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Particulate Matter Pollution in Urban Cities of India During Unusually Restricted Anthropogenic Activities

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The outbreak of COVID-19 is a global public health challenge and has affected many countries, including India. The nationwide lockdown was imposed in India from March 25 to May 31, 2020 to prevent the transmission of COVID-19. The study intends to assess the impact of the absence of major anthropogenic activities during the various phases of the COVID-19 lockdown (LDN) period on the daily mean concentrations of $PM_{2.5}$ and PM_{10} in six populated cities of Jaipur, Jodhpur, Kota, Udaipur, Ajmer, and Alwar in the state of Rajasthan. Investigation has been done for the different periods, including the pre-lockdown—PRELD (January 1–March 4, 2020), partial lockdown—PLDN (March 5–24, 2020), COVID-19 lockdown—LDN (March 25–May 31, 2020), and unlocking—ULC (June 1–August 31, 2020) phases. We have also compared the mean concentrations of $PM_{2.5}$ and PM_{10} with the same period of the year 2019. A significant improvement in air quality during the COVID-19 LDN period was noticed in all cities compared to 2019 and for the same period of the year 2020. However, the levels of $PM_{2.5}$ and PM_{10} were seen to rise during the second, third, and fourth LDN phases compared to the first LDN, indicating that the subsequent lockdowns started with some relaxations and dusty conditions. On the other hand, wind-blown dust is another vital source of PM_{10}, resulting in high concentrations in the summer months (April–May). Significant reductions in $PM_{2.5}$ (∼25–50%) and PM_{10} (20–37%) in all six cities during the LDN period compared with PRELD were estimated. However, with significant variations from city to city, the lowest reductions in $PM_{2.5}$ (∼25%) and PM_{10} (∼20%) were measured in Jodhpur and Ajmer, respectively. It was noticed that the episodes of rainfall and transport of oceanic air masses resulted in a reduction of particles during the ULC period compared to the LDN period. The air quality index was, more or less, in the "good to satisfactory" category during the first 3 LDN periods, whereas it was moderate for Jodhpur, Jaipur, and Ajmer during the last LDN period. The study will be helpful to determine mitigation policies to minimize air pollution, especially in developing regions.

Keywords: particulate matter, COVID-19 lockdown, air quality index, meteorology, India

HIGHLIGHTS

- The investigation shows the impact of the various phases of COVID-19 lockdown on $PM_{2.5}$ and PM_{10} in six cities of Rajasthan.
- There was a reduction during the COVID-19 lockdown, by 16–50% in $PM_{2.5}$ and by 22–47% in PM_{10}.
- Mineral dust pollution is prominent in particle loads over the Rajasthan state.
- Monsoon rains and winds dominate over emissions during the unlocking periods (June–August) in $PM_{2.5}$ and PM_{10} distribution.

INTRODUCTION

The entire world has been facing an acute pandemic and challenging circumstances because of the novel contamination of coronavirus disease (COVID-19) since the beginning of 2020. The first case was identified in Wuhan, China, in December 2019 (Li et al., 2020). In view of the expanding pace of COVID-19 cases worldwide, the transmittable disease has become a global pandemic (WHO, 2020). Therefore, many countries have declared a nationwide strict lockdown with varying rules and regulations to control the spread of COVID-19. In India, the first COVID-19 case was identified on January 30, 2020 in Trisharu, Kerala (India) (WHO, 2020) and in different parts of the country during the first week of March (https://www.mohfw.gov.in/). The multiple cases of infection from India started to come into view in the first week of March 2020. Later, the government of India (Prime Minister) announced "Janata Curfew" for a day on March 22, 2020, with a complete shutdown of daily activities. Later, complete lockdown for 21 days across India was officially announced, from March 25 to April 14, 2020. Later, to deal with the decline of the pandemic in the nation, the lockdown was extended up to May 3, 2020. After looking at the problematic situation, it continued until May 31, 2020 with some relaxation. The details of prohibited and permitted activities during the different lockdown phases, including LDN1 (March 25–April 14, 2020), LDN2 (April 15–May 3, 2020), LDN3 (May 04–17, 2020), LDN4 (May 18–31, 2020), are listed in **Table 1**. Improvements in air quality due to reductions in transport (flights, trains, and vehicles), industrial, academic, economic, and social-related activities are reported in several studies (Dantas et al., 2020; Kumari and Toshniwal, 2020; Nakada and Urban, 2020; Navinya et al., 2020; PPAC, 2020; Sharma et al., 2020; Sicard et al., 2020; Singh et al., 2020; Yadav et al., 2020). About 40–70% reductions were suggested in transport, industrial, and construction activities based on the fuel consumption data during the lockdown period, but ∼12% enhancement was estimated in biofuel consumption for cooking purposes (PPAC, 2020). The combustion-related emissions are considered one of the significant sources of air pollutants in Indian cities. The air quality, in terms of air quality index and health impact, is mainly determined by the levels of hazardous particulate pollutants in a year. In ambient air, the most important anthropogenic sources of fine particulate matter are the incomplete combustion of biofuel and fossil fuels (Sahu et al., 2011). In addition to local emissions, the long-range transport from the regions of biomass burning and dust sources also influence the receptor sites (Yadav et al., 2016, 2017). Exposure to elevated levels

TABLE 1 | Details of the prohibited and permitted activities during the study period.

Study phases and its duration/2020	Total days	Activities
PRELD January 1–March 4	63	Business as usual
PLDN March 5–24	21	Selective restrictions announced by the government, like mass gatherings in institutions, shopping malls, and theaters
LDN1 March 25–April 14	21	All were closed, with the exception of essential services like for health. Security and food delivery and others
LDN2 April 15–May 3, 2020	19	Allowed were agricultural businesses including dairy, banking, telecommunication, power-related services, manufacturing, and transportation units; interstate movement was also allowed for the delivery of essential goods and for law and order
LDN3 May 4–17, 2020	14	Allowed were all activities but with restrictions and social distancing, e.g., travel by air and rail around the metro; running of schools, colleges, and other educational and training/coaching institutions; hospitality services, including hotels and restaurants; places of large public gatherings, such as cinema halls and malls Gymnasiums, sports complexes, etc., were still closed
LDN4 May 18–31, 2020	14	Protection for vulnerable persons, i.e., persons above 65 years of age, persons with co-morbidities, pregnant women, and children below the age of 10 years shall stay at home, except for meeting essential requirements and for health purposes
ULC1 June 1–30, 2020	30	Shopping malls, religious places, hotels, and restaurants were permitted to reopen from June 8. Large gatherings were still banned, but there were no restrictions on interstate travel
ULC2 July 1–31, 2020	31	Shops were permitted to allow more than five persons at a time. Educational institutions, metros, and recreation centers remained close until July 31.
ULC3 August 1–31, 2020	31	Educational institutions would remain close until August 31. All inter- and intrastate travel and transportation modes are permitted. Independence Day celebrations are permitted with social distancing

MHA, 2020.

of $PM_{2.5}$ in ambient air can cause adverse health effects like respiratory and cardiovascular diseases (e.g., Pope et al., 2009). Several studies have reported the association of COVID-19-related mortality and morbidity along with air pollution and meteorological parameters during the lockdown period (Beig et al., 2020; Conticini et al., 2020; Wu et al., 2020; Yao et al., 2020). On the other hand, many studies have reported a significant reduction in air pollution across the world due to the COVID-19 restrictions (Bashir et al., 2020; Jain and Sharma, 2020; Kanniah et al., 2020; Kumar et al., 2020; Kumari and Toshniwal, 2020; Mahato et al., 2020; Nakada and Urban, 2020; Navinya et al., 2020; Singh and Chauhan, 2020; Singh et al., 2020; Tobías et al., 2020; Yadav et al., 2020; Goel et al., 2021; Sokhi et al., 2021). Most of the studies in India have been focused on megacities so far, including Delhi, Mumbai, Ahmedabad, Pune, Chennai, Kolkata, Lucknow, Jaipur, and Bangalore, etc. However, studies during the COVID-19 lockdown period in several cities of Rajasthan are reported for a very limited period (Sharma et al., 2020). Aside from local anthropogenic emissions, the air pollution footprints are unique in Rajasthan, where dust-related sources are also dominant. The geographic characteristics of Rajasthan are the Thar Desert and the Aravalli Range, and the north-western portion of Rajasthan is generally sandy and dry. Hence, due to being the driest region and given the different climatic zones, the study will be very prominent in these locations. The present study highlights the role of long-term COVID-19 lockdown on $PM_{2.5}$ and PM_{10} in six major cities of Rajasthan, including Jaipur, Jodhpur, Kota, Udaipur, Ajmer, and Alwar, and the alteration in air pollution levels during the unlocking periods. We have also discussed the change in the air quality index (AQI) for all cities. Overall, we present a detailed investigation by considering the combined effects of local emissions and meteorology during the lockdown period.

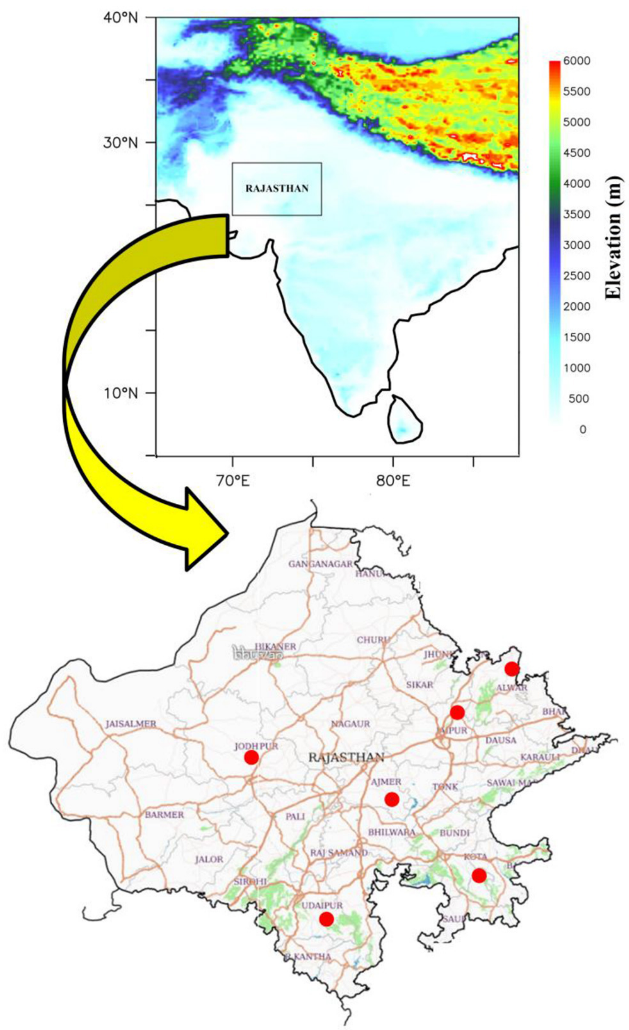

FIGURE 1 | Map of India on surface elevation depicting Rajasthan along with the location of selected cities such as Jaipur, Jodhpur, Kota, Udaipur, Ajmer, Alwar are shown by the red oval. The Rajasthan Map (bottom panel) has been used from ISRO's Earth visualization portal Bhuvan (https://bhuvan.nrsc.gov.in/).

METHODOLOGY

Data Sources, Locations, and Local Meteorology

The concentration data of $PM_{2.5}$ and PM_{10} as measured in six cities, namely, Jaipur, Jodhpur, Kota, Udaipur, Ajmer, and Alwar, in the state of Rajasthan were obtained from the Central Pollution Control Board (CPCB) for the years 2019 and 2020. The $PM_{2.5}$ and PM_{10} data in these cities located in the northwest part of India were analyzed to investigate the pollution levels during the long-term COVID-19 lockdown period. The locations of the study sites in the maps of India and Rajasthan are shown in **Figure 1**.

The data studied include during the pre-lockdown period (PRELD) (January 1 to March 4, 2020), partial lockdown (PLDN) (March 5 to 24, 2020), COVID-19 lockdown (LDN) (March 25 to May 31, 2020), and unlocking (ULC) period (June 1 to August 31, 2020). The average matching periods of the year 2019 were considered as the references to study the change in air quality during the COVID-19 lockdown period. We have used the National Centre for Environmental Prediction reanalysis datasets to derive the wind streamlines and temperature at a spatial resolution of 2.5° × 2.5° during the entire study period for 2019 and 2020, as shown in **Figure 2**. The precipitation rate (mm day^{-1}) data from the CPC Merged Analysis of Precipitation (CMAP), at a spatial resolution of 2.5° × 2.5°, was used. The Moderate Resolution Imaging Spectroradiometer (MODIS) active fire count maps over India during the entire study period for 2019 and 2020 are plotted in **Figure 3**. Rajasthan is the largest state of India, located in the north-western region with a population of ∼6.8 million (http://census2011.co.in). However, being located near most cities, the state has various types of industrial units, including those of marble, steel, cement, handicrafts, textiles, chemicals, IT, and thermal plants (Report 2018). The primary sources of air pollutants are vehicular, industrial, agriculture residual burning, municipal solid waste treatment,

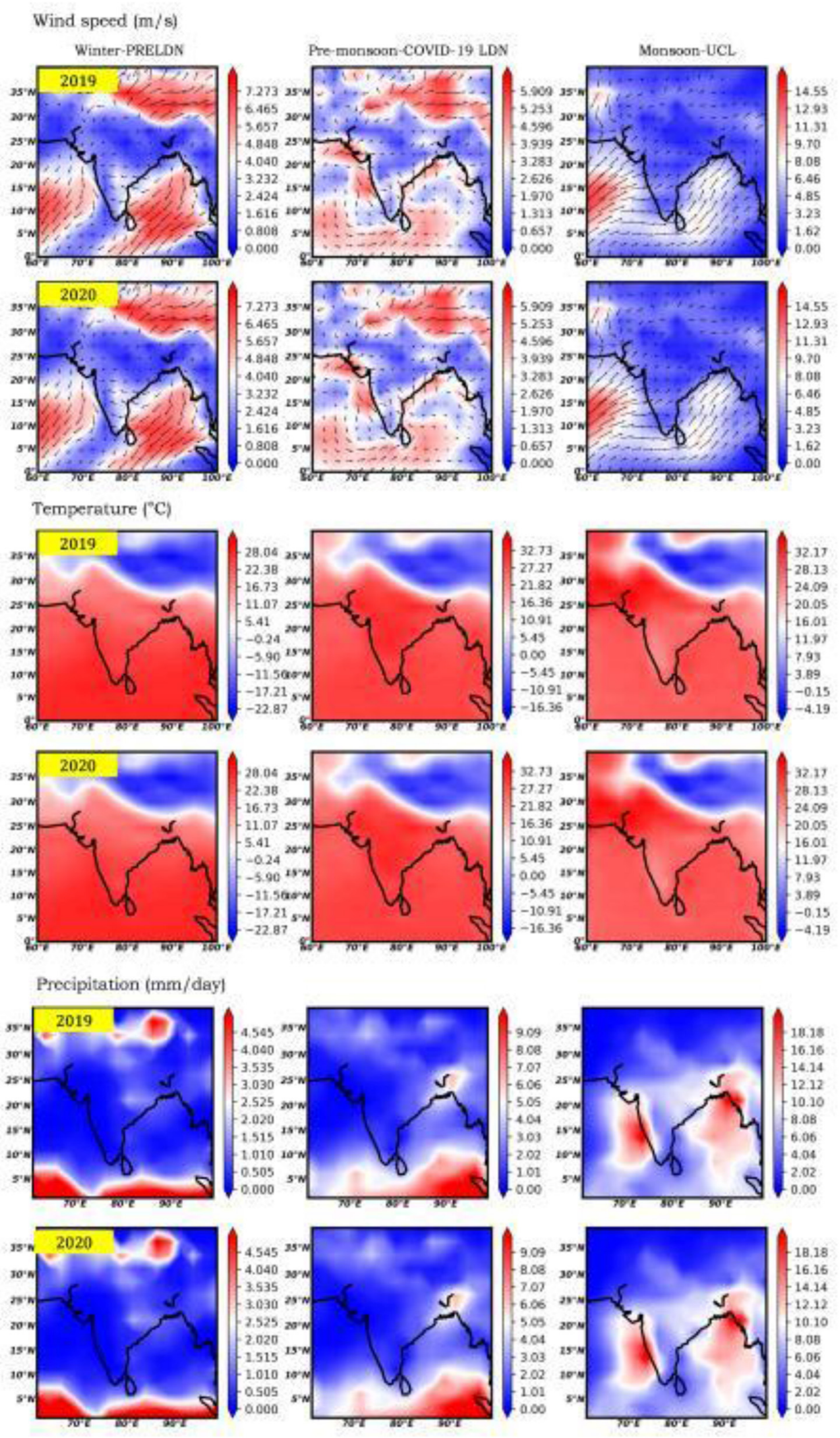

FIGURE 2 | Meteorological parameters during the different phases of the study in the years 2019 and 2020: **(top)** wind speed; **(middle)** temperature; **(bottom)** precipitation.

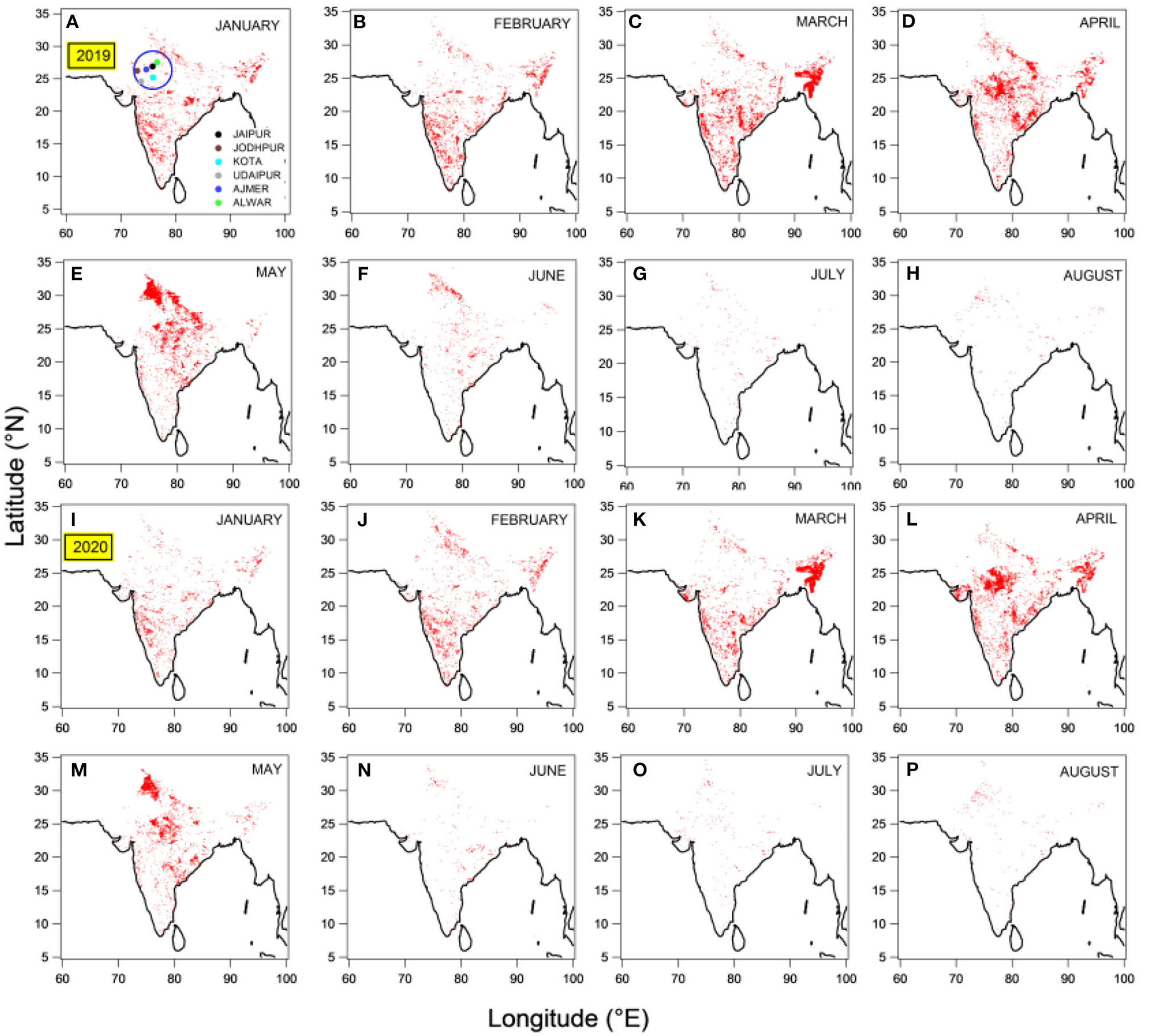

FIGURE 3 | MODIS fire count data maps from January to August for the years 2019 and 2020.

diesel generator, biofuel and LPG (residential cooking), and construction activities. The common sources of $PM_{2.5}$ and PM_{10} include biofuel and fossil fuel combustion, industrial processes, and biomass burning. However, for PM_{10}, wind-blown dust, road dust suspension, building construction, lime kilns, and slab polishing are important non-combustion sources (Yadav et al., 2017). Daily mean temperature ranges of 10–27, 32–45, and 35–40°C are recorded during winter (January–February), pre-monsoon (March–May), and monsoon (June–September) seasons, respectively. The strong hot winds called "Loo" blow from the west during pre-monsoon, while relatively low winds blow from the north and northeast during the winter (Yadav et al., 2014a). Rainfall values as high as 819 mm in the eastern part and as low as 170 mm in the western part of the state were recorded (Maanju and Saha, 2013). In the monsoon season, the inter-tropical convergence zone moves northward across India, and strong southwest (SW) winds prevail over the study region. Therefore, the measurements in this season are influenced by the transport of cleaner air masses from the Arabian Sea (see **Supplementary Figure S1**).

RESULTS AND DISCUSSION

Role of COVID-19 Lockdown in the Variation of $PM_{2.5}$ and PM_{10}

The time series analysis of $PM_{2.5}$ and PM_{10} over a period of 8 months (January 1–August 31, 2020) reveals interesting trends. The daily means of $PM_{2.5}$ and PM_{10} concentrations measured in Jaipur, Jodhpur, Kota, Udaipur, Ajmer, and Alwar are shown in **Figure 4**. The daily mean time series concentrations

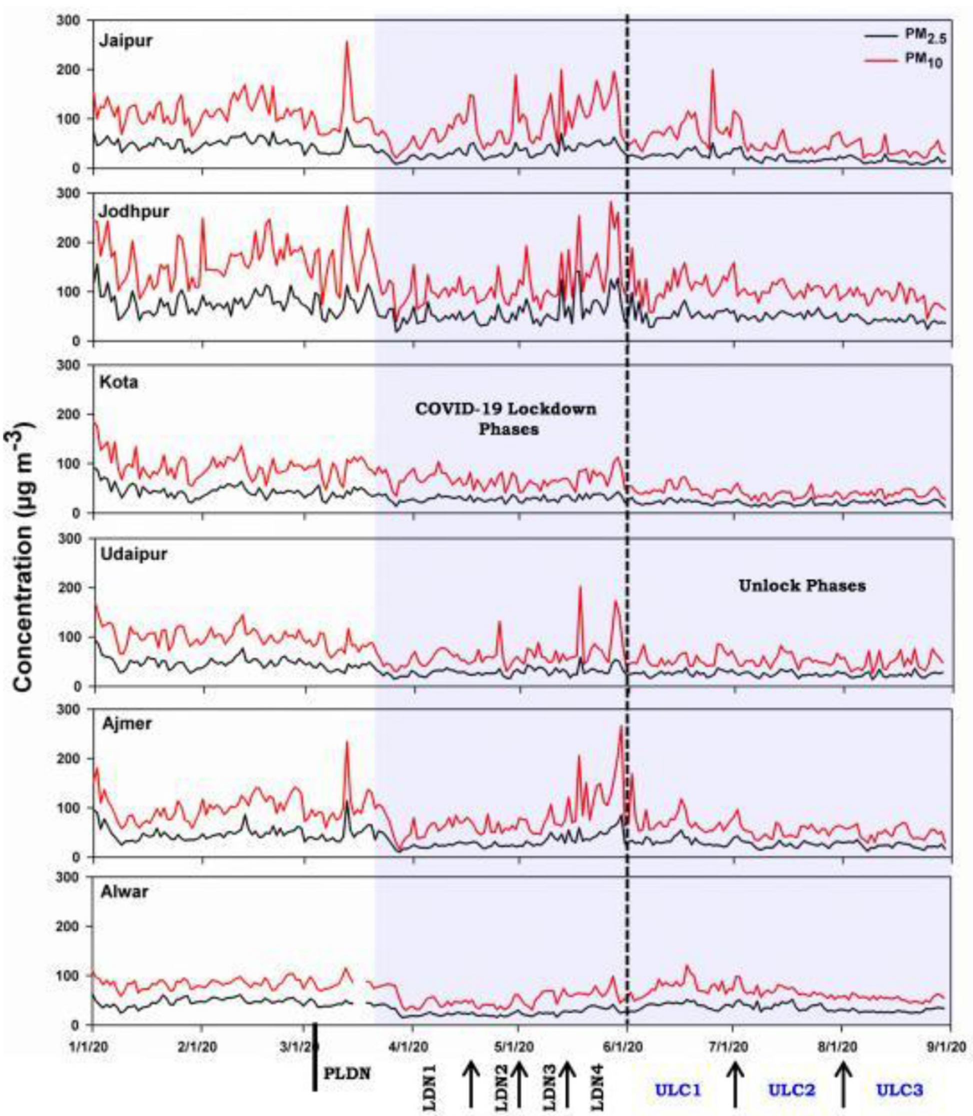

FIGURE 4 | Daily time series variations of $PM_{2.5}$ and PM_{10} in six major cities from January 1 to August 31, 2020.

of $PM_{2.5}$ and PM_{10} for all cities are divided into the four different periods of PRELD (January 1–March 4), PLDN (March 5–24), COVID-19 LDN (March 25–May 31), and ULC (June 1–August 31). During the business-as-usual period, many studies have reported a clear seasonality in the daily mean concentrations of $PM_{2.5}$ and PM_{10}, with the highest in the dry period (winter to pre-monsoon) and the lowest in the monsoon season, in different cities of India (Beig et al., 2007; Yadav et al., 2017; Hama et al., 2020). However, the findings become effectively more crucial in 2020 to researchers and policymakers because of the COVID-19-related consecutive LDN and ULC situations in which anthropogenic activities were restricted. The daily mean concentrations of $PM_{2.5}$ were in the ranges of 7–81, 18–156, 12–91, 14–93, 10–114, and 15–63 $\mu g\ m^{-3}$, while those of PM_{10} varied in the ranges of 20–256, 39–282, 23–185, 26–202, 15–266, and 30–121 $\mu g\ m^{-3}$, respectively, in Jaipur, Jodhpur, Kota, Udaipur, Ajmer, and Alwar during the entire study period. The mean concentrations of $PM_{2.5}$ were 51 ± 10, 78 ± 21, 45 ± 13, 49 ± 12, 47.3 ± 13, and 47.2 ± 8 $\mu g\ m^{-3}$ in the PRELD period, which reduced to 34 ± 09, 58 ± 16, 29 ± 3, 29 ± 2, 32 ± 11, and 24 ± 4.4 $\mu g\ m^{-3}$ during the LDN period in Jaipur, Jodhpur, Kota, Udaipur, Ajmer, and Alwar, respectively. On the other hand, the mean concentrations of PM_{10} were 115 ± 23, 162 ± 41, 97 ± 25, 104 ± 18, 100 ± 25, and 85 ± 9 $\mu g\ m^{-3}$ in the PRELD period, which decreased by 90 ± 27, 116 ± 29, 67 ± 8, 65 ± 14, 80 ± 35, and 53 ± 10 $\mu g\ m^{-3}$ during the LDN periods in Jaipur, Jodhpur, Kota, Udaipur, Ajmer, and Alwar, respectively. The

TABLE 2 | The daily average mass concentrations of $PM_{2.5}$ and PM_{10} during different periods, namely, PRELD, PLDN, and LDN phases and unlocking phases in six different cities of Rajasthan in India.

Cities	PRELD	PLDN	LDN1	LDN2	LDN3	LDN4	LDN periods	ULC1	ULC2	ULC3	ULC periods
$PM_{2.5}$											
Jaipur	50.8 ± 10	39.9 ± 12	23.3 ± 8	30.8 ± 11	36.8 ± 12	46.7 ± 8.4	34.4 ± 9.8	28.3 ± 7.1	19.9 ± 8.2	14.9 ± 5.5	21.0 ± 6.7
Jodhpur	78 ± 21	69.6 ± 23	47.8 ± 14	46 ± 11	57.7 ± 23.5	82.3 ± 30	58 ± 16	54.6 ± 14.7	51.7 ± 6.9	42.1 ± 6.5	49.5 ± 6.5
Kota	45.7 ± 13	38 ± 9	27.7 ± 5.3	28 ± 5	28.4 ± 5.3	33 ± 6.5	29 ± 3	22.4 ± 4	18.7 ± 4	21.8 ± 3.9	21 ± 1.9
Udaipur	49 ± 12	36 ± 7	26 ± 6	25 ± 5	31 ± 7	34 ± 11	29.3 ± 2.5	26.8 ± 5	25.1 ± 4.5	23.6 ± 5	25 ± 1.6
Ajmer	47 ± 13	49 ± 18	22 ± 5	24.7 ± 4.2	33.5 ± 10	47.7 ± 16	32.2 ± 11	31.7 ± 7.8	26.4 ± 6.6	23.5 ± 5	27.2 ± 4
Alwar	47 ± 8.2	41.6 ± 3.4	23 ± 5	20.6 ± 3	23.4 ± 3.8	32.5 ± 5	24 ± 4.4	39 ± 7	38 ± 7.2	28.7 ± 3.3	35.3 ± 5.7
PM10											
Jaipur	115 ± 23	96.6 ± 46	60.5 ± 24	81.3 ± 44	94 ± 41	125 ± 38	90.37 ± 27	74 ± 31	50.7 ± 23	36.5 ± 12	54 ± 19
Jodhpur	162 ± 41	154 ± 53	96.2 ± 26	96 ± 19	114 ± 40	159 ± 28	116 ± 29	113 ± 28	103 ± 15.3	89 ± 16	101 ± 12
Kota	96.6 ± 25	88 ± 20	69.8 ± 14.9	63 ± 13.9	59 ± 9	76 ± 19.9	67 ± 8	47.9 ± 10.6	37.5 ± 8.8	39.6±7	42 ± 5
Udaipur	103.6 ± 18.8	76.5 ± 19	54.7 ± 14	59 ± 22.6	60.5 ± 12	87.4 ± 47	65 ± 14	55.4 ± 14	53 ± 10.9	48.9 ± 15	52 ± 3
Ajmer	99.9 ± 25	103 ± 35	55.7 ± 18	60.6 ± 12.6	71.9 ± 20.9	131.6 ± 57	80 ± 25	72 ± 24	54 ± 14	49 ± 12	58 ± 12
Alwar	84.5 ± 9.9	83.4 ± 11	48.7 ± 15	41 ± 7.9	56 ± 13.2	65.3 ± 12	53 ± 10	75.9 ± 16	68.5 ± 10	54 ± 5.5	66 ± 11

PRELD, pre-lockdown; PLDN, partial lockdown; LDN, lockdown; ULC, unlocking.

daily mean concentrations of $PM_{2.5}$ and PM_{10} during PRELD, PLDN, various phases of LDN, and UCL situations are shown in **Table 2**. The National Ambient Air Quality Standards (NAAQS) recommend the daily permissible $PM_{2.5}$ of 60 $\mu g\ m^{-3}$ and PM_{10} of 100 $\mu g\ m^{-3}$ for India (MoEFCC, 2015). About 3, 33, and 6% of $PM_{2.5}$ daily data exceeded the permissible limit of NAAQS during the COVID-19 LDN period in Jaipur, Jodhpur, and Ajmer, while 35, 46, 4, 7, and 19% of PM_{10} exceeded in Jaipur, Jodhpur, Kota, Udaipur, and Ajmer, respectively. It is suggested that the concentrations of $PM_{2.5}$ significantly decreased in all cities that met the NAAQS limits. However, in a few cities, like Jodhpur, Jaipur, and Ajmer, the PM_{10} levels did not fall below the standard limit during most of the COVID-19 LDN period due to non-combustion-related sources like wind-blown dust. The highest reduction by 47% in $PM_{2.5}$ was observed in Alwar, followed by Udaipur (40%), Kota (36%), Jaipur (32%), and Ajmer (32%), while Jodhpur showed the lowest reduction of about 25% during the COVID-19 LDN, respectively. PM_{10} was reduced by 37% in Alwar and 36% in Udaipur. However, the lowest reductions of 19–30% were estimated for Jaipur, Jodhpur, Kota, and Ajmer cities (**Figure 5**). Additionally, we have compared the $PM_{2.5}$ and PM_{10} concentrations measured in 2020 with those during the previous year (2019) for the COVID-19 LDN and ULC periods (see **Figure 6**). The differences are, more or less, the same during PLDN, but significantly lower concentrations of both pollutants were estimated during the COVID-19 LDN and ULC periods. Wilcoxon test has been performed, and P-value < 0.05 was found, which was considered statistically significant in the LDN periods. The reductions in $PM_{2.5}$ and PM_{10} varied in the ranges of 16–50 and 22–47% during the COVID-19 LDN period with respect to the same period of the year 2019 (without meteorological normalization), as shown in **Figure 7**. The reductions of 6–46% in $PM_{2.5}$ and 28–49% in PM_{10} were estimated during the overall ULC period.

Overall, the declining trends of $PM_{2.5}$ and PM_{10} observed in all cities during the COVID-19 LDN period are attributed to the reduction in combustion-related emissions (NASA, 2020; Navinya et al., 2020). Conversely, to some extent, elevated levels of $PM_{2.5}$ and PM_{10} were observed during the LDN3 and LDN4 periods (see **Figure 4**). During all COVID-19 LDN phases, the restrictions were diverse and resulted in variations of $PM_{2.5}$ and PM_{10} in each LDN phase—for example, major anthropogenic and industrial activities were stopped, except for emergency services like the health sector (Yadav et al., 2020). Later, some relaxations with limitations were allowed in the subsequent LDN periods (MHA, 2020). Sahu et al. (2011) have reported that the emissions from transport and industrial sectors have significant contributions to the ambient concentrations of both $PM_{2.5}$ and PM_{10}. In addition to this, wind-blown dust is a more substantial source of coarser particles (PM_{10}) in the northern and western regions of India (Sahu et al., 2011; Yadav et al., 2014b). During the ULC period, only Alwar City exhibited higher values of $PM_{2.5}$ and PM_{10} compared with the overall LDN phases in the same year; this could have happened due to limited local rainfall events. Interestingly, the highest plummet can be attributed to rainfall in the ULC period (monsoon) compared to 2019. In the monsoon period, episodes of rainfall can wash out the dust particles (PM_{10}) much faster than the finer particles ($PM_{2.5}$), unless there is frequent rainfall for many days (Yadav et al., 2014c). **Figure 8** shows the ratios of $PM_{2.5}/PM_{10}$ during the study period in the year 2020 in six cities that were used to investigate aerosol combustion and non-combustion sources. The ratio of $PM_{2.5}/PM_{10}$ was observed to be $<0.50\ \mu g\ \mu g^{-1}$ in all cities due to higher temperatures during the COVID-19 LDN period (pre-monsoon months), leading to dry and dusty conditions (Chan and Yao, 2008). The emissions from wind-blown dust are highly significant, mainly contributing to PM_{10}, and are probably the reason for the high levels of coarser particles. Interestingly, about $0.40\ \mu g\ \mu g^{-1}$ ratio of $PM_{2.5}/PM_{10}$ was observed during all phases

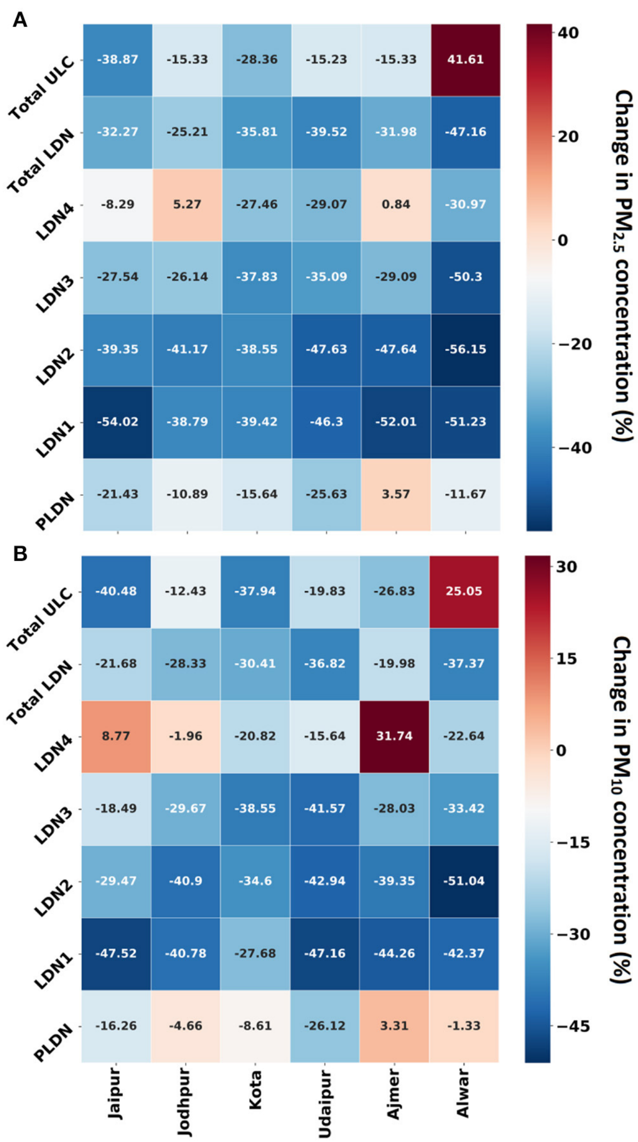

FIGURE 5 | Percentage change in the concentrations of $PM_{2.5}$ and PM_{10} during the COVID-10 lockdown (LDN) phases and unlocking period in six cities. The percentage change in the concentration of $PM_{2.5}$ and PM_{10} was calculated during partial lockdown and LDN phases by comparing the pre-lockdown period and the change in the unlocking period compared to the LDN period.

of COVID-19 LDN in Jaipur City (nearby Delhi) due to the impact of dust storm. In the pre-monsoon season, dust storms originate from Arab countries, and the Thar Desert can influence most regions, like Delhi, Rajasthan, etc., of India (Anand et al., 2019), thus rapidly increasing the PM_{10} levels. Overall, dust pollution is prominent in particle loads over the Rajasthan state. In addition to this, we have incorporated the plots of O_3/NO_2 and SO_2/NO_2 ratios during the study period in **Figure 8**. In the LDN periods (pre-monsoon months), the high O_3/NO_2 ratios were due to the transport of photochemical pollutants from higher altitudes. The efficient vertical mixing with free tropospheric air increases O_3 in the pre-monsoon months. The enhanced SO_2/NO_2 indicates that the predominant source of SO_2 is coal-based thermal power plants. In other words, the site receives reasonably aged SO_2 from distant regions, resulting in high ratios (Mor et al., 2021).

Impact of Meteorology and Biomass Burning on Air Quality

In addition to the local emissions, the variation in ambient air pollutants can also be influenced by the local meteorology, transport, transformation, and scavenging by the precipitation (Sahu et al., 2016a,b, 2020; Yadav et al., 2019a,b). Therefore, the mean wind streamlines along with temperature and precipitation at 925 mb pressure level are used in the study to investigate any unusual changes in meteorological and transport processes during the COVID-19 LDN period. The comparison of meteorological parameters during 2020 and 2019 for the PRELD, COVID-19 LDN, and UCL periods is shown in **Figure 2**. The trends in wind speed, temperature, and precipitation indicate the different features during the entire study period due to the change of seasons from winter to pre-monsoon and then monsoon (Yadav et al., 2014a; Sahu et al., 2017). Hence, the trends of $PM_{2.5}$ and PM_{10} may also include a factor related to the change of meteorological conditions in the same year in comparison with the PRELD period. In the pre-monsoon season (LDN period), high temperatures, high wind speeds, and more profound boundary layer heights may lead to a higher dispersion of pollutants and lower concentrations (Sahu et al., 2020). However, the difference between 2019 and 2020 does not show significant fluctuations in wind speed, temperature, and precipitation in the western region of India during the PRELD to ULC periods. The mean surface temperatures and rainfall were in ranges of 30–32°C and 0–1.5 mm day^{-1} during the COVID-19 LDN period in the years 2019 and 2020 over the study region. The strong westerly wind prevails over the area during both years in the COVID-19 LDN period. In general, all meteorological parameters were, more or less, similar during the study period, especially in the COVID-19 lockdown period in 2019 and 2020. Several studies have reported that the meteorological parameters were identical in the previous years and 2020 during the COVID-19 LDN over the Indian region (Navinya et al., 2020; Sharma et al., 2020; Singh et al., 2020; Yadav et al., 2020). Additionally, in the pre-monsoon season, the local emissions become lesser, but outside contributions become more prominent due to the increased transport of regional air masses. Furthermore, ~7% open agricultural burning in this season is mainly due to the burning of residues from wheat crops. **Figure 3** shows MODIS-active fire maps over India during the entire study period for the years 2019 and 2020. In addition to this, to some extent, the SW winds also influenced the region after passing through populated areas of central India; they may get polluted during the pre-monsoon-to-monsoon transition period (Sahu et al., 2020; Maji et al., 2021; Yadav et al., 2021). The maps clearly show that the pre-monsoon fire events in 2020 during COVID-19 LDN have

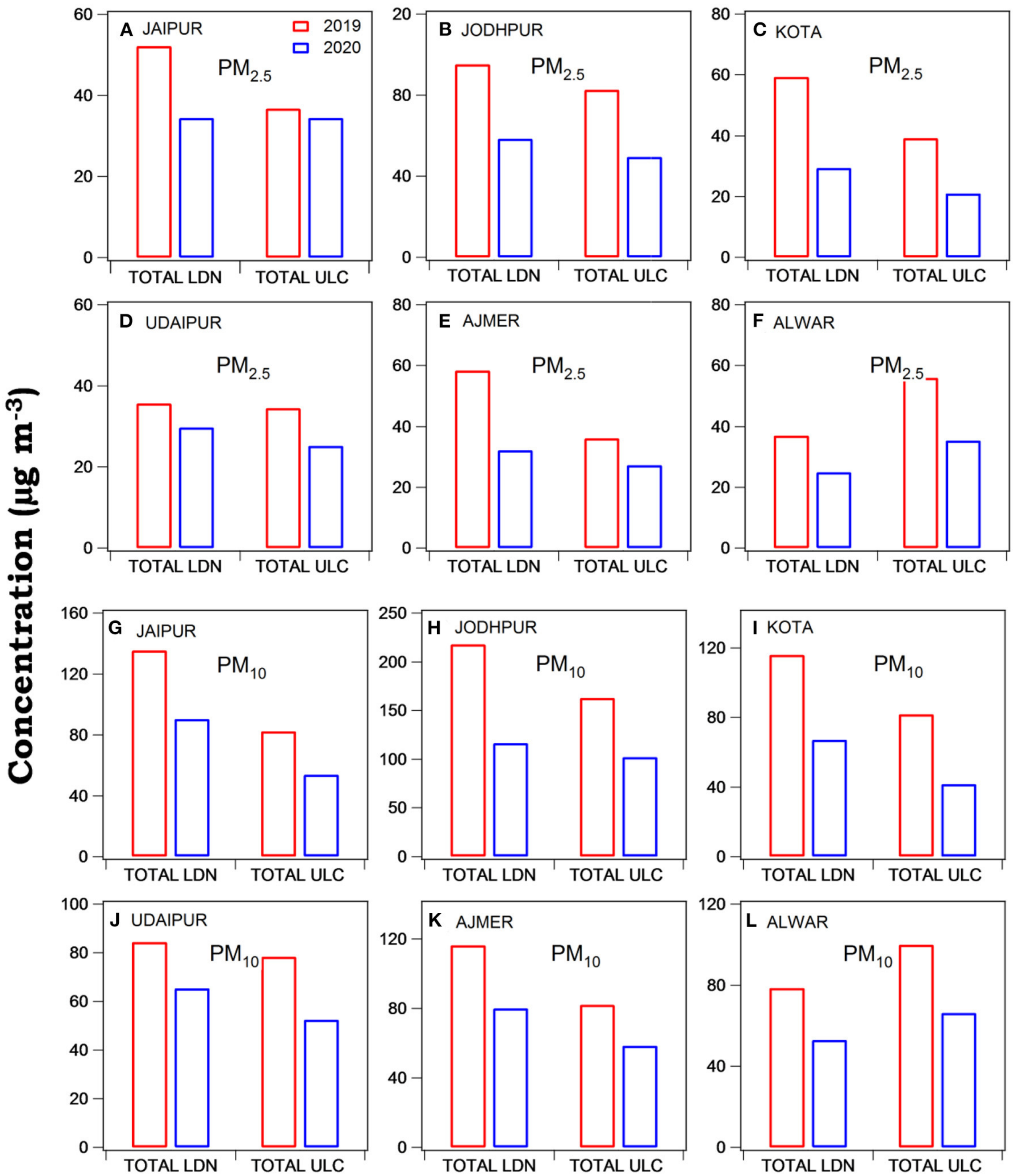

FIGURE 6 | Variations of $PM_{2.5}$ and PM_{10} in Jaipur, Jodhpur, Kota, Udaipur, Ajmer, and Alwar during COVID-19 lockdown and unlocking periods and a comparison to the same period of the previous year (2019).

somewhat decreased to a shallow level compared to those in 2019, especially in western, northern, and central India (Kant et al., bib2020), as biomass burning is a significant aerosol source. Overall, the reductions in fire events along with local emissions have also been deficient. Additionally, we have normalized the mass concentrations of $PM_{2.5}$ and PM_{10} with meteorology to investigate the actual change in emissions due to COVID-19 LDN. In the method, ventilation coefficient, a product of wind speed (WS) and boundary layer height (BLH), is used to see the role of weather dynamics for all cities of Rajasthan. The WS (above 10 m) and BLH datasets used in the study are from Copernicus Emergency Management Service (Climate Data Store) (https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset). The extensive details of normalizing the meteorological

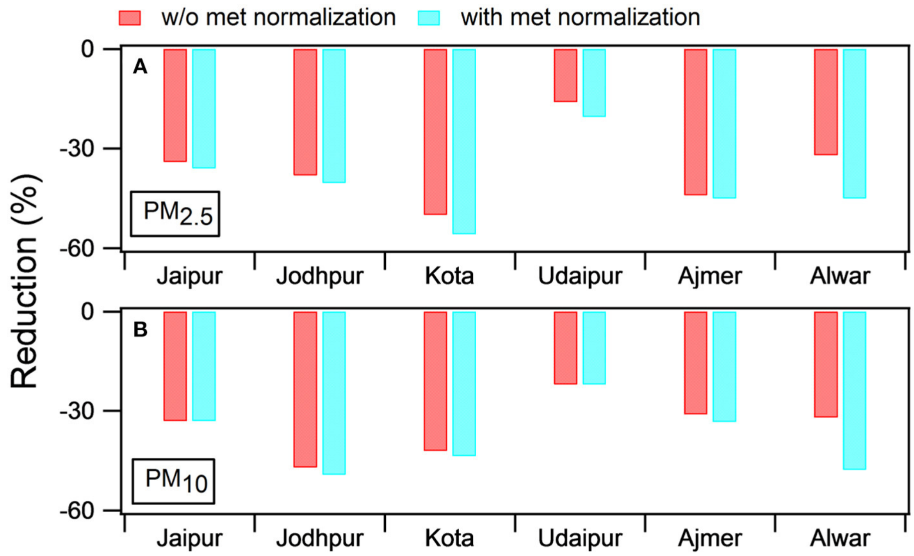

FIGURE 7 | Percentage reduction (without and with meteorology normalization) during the COVID-19 lockdown period in 2020 in all cities of Rajasthan with respect to the mean of the previous years for the same period.

effects on ambient pollutants are reported elsewhere (Dai et al., 2020; Falocchi et al., 2021; Mishra et al., 2021). The reductions in $PM_{2.5}$ and PM_{10} (with meteorology-normalized data) were in the ranges of 20–55 and 22–49% during the COVID-19 LDN period compared to the same period of 2019, as shown in **Figure 7**. Enhancement (differences ~10%) was observed in the reduction of $PM_{2.5}$ and PM_{10} (in meteorology-normalized data) compared to without meteorology-normalized data during the LDN period in all cities.

Air Quality Index in Rajasthan Cities

Air quality index is a tool for people to understand the air quality status in an easy way. This tool transforms the complex data of various pollutants into a single number (index value), classification, and color (Beig et al., 2010). AQI was calculated for all cities to identify the overall improvement in air quality, and the details of AQI are available elsewhere (CPCB, 2014). There are six AQI categories: good + satisfactory (0–100), moderately polluted (101–200), poor (201–200), very poor (301–400), and severe (401–500). We have converted the $PM_{2.5}$, PM_{10}, and SO_2 concentration values into AQI using typical values, as the minimum of three parameters was very much needed for the calculation. Therefore, only SO_2 concentration was used for the AQI analysis. Each category is decided based on the ambient concentration values of air pollutants and their likely health impacts known as health breakpoints. The AQ sub-index and breakpoint concentration of different pollutants are provided elsewhere (CPCB, 2014). **Figure 9** indicates the AQI variation during the entire study period over six cities. Overall, the AQI was satisfactory to moderately polluted categories during the whole study period (PRELD to ULC). The AQI varied in the ranges of 85–161 during PRELD in all cities, with the highest in Jaipur, Jodhpur, and Udaipur cities, during which the traffic was regular. Later, the AQI declined during various LDN periods compared to during PRELD in all cities, except Jaipur, Jodhpur, and Ajmer. More or less, in all cities, increasing values were seen during the subsequent LDN periods but with the highest of 117 in Jaipur, 174 in Jodhpur, and 121 in Ajmer. Overall, in LDN1 to LDN3, all cities were in satisfactory ranges, but Jaipur, Jodhpur, and Ajmer showed moderate air quality conditions in LDN4. Interestingly, Jodhpur City gets good air quality during the third phase of ULC since the LDN periods. It suggests that more contributions to coarser particles (PM_{10}) are wind-blown dust and dust storms and, of course, anthropogenic activities, which have been allowed with limitations in the subsequent LDNs.

CONCLUSIONS

We have investigated the trends of the daily mean concentrations of $PM_{2.5}$ and PM_{10} in six cities, including Jaipur, Jodhpur, Kota, Udaipur, Ajmer, and Alwar of Rajasthan in India. We have obtained the data from CPCB and analyzed it for the years 2019 and 2020 during eight specific months (January to August). The primary aim is to understand the role of unusually low anthropogenic emissions in ambient concentrations of particulate pollutants during the COVID-19 lockdown. The investigation combines the effects of local anthropogenic emissions, meteorology, and the transport of biomass burning in the variations of both pollutants. The $PM_{2.5}$ and PM_{10} concentrations were reduced significantly in all cities and met the national standards during the lockdown. However, in a few cities, like Jodhpur, Jaipur, and Ajmer, the PM_{10} levels have not fallen below the standard

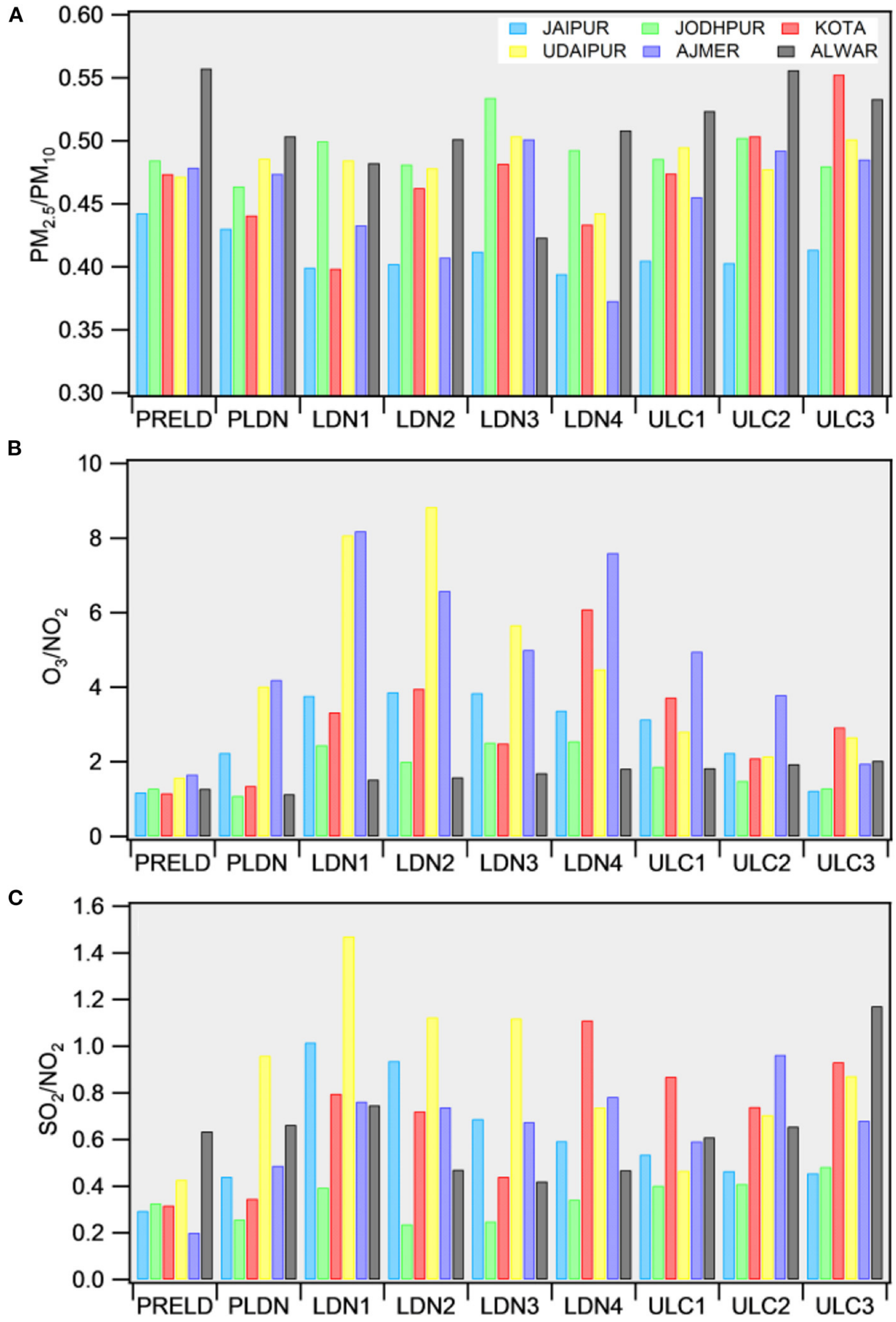

FIGURE 8 | $PM_{2.5}/PM_{10}$, O_2/NO_2 and SO_2/NO_2 ratios in six cities of Rajasthan during the different phases of the study.

limit (100 μg m^{-3}) most of the time during the COVID-19 LDN period due to non-combustion-related sources like wind-blown dust. The highest reduction in $PM_{2.5}$, by 47%, was observed in Alwar, followed by Udaipur (40%), Kota (36%), Jaipur (32%), and Ajmer (32%), while Jodhpur showed the lowest reduction of about 25% during the COVID-19 LDN, respectively. PM_{10} was reduced by 37 and 36% in Alwar and Udaipur. However, the lowest (19–30%) reductions were in Jaipur, Jodhpur, Kota, and Ajmer. More or less, there was 50% of $PM_{2.5}$ and PM_{10} in all cities due to higher temperatures during the COVID-19 LDN period (pre-monsoon months), supporting the uplifting of mineral and dust particles (PM10). In addition to the unusual local emissions, meteorological parameters, such as rainfall and movement of air masses, played a significant role in reducing the particle levels.

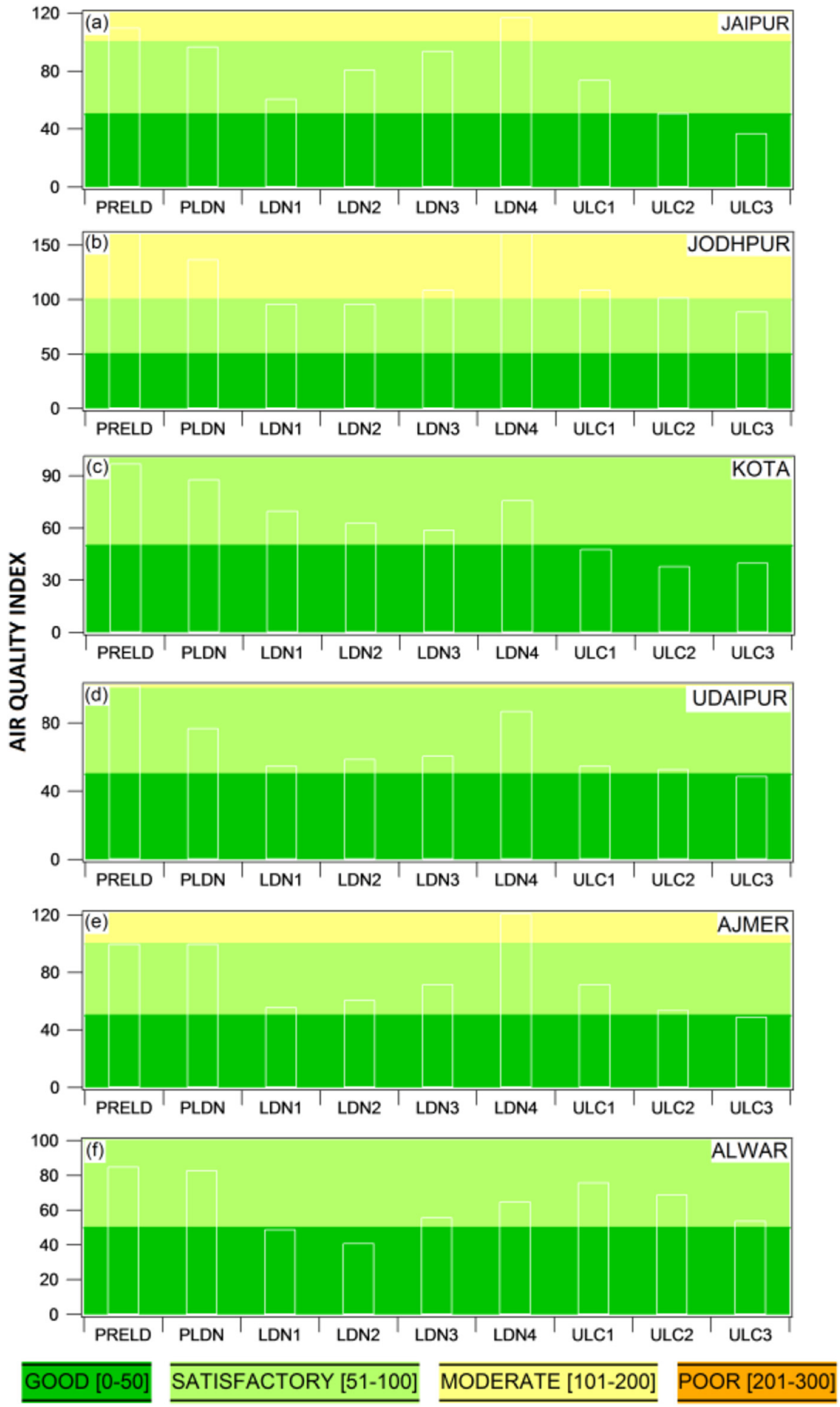

FIGURE 9 | Air quality index for major cities of Rajasthan during the study period in the year 2020.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This air quality data can be found form the CPCB (https://cpcb.nic.in/).

AUTHOR CONTRIBUTIONS

RY: conceptualization, software, and writing—original draft. PV: formal data analysis. PK and RY: data analysis. UP, PV, and VS: data collection. MG, PK, RY, and NT: methodology. PD, SJ, LS, GB, and DR: discussion. PD, SJ, LS, GB, DR, RY, PV, PK, UP, VS, MG, and NT: writing—review and editing. GB, RY, and LS: investigation. SJ, LS, and GB: visualization. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2022.792507/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.