York and Los Angeles [1].

The sudden outbreak of COVID-19, the global pandemic, significantly affected the ambient air quality of the world. Emergency shutdown, lockdown or similar arrangements were made by the respective governments of various countries to stop the propagation of the infection by minimizing the anthropogenic activities which in turn caused unprecedented decline in the emission rates. Literature review revealed that studies on the relationship between COVID-19-induced lockdown phases and concentration of air pollutants are going on at a global level [2–5]. Recently published reports and data indicated significant improvement in the ambient air quality of the global mega cities and countries like New York City, USA [6], Ontario, Canada [7], Korea [8], Japan [9], Spain [10], Gujarat India [11] etc.

India is one of the fastest growing economies of the globe. At the same time, deteriorating ambient air quality

*Corresponding author, E-mail: ashutosh.cest@gmail.com

of urban ecosystem, megacities in particular, has emerged as an environmental threat for the Indian population. The possible hazardous impact of gaseous and particulate matter has been well established by the scientific community [12, 13]. As COVID-19-induced lockdown imposed significant positive impact on the air quality in most part of the globe, similar observations were reported and published from various parts of the Indian states and cities. Government of India instantly took decisions to control the spread of the disease and imposed four phases of lockdowns and nearly all anthropogenic activities ceased. In Karnataka, the air quality has turned from hazardous to better within 24 h of imposing lockdown [14], while reduction in the concentrations of PM_{2.5}, PM₁₀, CO and NO₂ around 43, 31 and 18% when they were compared to the previous year was reported by [15]. Study conducted in Delhi revealed that an improvement in air quality by 40–50% was identified just after four days of lockdown commencement [16]. Results depicted that significant reduction in the concentrations of PM_{2.5} and PM₁₀ (up to 50%), carbon monoxide (30.35%) and nitrogen dioxide (– 52.68%) occurred. In another study, it was proved that the ambient air quality of Delhi improved significantly during the first phase of lockdown in India [17]. Similar results were found in Lucknow [18], Kolkata [19], Bangalore, Chennai, Mumbai, Delhi and Kolkata [20] etc. Similar findings were reported by Baldasano [21], Berman et al. [22], Broomandi et al. [23], He et al. [24], Kotnala et al. [25], Kumar [26], Lian et al. [27], Lokhandwala and Gautam [28], Menut et al. [3], Ming et al. [29], Mitra et al. [19], Mor et al. [30], Navinya et al. [31], Pei et al. [32], Sarfraz et al. [33], Zambrano-Monserrate et al. [34], Liu et al. [35], and Sathey et al. [36].

1.1. Phases of Lockdown

We divided all phases into two distinct phases like; pre-COVID-19 (January 2018–December 2019) and COVID-19 period (January 2020–December 2021). COVID-19 period has also been categorized into three phases; Pre-lockdown phase (January 1, 2020–March 23, 2020; 83 days), Lockdown phase (March 24, 2020–May 31, 2020; 67 days) and unlock period (June 1, 2020–December 31, 2021; 536 days) apart from April and May, 2021 due to the occurrence of second wave in April 2021 which led to strict lockdown from April 19, 2021 to May 24, 2021; 43 days.

First ever COVID-19 positive case in India came on January 30, 2020 while the disease claimed the first ever life on March 12, 2020. The Government of India announced nationwide complete lockdown on 24th March 2020. Since then, four phases of lockdown and six phases of unlock down phases have taken place. The duration of

each phase of lockdown and unlock down is described in Table 1.

Comprehensive literature review revealed that systematic and scientific work about the impact of lockdown on ambient air quality has not been done for Jaipur, the capital city of Rajasthan (India). Present study has been conducted with dual objectives; to observe the impact of lockdown on air quality parameters and understand the temporal variations of ambient air quality parameters for the last 4 years.

2. Materials and Methods

2.1. Study Area

Our analysis was focused on the Jaipur city, which is in the Jaipur district in east central part of Rajasthan (Fig. 1). It is known as pink city for its trademark building colour. Jaipur district has a total geographical area of 11,143 km² and is located at 27.1425146 N and 75.0397275 E. Jaipur district covers about 3.23% the total area of Rajasthan with very high population density. This famous district is the capital of Rajasthan which is the largest state of India. This district is decorated with attractive havelis, forts and beautiful palaces. It has a semi-arid climate with distinct seasons, i.e., winter, monsoon, and summer. Surrounded by the Aravalli hills in the east, the relative humidity ranges between 35 and 63% [39]. The mean annual rainfall is around 60 mm. Maximum rainfall is 198.8 mm which occurred in the month of August in 2006. The mean maximum & minimum temperature of the area are 45 °C and 5 °C, respectively [40]. The temperature fluctuates as high as 47 °C in the month of May & June and as low as 1.0 °C in the month of January. Due to rapid urbanization and industrialization, the land use of Jaipur city has significantly changed as the agriculture lands and wastelands have been transformed to industry zone and built-up areas.

This famous city's culture is greatly popular in foreign. Even UNESCO counted it district two forts in the world heritage. It is known as the popular destination for visitors. Jaipur city may be broadly categorized as residential (54.4% approx.), commercial (11.8% approx.) and transportation system (10% approx.). Although, motorized transportation infrastructure of the city can be classified into roadways and metro trains but the city of Jaipur has witnessed unprecedented rise in number of registered motor vehicle in the recent past (Fig. S1a, b [41–43]).

2.2. Data Sampling and Methodology

The ambient air quality of the Jaipur city has been degrading due to various anthropogenic activities, vehicular emissions and surrounding industrial activities.

Table 1 Phases of lockdown

Lockdown/ unlock period	Period	Restrictions/permissions
14 h people's curfew	March 22, 2020; 7:00 am to 9:00 pm	14 h curfew: no vehicular movement (except emergency cases) and industrial activities (with a few exceptions like thermal power plants etc.) were allowed
Lockdown 1.0	March 24, 2020–April 14, 2020 (21 days)	Complete Shutdown except emergency services
Lockdown 2.0	April 15, 2020–May 3, 2020 (18 days)	Complete Shutdown except emergency services
Lockdown 3.0	May 4, 2020–May 17, 2020 (14 days)	Urban areas were designated in different zones: Red Zone: Complete lockdown Orange Zone: no public transport Green Zone: Public transport buses with 50% capacity
Lockdown 4.0	May 18, 2020–May 31, 2020 (14 days)	Red Zones were divided into Containment zone and buffer zone
Unlock 1.0	June 1–June 30, 2020	Lockdown restrictions in red zone Phase-wise relaxations in activities in other zones. Public places like shopping malls, religious places, hotels, and restaurants to reopen from 8 June
Unlock 2.0	July 1–July 31, 2020	Restrictions are withdrawn in a phased manner
Unlock 3.0	August 1–August 31, 2020	Restrictions are withdrawn in a phased manner
Unlock 4.0	September 1–September 30, 2020	Restrictions are withdrawn in a phased manner
Unlock 5.0	October 1–October 31, 2020	Restrictions are withdrawn in a phased manner
Unlock 6.0	November 1–November 30, 2020	Restrictions are withdrawn in a phased manner
Unlock 7.0	December 1–December 31, 2020	Official, Commercial, and industrial activities continue with few restrictions
Unlock 8.0	January 1–January 31, 2021	Official, Commercial, and industrial activities continue with few restrictions
Unlock 9.0	February 1–February 28, 2021	Official, Commercial, and industrial activities continue with few restrictions
Unlock 10.0	March 1–April 18, 2021	Night curfews implemented
Lockdown 5.0 [#]	April 19–May 3, 2021	Official, Commercial, and industrial activities shut due to rise in cases (Lockdown). Night curfews implemented. Also called Public Display Fortnight [#]
Lockdown 6.0*	May 10–May 24, 2021	Complete Lockdown
Unlock 11.0	May 25–June 30, 2021	Restrictions are withdrawn in a phased manner
Unlock 12.0	July 1–July 31, 2021	Restrictions are withdrawn in a phased manner
Unlock 13.0	August 1–August 31, 2021	Restrictions are withdrawn in a phased manner
Unlock 14.0	September 1–September 30, 2021	Restrictions are withdrawn in a phased manner
Unlock 15.0	October 1–October 31, 2021	Religious programmes, shops, malls, and offices allowed to open till 10 pm
Unlock 16.0	November 1–November 30, 2021	Restrictions are withdrawn in a phased manner
Unlock 17.0	December 1–December 31, 2021	Restrictions are withdrawn in a phased manner

“Red zone”, indicating the presence of infection hotspots, “orange zone” indicating some infection, and “green zone” with no infections

*The Indian Express [37]

[#]The Economic Times [38]

Rajasthan State Pollution Control Board (RSPCB) has established three continuous and automatic real time ambient air quality monitoring stations at Adarsh Nagar (26.902909 N and 75.836858 E, Residential and Commercial), Shastri Nagar (26.9502929 N and 75.730943 E, Residential and Commercial) and Police Commissionerate

(26.9164092 N and 75.7994901 E, Commercial). Secondary data were fetched for the above said three sites from the Central Pollution Control Board (CPCB) web portal. The datasets analyzed during the current study are available in the Central Pollution Control Board (CPCB) repository, <https://app.cpcbcr.com/ccr/#/caaqm-dashboard-all/caaqm->

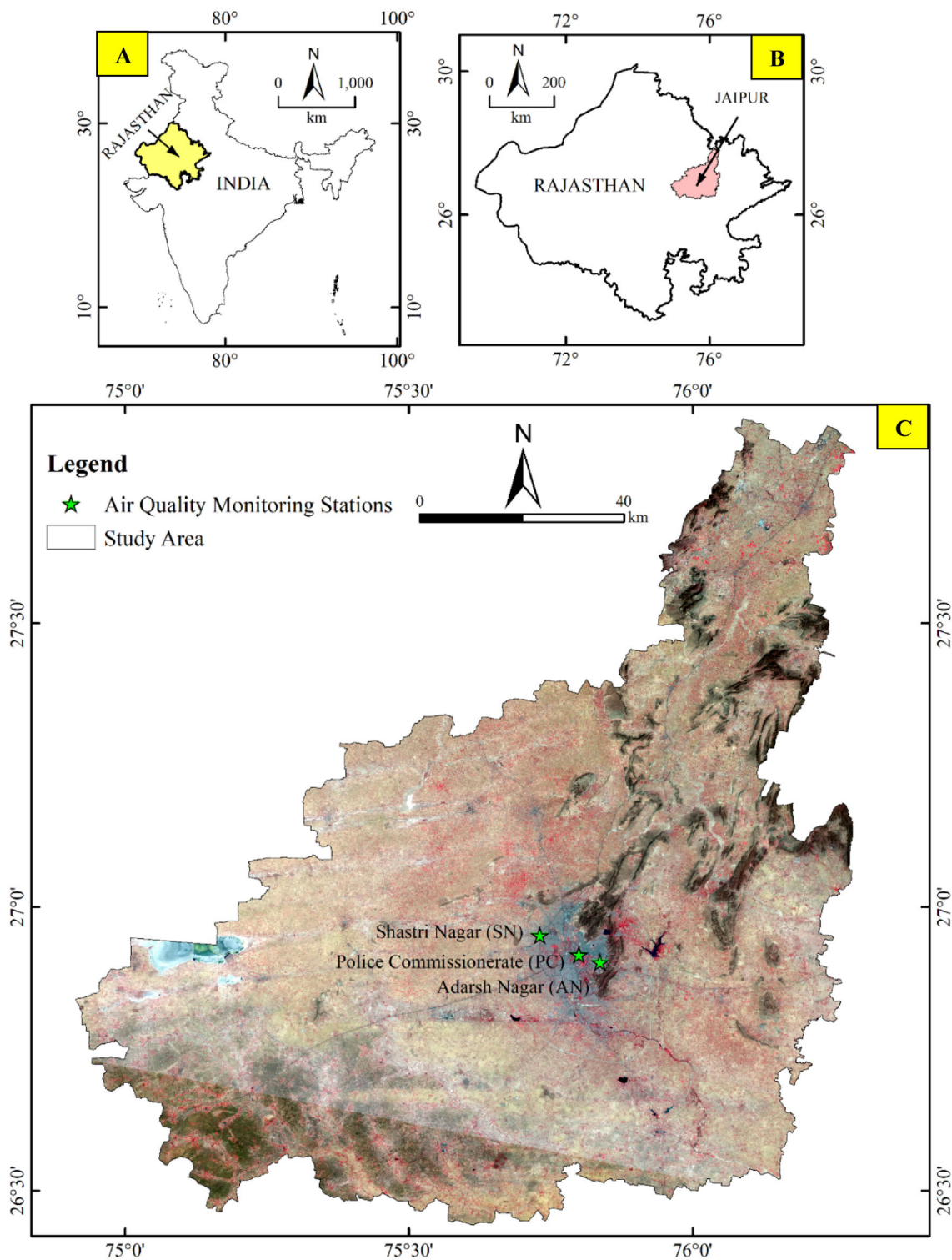


Fig. 1 Location map of study area and Ground data sampling sites. **A** and **B** are representing the locality of the study area in India and Rajasthan, respectively. **C** Study area for the present research (11,143

km²). Landsat—8 OLI datasets (two tiles) are used for visualization (R: 5; G: 4; B: 3) of the region

[landing/data](#). The concentrations of criteria pollutants (PM_{2.5}, PM₁₀, NO₂, Benzene, o-Xylene and O₃), wind speed (m/s) and wind direction (degree) in the present

study were collected at an interval of 24-h from the web portal for the period of 4 years (January 1, 2018–December 31, 2021). However, at a few places, data were missing

which may be due to maintenance shutdown of the monitoring stations or ill-working of probes. Coarser and finer particulate matter (PM₁₀ and PM_{2.5}) are considered as important pollutants originated from natural and anthropogenic sources. Nitrogen dioxide (NO₂) is a prominent and common gaseous pollutant which is mainly emitted from vehicular sources and is an important ingredient to form secondary pollutants like PAN and ozone. Benzene (C₆H₆) and o-Xylene [C₆H₄(CH₃)₂] are important volatile organic compounds which originate mainly from the anthropogenic sources like paint, dye, varnish, petroleum industries, vehicular emissions etc. and are considered as serious carcinogens. Particulate matter concentrations were monitored using beta ray attenuation method (BAM) while NO₂ and O₃ concentration was measured using chemiluminescence. The concentration of benzene and o-Xylene were monitored by automatic analyzer.

Beta attenuation method (BAM) is commonly used to monitoring the concentration of particulate matter in the air sample. Beta radiation passes through the particulate matter collected on a medium and attenuated radiation is proportional to the concentration of particulate matter. Concentration of oxides of nitrogen was measured using chemiluminescence which can be defined as emission of light as the result of chemical reaction. Nitric oxide reacts with ozone resulting into emission of lights which is proportional to the concentration of oxides of nitrogen. Automatic analyzer based on the principal of UV photometry was used to monitor the concentration of ozone in the present study. Concentrations of benzene and o-Xylene were measured by gas chromatographic separation and photoionization detector (PID). A brief information is mentioned in Table 2.

3. Results and Discussion

3.1. Temporal Variations of Ambient Air Quality

The temporal variation of the pollutants during pre-COVID period is clearly evident in the present study. Highest concentrations of particulate matter (PM₁₀ and PM_{2.5}) were observed in summer season followed by winter season and least concentrations were recorded in rainy season (Fig. 2b). Since the study area lies in semi-arid zone, circulation of air masses causes transportation of particulate matter in summer season (March–June) while the coarser and finer particulate matter remain in suspension in winter season (October–February) as the colder air mass hinders vertical mixing. However, in rainy season (July–September), air quality improves significantly as the pollutants get washed down. The annual mean concentration of particulate matter at all the sites during pre-COVID period was

found above the permissible standards given by the Indian standards (Table S1). Similarly, significantly higher concentrations of volatile pollutants (benzene and o-Xylene) were recorded in winter season at Adarsh Nagar (Fig. 2a). Data of the concentration of benzene and o-Xylene were not available for the month of March and April at Police Commissionerate. Similarly, o-Xylene concentration data could not be fetched for 2 months (August and September) at Shastri Nagar (Fig. 2a). Concentrations of ozone at all the sites were found well below the recommended guidelines of the nation (Table S1). At Adarsh Nagar, the concentrations of coarser and fine particulate matter were found higher in 2018 (PM₁₀ 148.33 ± 33.77 µgm⁻³; PM_{2.5} 50.31 ± 12.05 µgm⁻³) as compared to 2019 (PM₁₀ 100.91 ± 30.4 µgm⁻³; PM_{2.5} 36.6 ± 8.66 µgm⁻³). However, there were no significant differences in the concentrations of gaseous pollutants. Volatile organic compounds (VOCs) are considered as the serious pollutants with carcinogenic potential. The annual mean concentration of o-Xylene was higher in 2018 (0.93 ± 0.63 µgm⁻³) compared to 2019 (0.48 ± 0.35 µgm⁻³). The significant concentration of VOCs might have emerged from various anthropogenic sources like vehicular emissions, paint and dyeing industries etc. Ozone at lower tropospheric level might have originated directly from the anthropogenic sources (vehicular and industrial emission) or have formed by the photochemical reactions between nitrogen dioxide and VOCs. Significant concentrations of ozone were found at Adarsh Nagar (48.37 ± 15.43 µgm⁻³ and 51.5 ± 14.27 µgm⁻³), Police Commissionerate (43.26 ± 21.40 µgm⁻³ and 38.07 ± 8.61 µgm⁻³) and Shastri Nagar (52.14 ± 18.86 µgm⁻³ and 44.13 ± 12.44 µgm⁻³) in pre-COVID phase, 2018 and 2019, respectively.

Percentage change in the gaseous and particulate matter pollutants concentrations was calculated using the equation given below:

Percentage change in concentration = $\{(C_{2020} - C_Y) / C_Y\} \times 100$ where C_{2020} is mean concentration of pollutants in 2020 and C_Y is mean concentration of pollutants in previous years. A few readings of percentage change were exceptionally high or could not be calculated. This was due to intermittent absence of data during the sampling period and hence, these values should be neglected. Results revealed that at Adarsh Nagar, significant decline was observed for particulate matter and gaseous pollutants in 2019 as compared with 2018 (Table S4a). Concentration of coarser particulate matter (PM₁₀) decreased by almost 50% in the months of August and September while the maximum decline in finer particulate matter (PM_{2.5}) was observed in the month of June (− 48%), July (− 42%) and August (− 38%) (Table S4a). Similar trends were found at Police Commissionerate. However, at Shastri Nagar, concentration of PM_{2.5} was

Table 2 Sampling stations

Station name	Coordinates (DDS)	Region	PM ₁₀ (μgm^{-3})*	PM _{2.5} (μgm^{-3})*	NO ₂ (μgm^{-3})#	O ₃ (μgm^{-3})†	C ₆ H ₆ (μgm^{-3})‡	C ₆ H ₄ (CH ₃) ₂ (μgm^{-3})‡
Adarsh Nagar (AN)	26.902909 N	Residential and Commercial	[×] R: 16.34–486.77	R: 6.13–279.15 M: 45.15 SD: 25.14	R: 2.91–123.3 M: 34.01 SD: 17.17	R: 7.64–151.53 M: 49.51 SD: 19.0	R: 0.12–17.32 M: 2.15 SD: 2.54	R: 0.0–12.36 M: 1.07 SD: 1.45
	75.836858 E		[×] SD: 58.03					
Police Commissionerate (PC)	26.9164092 N	Commercial	R: 20.45–516.72 M: 131.7 SD: 56.67	R: 7.54–340.48 M: 63.43 SD: 31.03	R: 3.25–254.3 M: 44.52 SD: 26.22	R: 0.22–187.45 M: 40.19 SD: 19.47	R: 0–14.97 M: 1.45 SD: 1.26	R: 0.01–20.57 M: 1.16 SD: 1.07
	75.7994901 E							
Shastri Nagar (SN)	26.9502929 N	Residential and Commercial	R: 23.95–507.27 M: 116.62 SD: 56.52	R: 3.98–738.84 M: 51.81 SD: 33.77	R: 3.32–108 M: 24.33 SD: 14.99	R: 2.81–127.58 M: 49.89 SD: 19.83	R: 0–18.65 M: 2.14 SD: 2.46	R: 0.0–18.21 M: 1.43 SD: 2.15
	75.730943 E							

*Principle: β -ray attenuation, Resolution: 1% of the measurement range, Lower Detectable Limit: $< 4.8 \mu\text{g}/\text{m}^3$ (1 h)

Principle: Chemiluminescence, Lower Detectable Limit: 1 ppb

†Principle: UV Photometric/Chemiluminescence, Lower Detectable Limit: 1 ppb

‡Principle: Gas Chromatographic separation and Photo Ionization Detector (PID),

Resolution: 1% of the measurement range, Lower Detectable Limit: 0.2 ppb ($0.65 \mu\text{g}/\text{m}^3$) for 15 cycle for Benzene

[×] R Range, M Mean, SD Standard deviation; Period- January 2018–December 2021

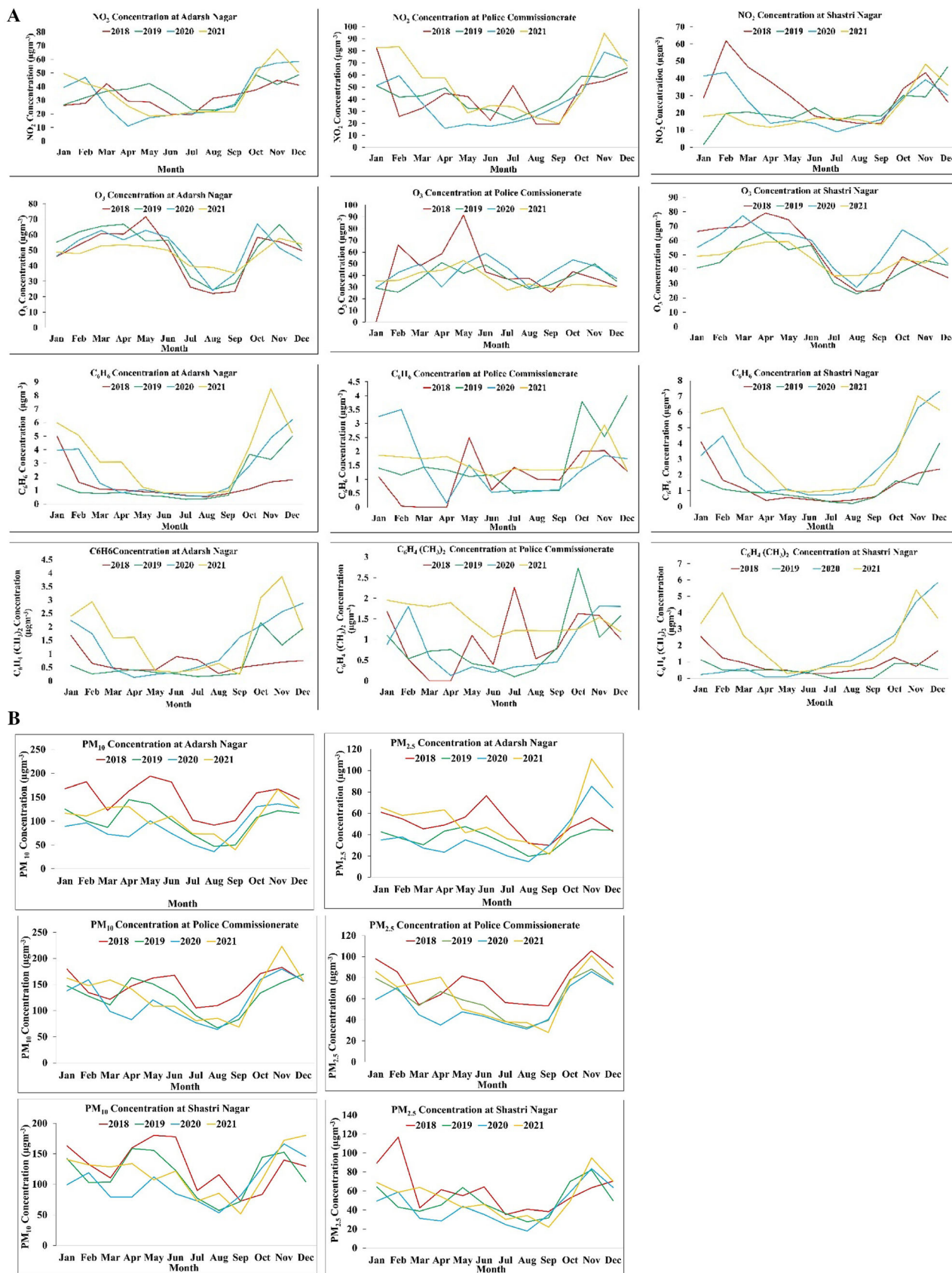


Fig. 2 a Monthly Mean Concentration of Gaseous Pollutants at all sites. b Monthly Mean Concentration of Particulate Pollutants at all sites

decreased by 63% in February while the concentration of PM₁₀ tremendously increased by 73% in the month of October. Similarly, gaseous pollutants (NO₂ and O₃) showed incremental and decline trends for all the sites. As compared to 2018, the concentration of NO₂ significantly and consistently increased in the months of April (30%), May (47%) and June (67%) while the maximum rise in the O₃ concentration was observed in the months July (24%) and September (23%) in the year 2019 at Adarsh Nagar. At Police Commissionerate, the concentration of NO₂ rose by 107% (September), 64% (February) and 58% (August) during 2019.

In the present study, the volatile organic compounds (Benzene and o-Xylene) also showed incremental and declining trend at all the sites during 2018–2019 (Table S4a). Comparing the data of 2018–2019 for VOCs at Adarsh Nagar, the concentration of Benzene consistently declined except in the month of October, November and December where it increased by 233%, 102% and 181%, respectively. Exactly similar trends were observed for o-Xylene. Benzene and o-Xylene showed declining trend at Police Commissionerate except in the month of December when the concentration of benzene increased up to 210% compared to 2018. At Shastri Nagar, the concentration of Benzene showed a declining trend except in April where it rose by 138%. However, o-Xylene concentration consistently decreased in the year 2019 and more than 50% decline was noticed in the months of January–March, July–September and December.

3.2. Impact of COVID-19-Induced Lockdown on Air Quality Parameter (January 2020–December 2021)

With the outbreak of COVID-19 pandemic, anthropogenic activities (vehicular, transportation, commercial and industrial) almost ceased during the lockdown phases (March 24–May 31, 2020) in India and this eventually resulted in unprecedented decline in the pollutants emission. Results depicted that the mean concentration of studied pollutants in 2020 was significantly lower than the previous year data. However, this was clearly evident that the concentration of pollutants rose quickly with the onset of unlock down phases and winter season (Fig. 2). The range of concentration of studied pollutants at the three sites during lockdown phases (March–May) were: PM₁₀ (67.23–120.41 µgm⁻³), PM_{2.5} (27.36–47.51 µgm⁻³), NO₂ (11.15–36.66 µgm⁻³), O₃ (30.22–77.13 µgm⁻³), benzene (0.92–1.94 µgm⁻³) and o-Xylene (0.07–0.6 µgm⁻³). Other than some sporadic events, the air quality index at the three sites during the COVID-19 phase occurred in good and satisfactory category (Table S2 and S3).

The concentration of particulate matter and nitrogen dioxide significantly decreased during COVID period at all

the sites as compared with the concentrations in 2018 and 2019. With ease in restrictions in the end of 2020, the concentration of pollutants increased during the winter season. But due to the rise in covid cases, India experienced the second wave of coronavirus during the third week of April, 2021, resulting in significant decline in the concentration of gaseous and particulate pollutants during the month of May to September, 2021 (Fig. 2). Percentage change in coarser particulate matter (PM₁₀) concentration between 2018–2020, 2019–2020 and 2020–2021 varied between – 13 to – 61% and 54 to – 54% and – 7 to 103%, respectively, at Adarsh Nagar (Table S4a–f). With reference to 2019 data, significant rise in PM₁₀, PM_{2.5} and NO₂ concentration was observed during pre-lockdown and unlock down phases at Adarsh Nagar and Police Commissionerate sites. Spike in NO₂ concentration was observed at Adarsh Nagar and Police Commissionerate in February 2020 as compared with 2018 data (132%). With reference to 2020 data, rise in NO₂ concentration was observed at Adarsh Nagar (131%), Police Commissionerate (268%) in April. (Table S4a–f).

Mobility of transportation vehicles and rapid urbanization have increased the mean monthly NO₂ concentration over the Jaipur city from 2018 to 2019 but in year 2020, NO₂ concentration has decreased due to pandemic lockdown which cause air quality to improve in Jaipur city and surrounding areas. Information about Air Quality Index (AQI) Category and AQI during COVID period (January 2020–December 2021) is mentioned in Tables S2 and S3, respectively.

Significant reduction in all pollutants was observed in the month of April 2020 when compared to April 2018 and 2019. Rise in concentration of pollutants was observed in April 2021 as all official, commercial and industrial activities continued with fewer restrictions. But due to rapidly rising coronavirus cases in the state, strict lockdown was implemented in May 2021 to curb the spread of the virus, which resulted in significant decline in the concentration of all pollutants when compared to April 2021. The concentration of Benzene increased in May 2020 at Adarsh Nagar (1.05 µg/m⁻³), Police Commissionerate (1.52 µg/m⁻³) and Shastri Nagar (1.08 µg/m⁻³) when compared to May 2018 and 2019. The concentration decreased in the year 2021 (1.4 µg/m⁻³ at Police Commissionerate and Shastri Nagar (0.99 µg/m⁻³) (Fig. 3).

Earlier, many workers have used t-test to check the significant difference in the mean concentration of air pollutants [44–47]. Statistically significant difference between the mean concentration of studied pollutants from April 01–May 31 for 4 years (2018, 2019, 2020 and 2021) was assessed by conducting Student *t*-test. Statistical analysis was conducted on non-covid datasets (2018 & 2019), pre-covid and during covid (2018 & 2020, 2018 &

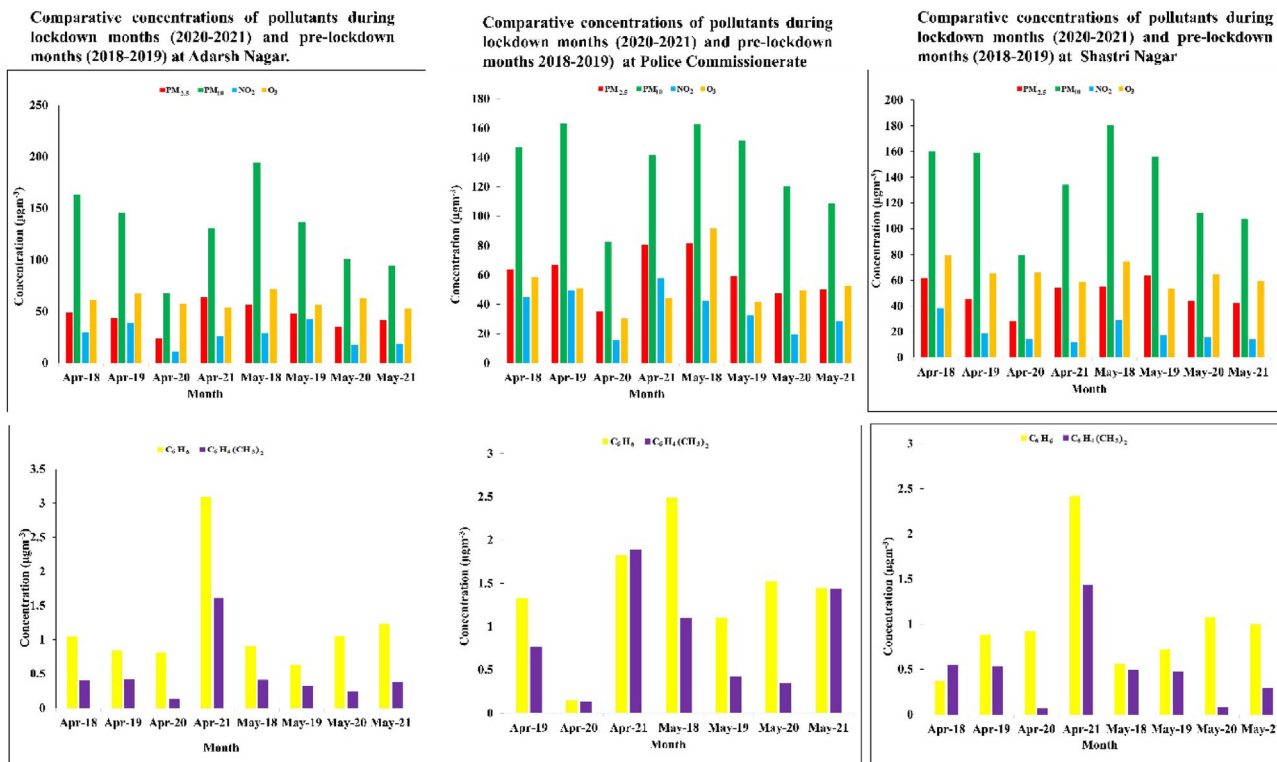


Fig. 3 Comparative Concentration of Pollutants during Lockdown Months (2020–2021) and pre-lockdown months (2018–2019) at all sites

Table 3 *T* test (two tailed significance < 0.05)

Year (April 01–May 31)	Adarsh Nagar (AN)	Police commissionerate (PC)	Shastri Nagar (SN)
2018 & 2019 (non-COVID)	NO ₂ , Benzene	O ₃ , Benzene	NO ₂ , O ₃ , Benzene
2018 & 2020 (Pre and during COVID)	PM ₁₀ , PM _{2.5} , NO ₂ , o-Xylene	PM ₁₀ , PM _{2.5} , NO ₂ , O ₃ , o-Xylene	PM ₁₀ , PM _{2.5} , NO ₂ , O ₃ , Benzene, o-Xylene
2018 & 2021 (Pre and during COVID)	PM ₁₀ , NO ₂ , O ₃ , Benzene, o-Xylene	PM ₁₀ , O ₃ , Benzene	PM ₁₀ , NO ₂ , O ₃ , Benzene
2019 & 2020 (Pre and during COVID)	PM ₁₀ , PM _{2.5} , NO ₂ , o-Xylene	PM ₁₀ , PM _{2.5} , NO ₂ , O ₃ , o-Xylene	PM ₁₀ , PM _{2.5} , NO ₂ , o-Xylene
2019 & 2021 (Pre and during COVID)	NO ₂ , O ₃ , Benzene, o-Xylene	Benzene, o-Xylene	NO ₂ , Benzene
2020 & 2021 (COVID)	PM ₁₀ , PM _{2.5} , NO ₂ , O ₃ , Benzene, o-Xylene	PM _{2.5} , NO ₂ , O ₃ , Benzene, o-Xylene	PM ₁₀ , PM _{2.5} , NO ₂ , Benzene, o-Xylene

2021, 2019 & 2020 and 2019 & 2021) and Covid period (2020 and 2021). Results (*p* < 0.05) revealed that there was no statistically significant difference was present for particulate matter (PM₁₀ and PM_{2.5}) between 2018 and 2019 (pre-covid) at all the three sites (Table 3). Statistical results supported the hypothesis that there was significant difference in the concentration of air pollutants between pre-covid and covid period. Results depicted that the concentration of studied pollutants was significantly lower during Covid-induced restriction period at all the sites as compared with the pre-covid period. Volatile organic compounds (Benzene/Xylene) were present during covid

also which indicates that various activities/sources were in operation even during the restrictions.

4. Conclusion

This study contributes to the knowledge on air pollution in Jaipur city. Results revealed that lockdown has improved the air quality in Jaipur. The extra-ordinary circumstances caused by the global outbreak of pandemic COVID-19 imposed significant effects on the environment. As the energy demand and anthropogenic activities reached its all-

time low levels, emissions also reduced unprecedentedly. In the present study, the ambient air quality of Jaipur city, Rajasthan, India was assessed by analyzing ground-based air quality parameters (PM₁₀ and PM_{2.5}, NO₂, O₃, Benzene and o-Xylene) for 36 months (January 2018–December 2021), categorized as pre-COVID and COVID phase. This study revealed that the concentration of air quality parameters significantly reduced during the lockdown phases. However, coupled with the meteorological effects, concentrations again rose at a fast pace as soon as the unlock down phases were introduced. Compared with the previous year's data, the gaseous and coarser particulate matter concentrations showed diverse trend as steep fall and hike in concentration was noticed. The monthly trends were observed using ground-based measurements. An unexpected downward trend in NO₂ and O₃ concentration was observed in the pre and post COVID-19 phases. Although, the air quality index remained under good and satisfactory categories, except a few events where AQI fell in moderate and poor categories.

Acknowledgements Authors are thankful to CPCB for providing the ambient air quality data and their respective institutions for providing necessary infrastructure.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] A. Chauhan and R.P. Singh, Decline in PM_{2.5} concentrations over major cities around the world associated with COVID-19. *Environ. Res.*, 187 (2020) 109634. <https://doi.org/10.1016/j.envres.2020.109634>.
- [2] A. Carteni, L.D. Francesco and M. Martino, How mobility habits influenced the spread of the COVID-19 pandemic: results from the Italian case study. *Sci. Total Environ.*, 741 (2020) 140489. <https://doi.org/10.1016/j.scitotenv.2020.140489>.
- [3] L. Menut, B. Bessagnet, G. Siour, S. Mailler, R. Pennel and A. Cholakian, Impact of lockdown measures to combat COVID-19 on air quality over western Europe. *Sci. Total Environ.*, 741 (2020) 140426.
- [4] M.A. Zoran, R.S. Savastru, D.M. Savastru and M.N. Tautan, Assessing the relationship between ground levels of ozone (O₃) and nitrogen dioxide (NO₂) with coronavirus (COVID-19) in Milan, Italy. *Sci. Total Environ.*, 740 (2020) 140005. <https://doi.org/10.1016/j.scitotenv.2020.140005>.
- [5] M.A. Zoran, R.S. Savastru, D.M. Savastru and M.N. Tautan, Assessing the relationship between surface levels of PM_{2.5} and PM10 particulate matter impact on COVID-19 in Milan, Italy. *Sci. Total Environ.*, 738 (2020) 139825. <https://doi.org/10.1016/j.scitotenv.2020.139825>.
- [6] S. Zangari, D.T. Hill, A.T. Charette and J.E. Mirowsky, Air quality changes in New York City during the COVID-19 pandemic. *Sci. Total Environ.*, 742 (2020) 140496. <https://doi.org/10.1016/j.scitotenv.2020.140496>.
- [7] M.D. Adams, Air pollution in Ontario, Canada during the COVID-19 state of emergency. *Sci. Total Environ.*, 742 (2020) 140516. <https://doi.org/10.1016/j.scitotenv.2020.140516>.
- [8] M.J. Ju, J. Oh and Y.H. Choi, Changes in air pollution levels after COVID-19 outbreak in Korea. *Sci. Total Environ.*, 750 (2021) 141521. <https://doi.org/10.1016/j.scitotenv.2020.141521>.
- [9] K. Azuma, N. Kagi, H. Kim and M. Hayashi, Impact of climate and ambient air pollution on the epidemic growth during COVID-19 outbreak in Japan. *Environ. Res.*, 190 (2020) 110042. <https://doi.org/10.1016/j.envres.2020.110042>.
- [10] Á. Briz-Redón, C. Belenguer-Sapiña and Á. Serrano-Aroca, Changes in air pollution during COVID-19 lockdown in Spain: a multi-city study. *J. Environ. Sci.*, 101 (2021) 16–26. <https://doi.org/10.1016/j.jes.2020.07.029>.
- [11] S. Selvama, P. Muthukumar, S. Venkatraman, P.D. Roy, K.M. Bharath and K. Jesuraja, SARS-CoV-2 pandemic lockdown: effects on air quality in the industrialized Gujarat state of India. *Sci. Total Environ.*, 737 (2020) 140391. <https://doi.org/10.1016/j.scitotenv.2020.140391>.
- [12] M. Pandey, A.K. Pandey, A. Mishra and B.D. Tripathi, Speciation of carcinogenic and non-carcinogenic metals in respirable suspended particulate matter (PM₁₀) in Varanasi, India. *Urban Clim.*, 19 (2017) 141–154. <https://doi.org/10.1016/j.uclim.2017.01.004>.
- [13] S. Prakash, M. Goswami, Y.D.I. Khan and S. Nautiyal, Environmental impact of COVID-19 led lockdown: a satellite database assessment of air quality in Indian megacities. *Urban Clim.*, 38 (2021) 100900. <https://doi.org/10.1016/j.uclim.2021.100900>.
- [14] Y. Kambalagere, A study on air quality index (AQI) of Bengaluru, Karnataka during lockdown period to combat coronavirus disease (COVID-19): air quality turns 'Better' from 'Hazardous.' *Stud. Indian Place Names*, 69 (2020) 59–66.
- [15] S. Sharma, M. Zhang, J. Gao, H. Zhang and S.H. Kota, Effect of restricted emissions during COVID-19 on air quality in India. *Sci. Total Environ.*, 728 (2020) 138878. <https://doi.org/10.1016/j.scitotenv.2020.138878>.
- [16] S. Mahato, S. Pal and K.G. Ghosh, Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. *Sci. Total Environ.*, 730 (2020) 139086. <https://doi.org/10.1016/j.scitotenv.2020.139086>.
- [17] M. Pandey, M.P. George, R.K. Gupta, D. Gusain and A. Dwivedi, Impact of COVID-19 induced lockdown and unlock down phases on the ambient air quality of Delhi, capital city of India. *Urban Clim.*, 39 (2021) 100945. <https://doi.org/10.1016/j.uclim.2021.100945>.
- [18] S. Srivastava, A. Kumar, K. Baudh, A.S. Gautam and S. Kumar, 21-day lockdown in India dramatically reduced air pollution indices in Lucknow and New Delhi, India. *Bull. Environ. Contam. Toxicol.* (2020). <https://doi.org/10.1007/s00128-020-02895-w>.
- [19] A. Mitra, T. Ray Chaudhuri, A. Mitra, P. Pramanick and S. Zaman, Impact of COVID-19 related shutdown on atmospheric carbon dioxide level in the city of Kolkata. *Parana J. Sci. Educ.*, 6(3) (2020) 84–92.
- [20] K.S.J.M.S. Ramasamy, Enchanted improvements in air quality across India: a study from COVID-19 lockdown perspective. *SSRN Electron. J.*, 9(5) (2020) 101–125. <https://doi.org/10.2139/ssrn.3596001>.
- [21] J.M. Baldasano, COVID-19 lockdown effects on air quality by NO₂ in the cities of Barcelona and Madrid (Spain). *Sci. Total Environ.*, 741 (2020) 140353. <https://doi.org/10.1016/j.scitotenv.2020.140353>.
- [22] J.D. Berman and K. Ebisu, Changes in U.S. air pollution during the COVID-19 pandemic. *Sci. Total Environ.*, 739 (2020) 139864. <https://doi.org/10.1016/j.scitotenv.2020.139864>.

- [23] P. Broomandi, F. Karaca, A. Nikfal, A. Jahanbakhshi, M. Tamjidi and J.R. Kim, Impact of COVID-19 event on the air quality in Iran. *Aerosol Air Qual. Res.*, 20 (2020) 1793–1804. <https://doi.org/10.4209/aaqr.2020.05.0205>.
- [24] G. He, Y. Pan and T. Tanaka, The short-term impacts of COVID-19 lockdown on urban air pollution in China. *Nat. Sustain.*, 3 (2020) 1005–1011. <https://doi.org/10.1038/s41893-020-0581-y>.
- [25] G. Kotnala, T.K. Mandal, S.K. Sharma and R.K. Kotnala, Emergence of blue sky over delhi due to coronavirus disease (COVID-19) lockdown implications. *Aerosol Sci. Eng.* (2020). <https://doi.org/10.1007/s41810-020-00062-6>.
- [26] S. Kumar, Effect of meteorological parameters on spread of COVID-19 in India and air quality during lockdown. *Sci. Total Environ.*, 745 (2020) 141021. <https://doi.org/10.1016/j.scitotenv.2020.141021>.
- [27] X. Lian, J. Huang, R. Huang, C. Liu, L. Wang and T. Zhang, Impact of city lockdown on the air quality of COVID-19-hit of Wuhan city. *Sci. Total Environ.* (2020). <https://doi.org/10.1016/j.scitotenv.2020.140556>.
- [28] S. Lokhandwala and P. Gautam, Indirect impact of COVID-19 on environment: a brief study in Indian context. *Environ. Res.*, 188(April) (2020) 109807. <https://doi.org/10.1016/j.envres.2020.109807>.
- [29] W. Ming, Z. Zhou, H. Ai, H. Bi and Y. Zhong, COVID-19 and air quality: evidence from China. *Emerg. Mark. Financ. Trade*, 56(10) (2020) 2422–2442.
- [30] S. Mor, S. Kumar, T. Singh, S. Dogra, V. Pandey and K. Ravindra, Impact of COVID-19 lockdown on air quality in Chandigarh, India: understanding the emission sources during controlled anthropogenic activities. *Chemosphere* (2020). <https://doi.org/10.1016/j.chemosphere.2020.127978>.
- [31] C. Navinya, G. Patidar and H.C. Phuleria, Examining effects of the COVID-19 National lockdown on ambient air quality across urban India. *Aerosol Air Qual. Res.*, 20 (2020) 1759–1771. <https://doi.org/10.4209/aaqr.2020.05.0256>.
- [32] Z. Pei, G. Han, X. Ma, H. Su and W. Gong, Response of major air pollutants to COVID-19 lockdowns in China. *Sci. Total Environ.* (2020). <https://doi.org/10.1016/j.scitotenv.2020.140879>.
- [33] M. Sarfraz, K. Shehzad and S.G. Meran Shah, The impact of COVID-19 as a necessary evil on air pollution in India during the lockdown. *Environ. Pollut.* (2020). <https://doi.org/10.1016/j.envpol.2020.115080>.
- [34] M.A. Zambrano-Monserrate and M.A. Ruano, Has air quality improved in Ecuador during the COVID-19 pandemic? A parametric analysis. *Air Qual. Atmos. Health*, 13(8) (2020) 929–938.
- [35] Q. Liu, J.T. Harris, L.S. Chiu, D. Sun, P.R. Houser, M. Yu, D.Q. Duffy, M.M. Little and C. Yang, Spatiotemporal impacts of COVID-19 on air pollution in California, USA. *Sci. Total Environ.*, 750 (2021) 141592.
- [36] Y. Sathey, P. Gupta, M. Bawase, L. Lamsal, F. Patadia and S. Thipse, Surface and satellite observations of air pollution in India during COVID-19 lockdown: implication to air quality. *Sustain. Cities Soc.*, 66 (2021) 102688.
- [37] The Indian Express (2021). COVID-19 second wave: here's a list of states that have imposed full lockdown. Retrieved from: <https://indianexpress.com/article/india/coid-19-second-wave-here-a-list-of-states-that-have-imposed-full-lockdowns-7306634/>
- [38] The Economic Times (2021). Situation very dangerous, restrictions imposed to combat COVID-19 threat in Rajasthan: Ashok Gehlot. Retrieved from: <https://economictimes.indiatimes.com/news/elections/lok-sabha/india/situation-very-dangerous-restrictions-imposed-to-combat-COVID-19-threat-in-rajasthan-ashok-gehlot/articleshow/82142302.cms>.
- [39] A.P. Dadhich, R. Goyal and P.N. Dadhich, Assessment of spatio-temporal variations in air quality of Jaipur city, Rajasthan, India. *Egypt. J. Remote Sens. Space Sci.*, 21(2) (2018) 173–181. <https://doi.org/10.1016/j.ejrs.2017.04.002>.
- [40] Government of Rajasthan. Retrieved from: https://rajasthan.gov.in/LandAndEnvironment.aspx?menu_id=40.
- [41] DIP, Brief Industrial Profile of Jaipur District 2015–2016, District Industrial Profile of Jaipur, MSME, 2016
- [42] Mehta S. (2019). Jaipur development authority, Jaipur, India, assessment of urban mobility in jaipur using the sustainable urban transport index (SUTI), United nations economic and social commission for Asia and the Pacific (UN ESCAP)
- [43] Motor Vehicles- Statistical Year Book India 2018, Ministry of statistics and programme implementation, visited on 19.12.2020
- [44] A.C.T. Silva, P.T.B.S. Branco and S.I.V. Sousa, Impact of COVID-19 pandemic on air quality: a systematic review. *Int. J. Environ. Res. Public Health*, 19(4) (2022) 1950. <https://doi.org/10.3390/ijerph19041950>.
- [45] K.P. Vadrevu, A. Eaturu, S. Biswas et al., Spatial and temporal variations of air pollution over 41 cities of India during the COVID-19 lockdown period. *Sci. Rep.*, 10 (2020) 16574. <https://doi.org/10.1038/s41598-020-72271-5>.
- [46] L. Wu, J. Xie and K. Kang, Changing weekend effects of air pollutants in Beijing under 2020 COVID-19 lockdown controls. *npj Urban Sustain.*, 2 (2022) 23. <https://doi.org/10.1038/s42949-022-00070-0>.
- [47] P. Sharma, P. Yadav, C. Ghosh and B. Singh, Heavy metal capture from the suspended particulate matter by *Morus alba* and evidence of foliar uptake and translocation of PM associated zinc using radiotracer (^{65}Zn). *Chemosphere*, 254 (2020) 126863. <https://doi.org/10.1016/j.chemosphere.2020.126863>.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.