



SPATIO-TEMPORAL VARIATION OF AMBIENT PARTICULATE MATTER POLLUTION IN RAJASTHAN FROM 2018 TO 2022

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ABSTRACT

In late 2019, World Health Organization (WHO) affirmed coronavirus disease (COVID-19), prompting global lockdowns. The present study assessed impact of lockdowns on fine ($PM_{2.5}$) and coarse (PM_{10}) particulate matter and compared them with unlock phases across major cities, Rajasthan. The air quality stations are established and monitored by the Central Pollution Control Board (CPCB), New Delhi, as part of National Ambient Air Quality Monitoring Series (NAAQMS). Spatio-temporal fluctuations in $PM_{2.5}$ and PM_{10} concentrations were analyzed during lockdown periods in 2020 and 2021, compared with corresponding periods of unlock phases in pre-lockdown (2019) and post-lockdown (2022). Results showed large $\rightarrow PM_{2.5}$ and PM_{10} reductions (by 15–64% approx.) during first lockdown in 2020, due to stringent nationwide restrictions. Whereas, second wave lockdown in 2021, characterized by more relaxed and less restrictions, showed comparatively lower $\rightarrow PM_{2.5}$ and PM_{10} reductions (approx. 7–33%). Hence, maximum reduction occurred during first wave 2020 when anthropogenic activities were most restricted compared to second wave lockdown due to liberation provided in second wave. Notably, during both lockdown periods, $PM_{2.5}$ and PM_{10} concentrations remained below the NAAQS thresholds of $60\mu g/m^3$ and $100\mu g/m^3$, based on 24-hour average, in all study locations. The study concludes that traffic restrictions and short-term lockdowns can mitigate particulate pollution. Policymakers can utilize the findings of this investigation to implement essential guidelines for mitigating air pollution emissions.

KEYWORDS: Air Pollution, Anthropogenic Emissions, COVID-19 Lockdown, Air Quality Improvement, Particulate Matter ($PM_{2.5}$, PM_{10}), Environmental Impact, Urban Air Pollution, Rajasthan

How to Cite:

Dr. Nataraja R, Kubra Siddiqha (2025), Spatio-Temporal Variation of Ambient Particulate Matter Pollution in Rajasthan From 2018 to 2022, International Educational Journal of Science & Engineering (IEJSE), Vol: 8, Issue: 10, 01-13

1. INTRODUCTION

Air pollution has increasingly emerged as serious global concern over last few decades in developing countries due to rapid urbanization, industrialization, traffic and population growth (Chen et al. 2018a, b; Kota et al. 2018; Mukherjee & Agrawal 2018). It poses severe and adverse impacts on air quality and human health risks worldwide, including in India (Chen et al. 2018a, b; Ghude et al. 2016). Particulate matter (PM) is a significant component of ambient air pollution, consisting heterogeneous mixture of solid and liquid particles

suspended in atmosphere, including organic compounds, inorganic, metallic elements, acidic species, soil particles, and dust (Dong et al. 2020). PM is classified as fine particles ($PM_{2.5}$, with diameters $\leq 2.5 \mu m$) and coarse particles (PM_{10} , with diameters $\leq 10 \mu m$), both used to assess air quality. Major $PM_{2.5}$ and PM_{10} sources include agricultural biomass and fossil fuel burning, road dust resuspension, vehicular emissions, industrial activities, and construction (Guo et al. 2019; Khaniabadi et al. 2017; Yadav et al. 2014). Road traffic and industrial activities are predominant contributors to both

PM_{2.5} and PM₁₀ (Guttikunda et al. 2019; Thorpe & Harrison, 2008). These emissions frequently exceed National Ambient Air Quality Standards (NAAQS) limits, causing severe environmental and human health risks (Almetwally et al. 2020; Chai et al. 2019; Jain & Mandowara, 2019; Kermani et al. 2022; WHO, 2018). These health outcomes underscore the need for enhanced air quality monitoring and regulatory interventions to mitigate air pollution.

During COVID-19 lockdown, restrictions on human activities led to a decline in anthropogenic PM_{2.5} and PM₁₀ emissions, resulting in positive environmental impacts (Agarwal et al. 2020; Srivastava et al. 2020). COVID-19, caused by SARS-CoV-2, rapidly escalated into a global health crisis with symptoms like fever, dry cough, dyspnea, respiratory complications, and, in severe cases, multiorgan failure, resulting in death outcomes (Chen et al. 2020; Guo et al. 2019; Lauer et al. 2020; Sohrabi et al. 2020). By 31st May 2020, over 6.24 million cases and 379,369 deaths were reported worldwide (Cortegiani et al. 2020), including 190,648 cases and 2,286 deaths in India (<https://www.covid19india.org/>). Due to this World Health Organization (WHO) declared COVID-19 a “global pandemic” on 11th March 2020, implemented global lockdowns to reduce human mobility and break the transmission chain (WHO, 2020). Following these guidelines, numerous countries imposed strict lockdowns by the end of March 2020. In alignment with these directives, government of India implemented nationwide lockdown across states starting on 23 March 2020 to 31st May 2020 (Saha et al. 2020; The Hindu, 2020a, b), including Rajasthan (Ministry of Home Affairs, 2020). Amidst this nationwide lockdown in 2020, strict restrictions on commercial, industrial, transportation sectors, businesses, restaurants, and institutions led to significant reduction in anthropogenic activities, resulting in improved air quality (Business Standard, 2020; Hu et al. 2021; Mahato et al. 2020; Ministry of Home Affairs, 2020). In contrast, the partial lockdown during second wave in 2021 imposed less restrictions, causing higher pollution levels than in 2020 but still lower than pre- and post-lockdown levels (Government of Rajasthan, 2021; Mahato & Pali, 2022; Nandhini et al. 2022; Saharan et al. 2022). Because pre- and post-lockdown still experience heavy air pollution levels arising from transportation,

industrial activities, and other various routine activities, resulting in deterioration of air quality (Barupal et al. 2022; Nigam et al. 2021; Ruhela et al. 2022). Overall, complete (2020) and partial (2021) lockdown phases led to decrease in anthropogenic emissions result in discernible enhancement in air quality across India and globally, with notable declines in PM_{2.5} and PM₁₀ concentrations in several cities (Bao & Zhang, 2020; Business Standard, 2020; Chauhan & Singh, 2020; Pratap et al. 2021).

Previous studies on assessing air pollution have revealed a few noteworthy research gaps. First, Rajasthan State Pollution Control Board (RSPCB) reported a 40–50% reduction in air pollutant levels during lockdown (Sharma et al. 2020a), but over a limited period. Second, most studies focused on the first wave, with little attention to the second wave. Third, comparative assessment of PM_{2.5} and PM₁₀ between the two waves in Rajasthan has not been done yet. This study addresses these gaps by analyzing spatiotemporal variations in PM_{2.5} and PM₁₀ during 2020 (24 March–31 May) and 2021 (19 April–24 May) lockdowns, compared with identical periods of pre-lockdown (2019) and post-lockdown (2022) across selected sites of Rajasthan (Table 1), and possible reasons for these changes were investigated. Results revealed significant reductions in PM concentrations during both lockdowns, indicating short-term lockdowns can improve urban air quality and provide public health benefits.

2. DATA SOURCES AND METHODOLOGY

To examine the fluctuation in air pollution levels during the first and second waves of lockdown, we collected data of ambient PM_{2.5} and PM₁₀. Continuous ambient air quality data were gathered from eight selected ambient air quality monitoring stations operating by RSPCB, located in Ajmer (site-1), Alwar (site-2), Bhiwadi (site-3), Jaipur (site-4), Jodhpur (site-5), Kota (site-6), Pali (site-7), and Udaipur (site-8). The geographical distribution of these cities of Rajasthan was mapped using ArcGIS software in Fig. 1. Collected data across three comparative periods: pre-lockdown (2019), during lockdown (2020 and 2021), and post-lockdown (2022), to evaluate variations in pollutant concentrations. Daily or hourly average PM_{2.5} and PM₁₀ have been obtained from Central Pollution Control Board,

New Delhi (CPCB), through its online database air quality monitoring portal (CPCB, 2020). It provides data quality guarantee through accurate sampling, analysis, and calibration procedures.

2.1 Study area and lockdown scenario

The largest state of India i.e., Rajasthan, covers area of 342,239 square kilometers or 10.4 % of total geographical area of India, has 33 districts, and is ranked seventh in terms of population approx. 68,548,437 according to the 2011 census (<https://www.censusindia.co.in/states/rajasthan>). Rajasthan has a prosperous history and rich culture heritage, famous for its majestic beautiful forts, beautiful decorative Havelis, and ornamented temples. Jaipur is the capital of Rajasthan and was the planned city of its time known as 'Pink City' which was built by Sawai Jai Singh-II. Jaipur is well known for its history, attractive monuments, luxurious hotels, parks, and forts making it a tourist paradise. Unplanned urbanization and rapid industrial growth in Rajasthan have significantly transformed agricultural and wastelands into urban areas. At present, the area of the developing cities may broadly be categorized as residential, commercial, and transportation. The geographical features of Rajasthan include the Aravalli Range. Rajasthan lies in northwestern part of India, which has a warm, dry, semiarid climate,

famous as the "Thar Desert". The prominent districts of Rajasthan (Ajmer, Alwar, Bhiwadi, Jaipur, Jodhpur, Kota, Pali, and Udaipur) have monitoring stations to measure the ambient air quality. Rajasthan has a hot semi-arid climate, and has a dry climate with scorching summers, cold winters, and short-lived monsoon season. The geographical position of eight major cities of Rajasthan is Jaipur ($26^{\circ}55'19.4520''\text{N}$, $75^{\circ}46'43.9860''\text{E}$) forms east-central part, and is situated at altitude distance from the ground of 431m above sea level, Ajmer ($26^{\circ}26'59.6256''\text{N}$, $74^{\circ}38'23.6940''\text{E}$) western part of Rajasthan; Alwar ($27^{\circ}33'39.3552''\text{N}$, $76^{\circ}37'30.0540''\text{E}$) northern part of Rajasthan, Bhiwadi ($28^{\circ}12'36.87''\text{N}$ $76^{\circ}51'38.03''\text{E}$), Jodhpur ($26^{\circ}14'20.2100''\text{N}$, $73^{\circ}01'27.5100''\text{E}$), Udaipur ($23^{\circ}32'09.6800''\text{N}$, $71^{\circ}29'13.1500''\text{E}$) located in the southernmost part of Rajasthan, Pali ($25^{\circ}46'16.7340''\text{N}$, $73^{\circ}19'25.2660''\text{E}$) 70 km southeast of Jodhpur; Kota ($25^{\circ}09'46.7928''\text{N}$, $75^{\circ}50'43.1592''\text{E}$) northern part Rajasthan (Fig. 1). Our study was conducted in these eight major cities of Rajasthan, and selected them based on the availability of secondary data, geographical features, urbanization, and variable pollution levels, which give comprehensive understanding of air pollution concentration levels in major urban centers of Rajasthan.

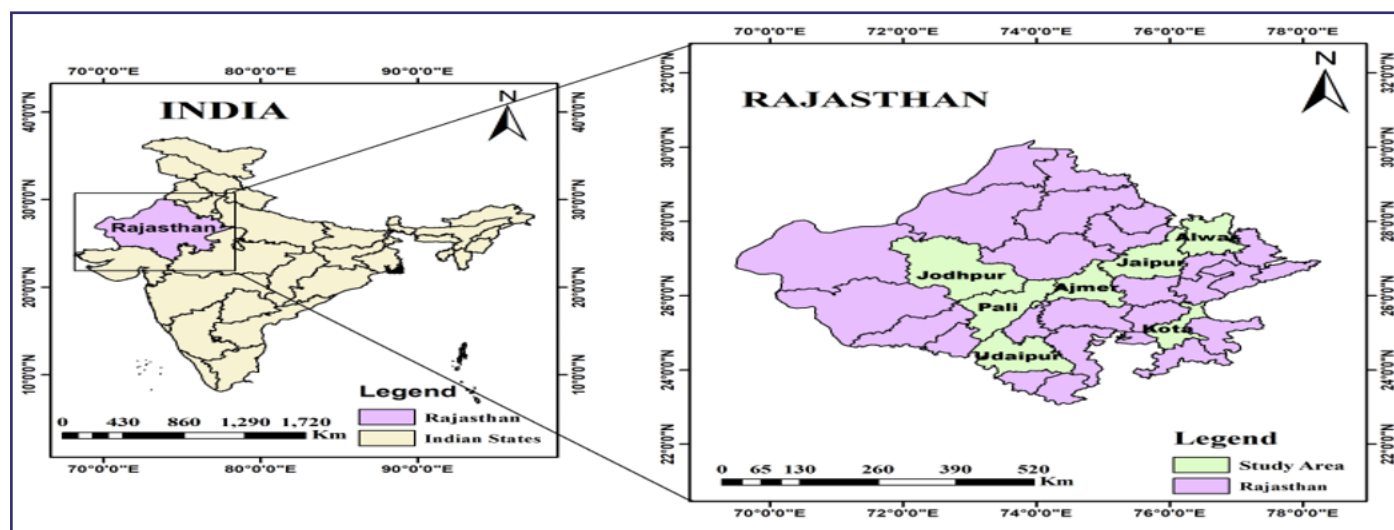


Fig. 1. The air quality monitoring station in Rajasthan state, India

To explore impacts of several restrictions on Rajasthan's air quality, we categorize our observations into pre-lockdown, lockdown, and post-lockdown phases:

- 1st wave of COVID-19 lockdown duration comparison.
 1. Unlock pre-lockdown phases: 24th March 2019 to 31st May 2019.
 2. During lockdown phases: 24th March 2020 to 31st May 2020.
 3. Unlock post-lockdown phases: 24th March 2022 to 31st May 2022.
- 2nd wave COVID-19 lockdown duration comparison.
 4. Unlock pre-lockdown phases: 19th April 2019 to 24th May 2019.
 5. During lockdown phases: 19th April 2021 to 24th May 2021.
 6. Unlock post-lockdown phases: 19th April 2022 to 24th May 2022.

Table 1. Phases of lockdown durations during 2020 (1st wave) and 2021 (2nd wave) of the COVID-19 pandemic in Rajasthan, India.

Year	Lockdown phases	Date	Duration
2020	Phase 1	24 Mar to 14 Apr	22
	Phase 2	15 Apr to 3 May	19
	Phase 3	4 May to 17 May	14
	24 Mar to 14 Apr	18 May to 31 May	14
2021	Phase 5	19 Apr to 3 May	15
	Phase 6	10 May to 24 May	15

Sources: <https://www.mha.gov.in/notifications/circulars-covid-19>, Ministry of Home Affairs, 2020; Government of Rajasthan, 2021; The Economic Times, 2021; The Indian Express, 2021

3. RESULTS AND DISCUSSION

To evaluate spatiotemporal fluctuations in average PM_{2.5} and PM₁₀ concentrations during the first and second waves of lockdown: pre-lockdown (2019), lockdown (2020 and 2021), and post-lockdown (2022) were analyzed (Figs. 2, 3, and Tables 2,

3). Furthermore, we conducted a comparative assessment of pollutant concentrations obtained between the first (2020) and second (2021) lockdown phases (Fig. 4 and Table 4).

3.1 Effect of lockdown wave-1 on air quality by PM_{2.5} and PM₁₀ in different cities of Rajasthan

The first wave of COVID-19 lockdown (2020) had a noticeable impact on air pollution levels across various cities in Rajasthan. By looking at the data from 2019 (pre-lockdown), during 2020 (lockdown), and 2022 (post-lockdown), we can see how air pollutants (PM_{2.5} and PM₁₀) levels changed in eight selected Rajasthan cities in four phases of the first lockdown in 2020, as recorded in Fig. 2 and Table 2.

3.1.1 City-wise analysis of PM_{2.5} variations in major cities of Rajasthan

Ajmer experienced a significant decline (46.30%) in PM_{2.5} concentration during lockdown, dropping from 57.52 µg/m³ in 2019 to 30.88 µg/m³ in 2020. However, in post-lockdown (2022), concentration sharply increased to 64.20 µg/m³, showing a 51.89% rise compared to the lockdown phase, and exceeding pre-lockdown levels. In Alwar, PM_{2.5} reduced drastically by 49.46% during lockdown (from 49.89 µg/m³ in 2019 to 25.21 µg/m³ in 2020). Following the lockdown, concentration increased to 44.17 µg/m³ in 2022, representing a 42.91% rise from 2020. Bhiwadi, an industrial hub, recorded one of the highest PM_{2.5} (108.57 µg/m³ in 2019). During lockdown, concentrations nearly halved to 54.10 µg/m³, showing a 50.16% reduction. However, in 2022, PM_{2.5} escalated sharply to 137.05 µg/m³, a 60.52% increase compared to lockdown, even exceeding pre-lockdown levels. Jaipur's PM_{2.5} dropped moderately, with 21.98% from 43.87 µg/m³ in 2019 to 34.22 µg/m³ in 2020. However, in 2022, PM_{2.5} surged to 72.44 µg/m³, reflecting a 52.77% increase over lockdown concentrations, highest rebound among the cities. Jodhpur recorded a substantial decline (47.32%) during lockdown, with PM_{2.5} reducing from 105.99 µg/m³ in 2019 to 55.83 µg/m³ in 2020. Post-lockdown, levels rose to 93.89 µg/m³ in 2022, showing a 40.53% increase over lockdown, yet remaining slightly below pre-lockdown values. Kota observed a sharp decrease (49.39%) in PM_{2.5} during lockdown, falling from 58.51 µg/m³ in 2019 to 29.61 µg/m³ in 2020. In post-lockdown, concentrations escalated to 74.57 µg/m³.

m^3 , showing a 60.29% increase over lockdown and exceeding pre-lockdown levels. Pali exhibited highest reduction (63.74%) in $\text{PM}_{2.5}$ during lockdown, from $105.98 \mu\text{g}/\text{m}^3$ in 2019 to $38.43 \mu\text{g}/\text{m}^3$ in 2020. However, $\text{PM}_{2.5}$ rebounded to $70.72 \mu\text{g}/\text{m}^3$ in 2022, marking a 45.66% increase over lockdown, but still below pre-lockdown levels. Udaipur recorded lowest reduction among all cities (15.69%), with $\text{PM}_{2.5}$ only slightly dropping from $35.00 \mu\text{g}/\text{m}^3$ in 2019 to $29.51 \mu\text{g}/\text{m}^3$ in 2020. By 2022, concentrations increased sharply to $64.03 \mu\text{g}/\text{m}^3$, representing a 53.91% rise over lockdown and nearly doubling pre-lockdown levels and exceeding pre-lockdown levels.

3.1.2 City-wise analysis of PM_{10} variations in major cities of Rajasthan

In Ajmer, PM_{10} concentration declined by 35.17% during lockdown, dropping from $120.31 \mu\text{g}/\text{m}^3$ in 2019 to $78.00 \mu\text{g}/\text{m}^3$ in 2020. However, in 2022, PM_{10} rebounded to $140.99 \mu\text{g}/\text{m}^3$, a 44.65% increase compared to lockdown, exceeding pre-lockdown levels. Alwar experienced a 51.32% reduction in PM_{10} during lockdown (from $109.85 \mu\text{g}/\text{m}^3$ in 2019 to $53.48 \mu\text{g}/\text{m}^3$ in 2020). By 2022, concentrations increased again to $111.80 \mu\text{g}/\text{m}^3$, reflecting a 52.16% increase compared to lockdown and slightly exceeding pre-lockdown levels. Bhiwadi, heavily industrialized region, had highest PM_{10} ($260.97 \mu\text{g}/\text{m}^3$ in 2019). Lockdown measures reduced concentrations sharply by $112.09 \mu\text{g}/\text{m}^3$, resulting in a 57.06% reduction. However, in 2022, PM_{10} increased drastically to $274.27 \mu\text{g}/\text{m}^3$, marking 59.15% increase compared to lockdown and even exceeding pre-lockdown levels. Jaipur recorded a 35.56% decrease in PM_{10} during lockdown (from $135.46 \mu\text{g}/\text{m}^3$ in 2019 to $87.30 \mu\text{g}/\text{m}^3$ in 2020). However, in 2022, concentrations increased to $167.12 \mu\text{g}/\text{m}^3$, showing a 47.75% rise over lockdown and exceeding pre-lockdown values. In Jodhpur, PM_{10} decreased by 49.02% during lockdown, from $223.70 \mu\text{g}/\text{m}^3$ in 2019 to $114.03 \mu\text{g}/\text{m}^3$ in 2020. By 2022, concentrations increased to $211.60 \mu\text{g}/\text{m}^3$, a 46.09% rise over lockdown levels. Kota exhibited a 41.47% reduction in PM_{10} during lockdown (from $115.88 \mu\text{g}/\text{m}^3$ in 2019 to $67.82 \mu\text{g}/\text{m}^3$ in 2020). In post-lockdown, PM_{10} increased to $158.29 \mu\text{g}/\text{m}^3$ in 2022, a 57.15% increase compared to lockdown, exceeding pre-lockdown levels. Pali's PM_{10} concentrations declined by 38.73% during lockdown (from $153.00 \mu\text{g}/\text{m}^3$ in 2019 to $93.74 \mu\text{g}/\text{m}^3$ in 2020).

In 2022, PM_{10} increased to $152.23 \mu\text{g}/\text{m}^3$, marking a 38.43% rise compared to lockdown. Udaipur recorded smallest decline in PM_{10} during lockdown (23.97%), dropping from $84.67 \mu\text{g}/\text{m}^3$ in 2019 to $64.35 \mu\text{g}/\text{m}^3$ in 2020. By 2022, however, PM_{10} surged to $153.46 \mu\text{g}/\text{m}^3$, representing a 58.07% increase compared to lockdown.

Therefore, concentration levels and percentage change in $\text{PM}_{2.5}$ and PM_{10} was established to be drastically declined over each monitored station during lockdown (2020) might initially had positive impact on air quality due to lower industrial and traffic emissions as compared with similar periods 2019 (pre-lockdown) and 2022 (post-lockdown), due to pollution sources existence as depicted in Fig. 2 and Table 2, respectively. Several comprehensive studies have investigated spatiotemporal variations of $\text{PM}_{2.5}$ and PM_{10} worldwide, with significant reductions observed during lockdown measures (Krecl et al. 2020; Mahato et al. 2020; Sahoo et al. 2021; Sharma et al. 2020; Singh & Chauhan, 2020; Tobías et al. 2020; Xu et al. 2020). In China, significant drops in $\text{PM}_{2.5}$ and PM_{10} were reported, up to 30.1% and 40.5% in major cities, following the implementation of lockdown measures (Xu et al. 2020). Another investigation conducted in 44 Chinese cities during lockdown observed falls in $\text{PM}_{2.5}$ (5.9%) and PM_{10} (13.6%) (Bao & Zhang, 2020). Similar outcomes were detected in metropolitan regions of Spain, Brazil, and Morocco (Dantas et al. 2020; Otmani et al. 2020; Tobías et al. 2020). In India, multiple investigations reported noteworthy reductions of approximately 40%–60% in $\text{PM}_{2.5}$ and PM_{10} within major urban centers throughout lockdown periods (Jain & Sharma, 2020; Mahato & Ghosh, 2020; Mahato et al. 2020; Sharma et al. 2020b; Singh & Chauhan, 2020; Singh et al. 2020). Gujarat, a prominent industrialized state, detected a notable decline in air pollutants during lockdown, primarily attributed to imposed traffic restrictions and slowdown of industrial activities (Nigam et al. 2021). Decrease in $\text{PM}_{2.5}$ and PM_{10} concentrations across multiple zones in Gujarat during lockdown as compared with pre-lockdown. In Zone 1 (Surat, Ankleshwar, Vadodara), $\text{PM}_{2.5}$ and PM_{10} decreased by 51% and 48%, respectively; in Zone 2 (Ahmedabad, Gandhinagar), reductions were 34% ($\text{PM}_{2.5}$) and 47% (PM_{10}); Zone 3 (Jamnagar, Rajkot) exhibited the highest reductions with 78% ($\text{PM}_{2.5}$) and 80%

(PM₁₀); and in Zone 4 (Bhuj, Palanpur), PM_{2.5} and PM₁₀ declined by 38% and 32%, respectively (Selvam et al. 2020). Similarly, at Peenya industrial monitoring station in Bengaluru, PM_{2.5} and PM₁₀ levels declined during lockdown phases but again started increasing gradually with easing of restrictions during unlock period (Navasakthi et al. 2023). During lockdown, drops PM₁₀ concentrations ranged from 34.18 to 64.42 µg/m³, and increased to 24.47–118.25 µg/m³ during unlock period. PM_{2.5} concentrations ranged from 30.12–42.49 µg/m³ during lockdown and observed extremes of 14.82–63.67 µg/m³ during unlock periods. This dropped in PM_{2.5} and PM₁₀

during lockdown was primarily attributed to vehicle and industrial restrictions (Jain & Sharma, 2020). As restrictions were being removed gradually during successive unlock phases, a corresponding rise in PM_{2.5} and PM₁₀ levels was observed. These findings are consistent with several global investigations that recorded drop in PM_{2.5} and PM₁₀ during first wave lockdown, as compared with unlock pre- and post-lockdown phases (Bhatti et al. 2022a, b; Chauhan & Singh, 2020; Dangayach et al. 2023; Das et al. 2021; Hasnain et al. 2021; Jain & Sharma, 2020; Navasakthi et al. 2023; Patel & Singh, 2023; Sahoo et al. 2021; Selvam et al. 2020; Wang et al. 2020; Xu et al. 2020).

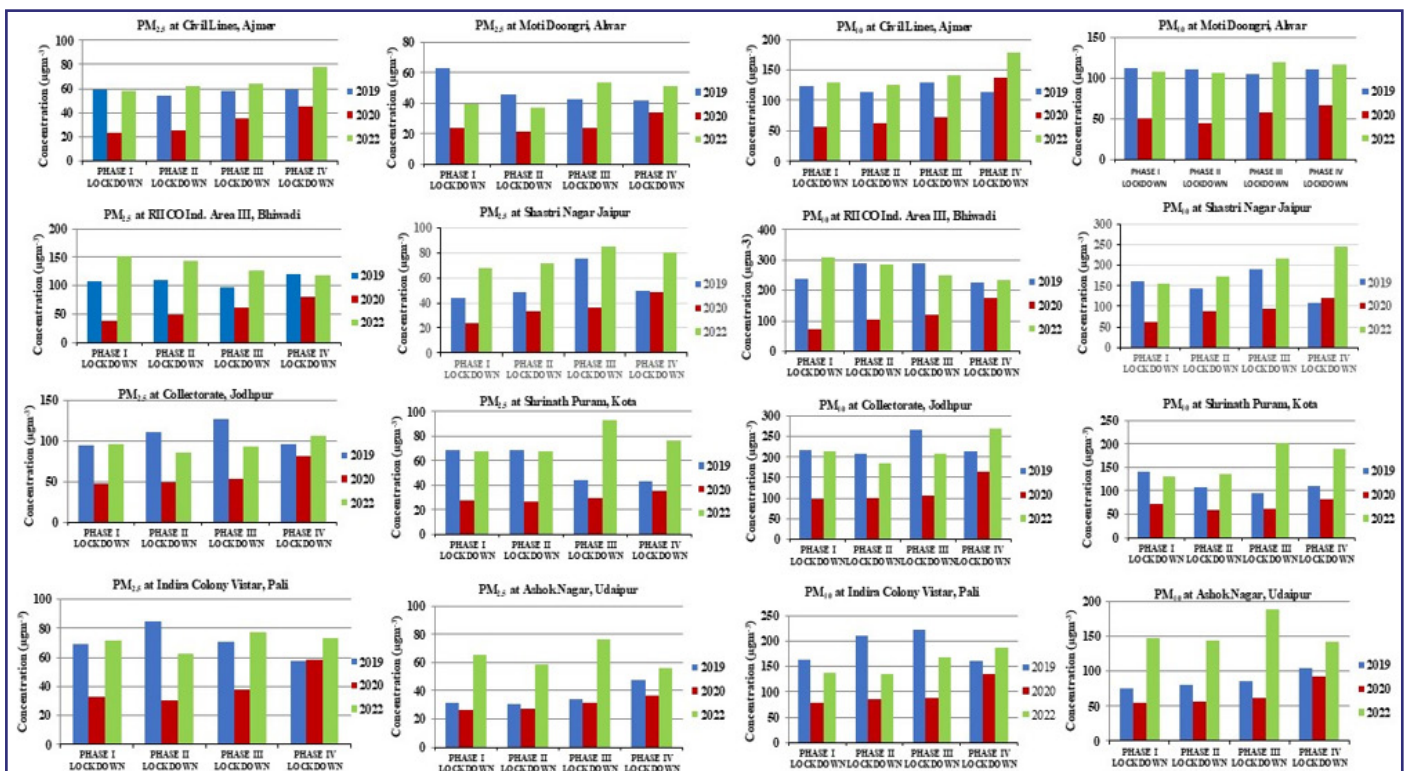


Fig. 2. Particulate matter (PM_{2.5} and PM₁₀) in various preferred cities of Rajasthan before, during, and after lockdown (first wave of COVID-19)

Table 2: Percentage change in the PM_{2.5} and PM₁₀ of preferred cities in Rajasthan, before (2019), during (2020), and after lockdown (2022) amid COVID-19 (average of the four phases of lockdown from 24th March to 31st May 2020).

Cities	Percentage change in PM _{2.5} (Before lockdown)	Percentage change in PM _{2.5} (After lockdown)	Percentage change in PM ₁₀ (Before lockdown)	Percentage change in PM ₁₀ (After lockdown)
Ajmer	–46.30%	51.89%	–35.17%	44.65%
Alwar	–49.46%	42.91%	–51.32%	52.16%
Bhiwadi	–50.16%	60.52%	–57.06%	59.15%
Jaipur	–21.98%	52.77%	–35.56%	47.75%

Jodhpur	-47.32%	40.53%	-49.02%	46.09%
Kota	-49.39%	60.29%	-41.47%	57.15%
Pali	-63.74%	45.66%	-38.73%	38.43%
Udaipur	-15.69%	53.91%	-23.97%	58.07%

3.2 Effect of lockdown wave-2 on air quality by PM_{2.5} and PM₁₀ in different cities of Rajasthan

The second surge of COVID-19 lockdown (2021) had a noticeable impact on air pollution levels across various cities in Rajasthan. By looking at the data from 2019 (pre-lockdown), during 2021 (partial lockdown), and 2022 (post-lockdown), we can see how air pollutants (PM_{2.5} and PM₁₀) levels changed in eight selected Rajasthan cities in two phases of the second lockdown in 2021, as recorded in Fig. 3 and Table 3.

3.2.1 City-wise analysis of PM_{2.5} variations in major cities of Rajasthan

In Ajmer, PM_{2.5} concentrations decreased from 58.35 µg/m³ (2019) to 43.15 µg/m³ (2021), showing a reduction of 26.05%. However, post-lockdown, concentration increased to 68.49 µg/m³, representing a sharp rise of 36.99% compared to lockdown levels. In Alwar, the concentration reduced from 42.20 µg/m³ (2019) to 34.43 µg/m³ (2021), a decline of 18.41%. In 2022, PM_{2.5} reached 47.05 µg/m³, marking a significant increase of 26.83% compared to lockdown. Bhiwadi, pre-lockdown values (108.27 µg/m³) increased to 116.16 µg/m³ during lockdown, an increase of 7.28%, and further increased to 139.78 µg/m³ post-lockdown, showing a rise of 16.90% from lockdown. In Jaipur, PM_{2.5} declined from 58.78 µg/m³ in 2019 to 44.49 µg/m³ in 2021, a reduction of 24.35%. However, levels increased after restrictions, reaching 78.23 µg/m³, a sharp increase of 43.16%. Jodhpur recorded the largest PM_{2.5} reduction during lockdown, dropping from 101.28 µg/m³ in 2019 to 73.13 µg/m³ in 2021, a reduction of 27.80%. Post-lockdown, PM_{2.5} increased to 92.45 µg/m³, showing a rise of 20.88%, but remained lower than pre-lockdown values. In Kota, concentrations decreased slightly from 57.45 µg/m³ (2019) to 50.99 µg/m³ (2021), equivalent to a 11.25% reduction. After lockdown, levels spiked to 77.08 µg/m³, showing a rise of 33.85%. Pali recorded 68.28 µg/m³ in 2019, which decreased to 59.75 µg/m³ during lockdown, corresponding to a 12.48% reduction. Post-lockdown, PM_{2.5} levels increased to 69.12 µg/m³, an increase

of 13.55%. In Udaipur, concentrations increased during lockdown from 34.14 µg/m³ (2019) to 41.26 µg/m³ (2021), a rise of 20.85%. Post-lockdown, concentrations further increased to 66.65 µg/m³ an increase of 38.09%, respectively.

3.2.2 City-wise analysis of PM₁₀ variations in major cities of Rajasthan

In Ajmer, PM₁₀ concentrations decreased from 124.22 µg/m³ before lockdown to 98.14 µg/m³ during lockdown, reflecting a reduction of 21.03%. Post-lockdown, concentrations increased to 154.94 µg/m³, showing an increase of 36.64% relative to lockdown levels. Alwar exhibited a substantial decline in PM₁₀ from 103.94 µg/m³ to 72.64 µg/m³ during lockdown, representing a reduction of 30.16%. Post-lockdown, concentration increased sharply to 114.82 µg/m³, an increase of 36.75% from lockdown. In Bhiwadi, the PM₁₀ concentration decreased slightly from 254.21 µg/m³ before lockdown to 232.02 µg/m³ during lockdown, a reduction of 8.73%. Post-lockdown, concentrations increased to 271.93 µg/m³, indicating an increase of 14.67%. Jaipur experienced a significant improvement during lockdown, with PM₁₀ decreasing from 152.89 µg/m³ to 103.55 µg/m³, a reduction of 32.27%. However, post-lockdown, PM₁₀ enhanced to 200.47 µg/m³, an increase of 48.37% from lockdown. Jodhpur recorded a decrease in PM₁₀ from 219.50 µg/m³ to 169.11 µg/m³ during lockdown, a 22.97% reduction. After lockdown, concentrations increased to 210.30 µg/m³, representing an increase of 19.60%. In Kota, concentrations showed only a slight decrease during lockdown, from 109.38 µg/m³ to 101.64 µg/m³, a reduction of 7.11%. After restrictions were lifted, PM₁₀ increased substantially to 179.94 µg/m³, an increase of 43.51%. Pali experienced a reduction from 181.61 µg/m³ to 139.33 µg/m³ during lockdown, a 23.23% percent decrease, followed by a post-lockdown rise to 166.47 µg/m³, an increase of 16.28%. Interestingly, Udaipur showed an increase in PM₁₀ during lockdown, from 84.34 µg/m³ to 100.60 µg/m³, a rise of 19.29%. After lockdown, concentrations further increased to 166.96 µg/m³, showing a 39.71% increase relative to lockdown.

Decreased and increased $PM_{2.5}$ and PM_{10} concentration and percentage levels were observed during the partial lockdown, due to a decrease and increase in anthropogenic emission sources, such as vehicle traffic movement, and resumption of industrial activities. Therefore, throughout partial lockdown phases from April 19th to May 24th 2021, significant reductions in average $PM_{2.5}$ and PM_{10} concentrations were observed across several cities in Rajasthan, as depicted in Fig. 3 and Table 3, respectively. Consistent with first wave, second wave lockdown also demonstrated notable reductions in

$PM_{2.5}$ and PM_{10} during both complete lockdowns in 2020 and partial lockdowns in 2021, when compared with pre-lockdown (2019) and post-lockdown (2022) across various regions (Akan & Coccia, 2022; Macías-Hernández & Tello-Leal, 2022; Sharma et al. 2022; Sundarakumar et al. 2022). The present study observed consistent trends during first and second waves, with $PM_{2.5}$ and PM_{10} reductions aligning with earlier investigations (Figs. 2, 3; Tables 2, 3) (Aswin et al. 2023; Kolluru et al. 2021; Kolluru et al. 2023; Mahato et al. 2020; Sahoo et al. 2021; Sharma et al. 2020a, b; Shukla et al. 2021).

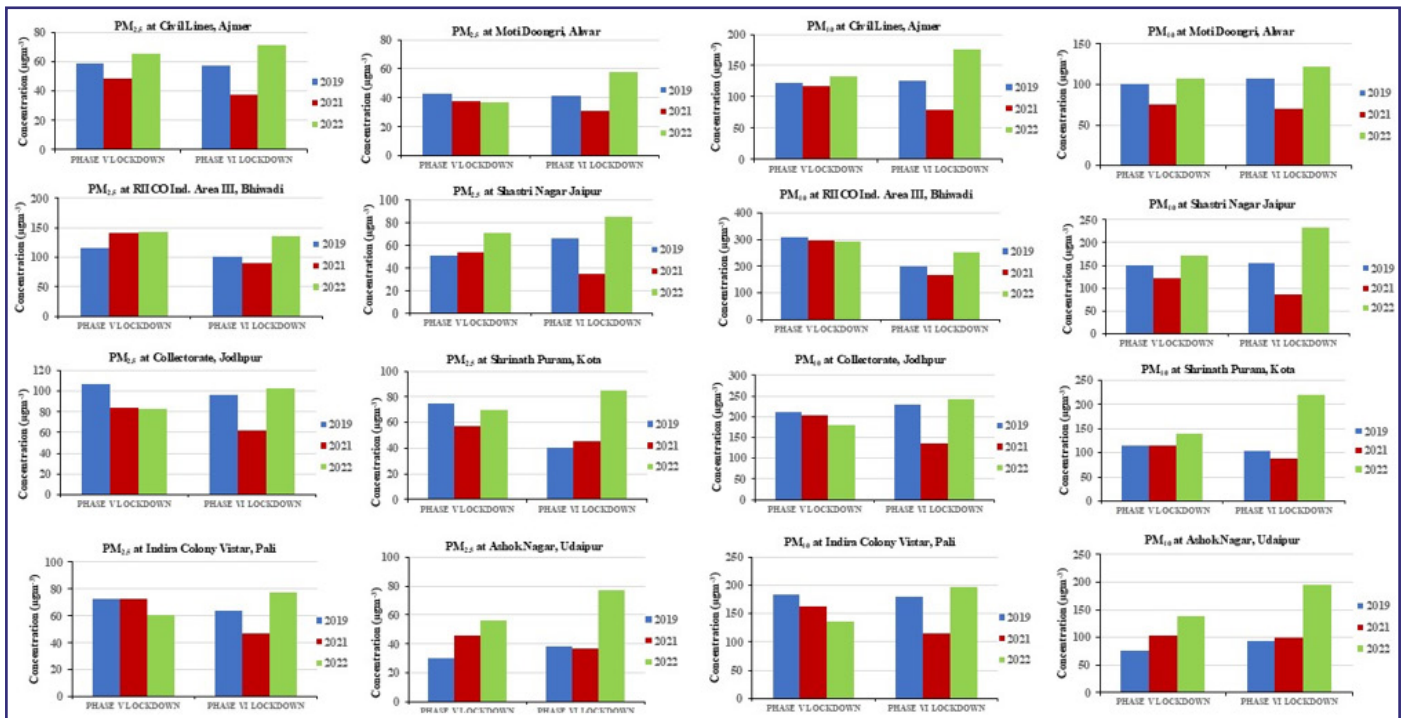


Fig. 3. Particulate matter ($PM_{2.5}$ and PM_{10}) in various preferred cities of Rajasthan before, during, and after lockdown (second wave of COVID-19)

Table 3. Percentage of change in the $PM_{2.5}$ and PM_{10} of preferred cities in Rajasthan, before (2019), during (2021), and after lockdown (2022) amid COVID-19 (average of the two phases of lockdown from 19th April to 24th May 2021)

Cities	Percentage change in $PM_{2.5}$ (Before lockdown)	Percentage change in $PM_{2.5}$ (After lockdown)	Percentage change in PM_{10} (Before lockdown)	Percentage change in PM_{10} (After lockdown)
Ajmer	-26.05%	36.99%	-21.03%	36.64%
Alwar	-18.41%	26.83%	-30.16%	36.75%
Bhiwadi	7.28%	16.90%	-8.73%	14.67%
Jaipur	-24.35%	43.16%	-32.27%	48.37%
Jodhpur	-27.80%	20.88%	-22.97%	19.60%
Kota	-11.25%	33.85%	-7.11%	43.51%
Pali	-12.48%	13.55%	-23.23%	16.28%
Udaipur	20.85%	38.09%	19.29%	39.71%

3.3. Cumulative Effect of lockdown wave-1 and wave-2 on air quality by $PM_{2.5}$ and PM_{10} in different cities of Rajasthan

During lockdowns in 2020 and 2021, various cities in Rajasthan saw significant changes in air pollution levels. Here's a detailed look at the percentage changes in $PM_{2.5}$ and PM_{10} across selected cities during lockdown periods, covering first and second waves (all six phases) of COVID-19 lockdowns as shown in Fig. 4 and Table 4.

3.3.1 City-wise analysis of $PM_{2.5}$ and PM_{10} variations in major cities of Rajasthan

In Ajmer, the concentration of $PM_{2.5}$ increased from $30.88 \mu\text{g}/\text{m}^3$ in 2020 to $43.15 \mu\text{g}/\text{m}^3$ in 2021, indicating an increase of 28.44%. Similarly, PM_{10} increased from $78.00 \mu\text{g}/\text{m}^3$ in 2020 to $98.14 \mu\text{g}/\text{m}^3$ in 2021, reflecting a rise of 20.52%. Alwar recorded an increase in $PM_{2.5}$ from $25.21 \mu\text{g}/\text{m}^3$ in 2020 to $34.43 \mu\text{g}/\text{m}^3$ in 2021, a 26.73% rise. PM_{10} increased from $53.48 \mu\text{g}/\text{m}^3$ to $72.64 \mu\text{g}/\text{m}^3$, showing a 26.38% rise. In Bhiwadi, $PM_{2.5}$ levels more than doubled, rising from $54.10 \mu\text{g}/\text{m}^3$ in 2020 to $116.16 \mu\text{g}/\text{m}^3$ in 2021, a sharp 53.44% increase. PM_{10} concentrations increased drastically from $112.09 \mu\text{g}/\text{m}^3$ to $232.01 \mu\text{g}/\text{m}^3$, a 51.70% rise. In Jaipur, $PM_{2.5}$ increased from $34.22 \mu\text{g}/\text{m}^3$ in 2020 to $44.49 \mu\text{g}/\text{m}^3$ in 2021, reflecting a 23.11% increase. PM_{10} levels increased from $87.30 \mu\text{g}/\text{m}^3$ to $103.54 \mu\text{g}/\text{m}^3$, indicating an increase of 15.68%. Jodhpur experienced an increase in $PM_{2.5}$ from $55.83 \mu\text{g}/\text{m}^3$ in 2020 to $73.13 \mu\text{g}/\text{m}^3$ in 2021, which is a 23.65% rise. PM_{10} showed a sharp increase from $114.03 \mu\text{g}/\text{m}^3$ to $169.10 \mu\text{g}/\text{m}^3$, a 32.55% increase. In Kota, $PM_{2.5}$

concentrations increased from $29.61 \mu\text{g}/\text{m}^3$ in 2020 to $50.99 \mu\text{g}/\text{m}^3$ in 2021, a 41.95% rise. PM_{10} increased from $67.82 \mu\text{g}/\text{m}^3$ to $101.63 \mu\text{g}/\text{m}^3$, a 33.27% rise. Pali showed an increase in $PM_{2.5}$ from $38.43 \mu\text{g}/\text{m}^3$ in 2020 to $59.75 \mu\text{g}/\text{m}^3$ in 2021, an increase of 35.72%. PM_{10} increased from $93.74 \mu\text{g}/\text{m}^3$ to $139.33 \mu\text{g}/\text{m}^3$, recording a 32.74% increase. In Udaipur, $PM_{2.5}$ increased from $29.51 \mu\text{g}/\text{m}^3$ in 2020 to $41.26 \mu\text{g}/\text{m}^3$ in 2021, a 28.47% rise. PM_{10} concentrations increased significantly from $64.35 \mu\text{g}/\text{m}^3$ to $100.59 \mu\text{g}/\text{m}^3$, which is a 36.04% increase, as shown in Fig. 4 and Table 4. The reduction in PM concentrations was more noteworthy in first wave of lockdown (Phases 1–4, 2020) compared to second wave (Phases 5–6, 2021). While nationwide lockdown in 2020 and city-scale restrictions in 2021 contributed to improved air quality in Rajasthan, the percentage of improvement was greater during first wave. This disparity is attributed to more stringent and uniform restrictions during first lockdown, whereas second wave involved partial and less restrictions. Similar observations have been reported by Saharan et al. (2022), Mohan & Mishra, (2022), who noted higher PM concentrations during second wave in comparison to first-wave lockdown in 2020. This is due to partial relaxation, less stringent measures, and not imposition of complete lockdown during 2021 lockdown led to increased anthropogenic activities, resulting in increased air pollution. Moreover, 2020 lockdown saw partial relaxations, contributing to increased anthropogenic emissions, which helped to increase the air pollution.

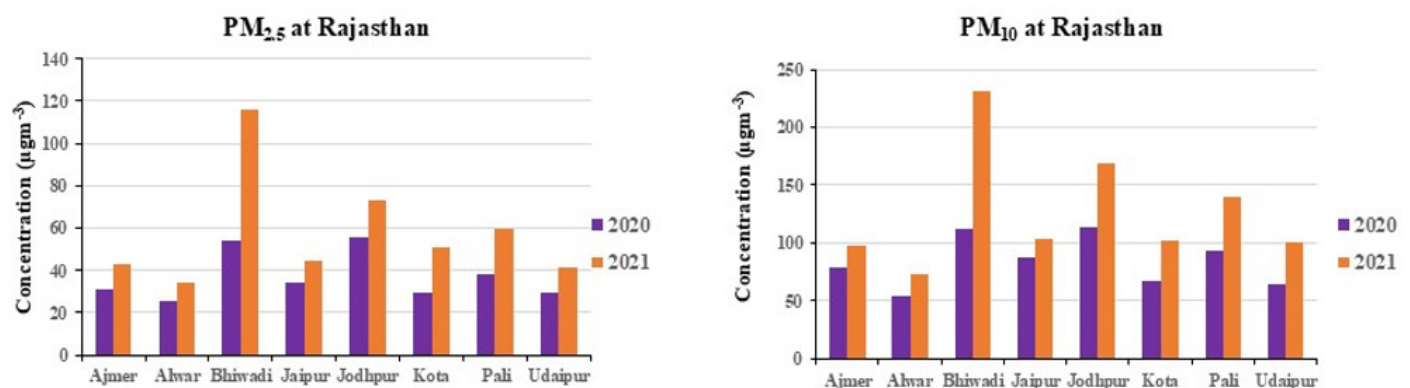


Fig. 4. $PM_{2.5}$ and PM_{10} in major metropolitan cities of Rajasthan throughout lockdown

Table 4. Percentage change in PM_{2.5} and PM₁₀ of preferred cities in Rajasthan, throughout lockdown period of 2020 and 2021 (average of six-phase segments of lockdown)

Cities	Percentage change in PM _{2.5}	Percentage change in PM ₁₀
Ajmer	28.44%	20.52%
Alwar	26.73%	26.38%
Bhiwadi	53.44%	51.70%
Jaipur	23.11%	15.68%
Jodhpur	23.65%	32.55%
Kota	41.95%	33.27%
Pali	35.72%	32.74%
Udaipur	28.47%	36.04%

4. CONCLUSION

COVID-19 outbreak has had some good environmental consequences. Governments across the globe were obliged to impose partial and total lockdowns. Economic, transportation, and social activities were all shut down as a result of the lockdowns. Nature's resilience provided a fresh advantage to humanity by enhancing air quality throughout lockdown. Across all cities of Rajasthan, a substantial reduction in ambient PM_{2.5} and PM₁₀ concentrations was detected during lockdown in 2020 as compared with corresponding periods in 2019 (pre-lockdown) and 2022 (post-lockdown). PM_{2.5} concentrations during lockdown declined by approximately 15–65%, and PM₁₀ by 23–60%, attributed to restricted vehicular movement and industrial activities. Similarly, during 2021 partial lockdown, PM_{2.5} and PM₁₀ levels decreased by approximately 2–30% and 3–40%, respectively (Tables 2, 3; Figs. 2, 3). Therefore, the maximum PM reduction occurred during first wave of 2020, when anthropogenic activities were most restricted, compared to second wave of 2021 lockdown due to the relaxation provided. The lockdown periods provided unique opportunity to evaluate impact of anthropogenic activities on air quality. The reduction and enhancement in PM_{2.5} and PM₁₀ show contribution of anthropogenic emissions to improvement and deterioration of ambient air quality. These findings reinforce that anthropogenic emissions are a primary contributor to urban air pollution. However, lockdowns revealed the air quality benefits of reduced human activity, such measures are not sustainable long-term. Therefore, it is important that policymakers to prioritize advanced technology, promote sustainable transportation and industrialization, planning, and implementing

efficient policies remains essential for long-term air quality improvement to improve air pollution levels and healthier urban environments.

REFERENCES

- Agarwal, A., Kaushik, A., Kumar, S., Mishra, R.K. (2020). Comparative study on air quality status in Indian and Chinese cities before and during the COVID-19 lockdown period. *Air Qual. Atmos. Health.* 13 (10), 1167-1178. <https://doi.org/10.1007/s11869-020-00881-z>.
- Akan, A. P., & Coccia, M. (2022). COVID-19 Lockdown Impact on Air Pollution: A Global Comparative Analysis.
- Almetwally, A. A., Bin-Jumah, M., & Allam, A. A. (2020). Ambient air pollution and its influence on human health and welfare: an overview. *Environmental Science and Pollution Research*, 27(20), 24815-24830. <https://doi.org/10.1007/s11356-020-09042-2>.
- Aswin Giri, J., Schäfer, B., Verma, R., He, H., Shiva Nagendra, S. M., Khare, M., & Beck, C. (2023). Lockdown effects on air quality in megacities during the first and second waves of COVID-19 pandemic. *Journal of The Institution of Engineers (India): Series A*, 104(1), 155-165. <https://doi.org/10.1007/s40030-022-00702-9>.
- Bao, R., & Zhang, A. (2020). Does lockdown reduce air pollution? Evidence from 44 cities in northern China. *Science of the Total Environment*, 731, 139052. <https://doi.org/10.1016/j.scitotenv.2020.139052>.
- Barupal, T., Tak, P. K., Meena, M., Vishwakarma, P. K., & Swapnil, P. (2022). The Impact of COVID-19 Strict Lockdown on the Air Quality of Smart Cities of Rajasthan, India. *The Open COVID Journal*, 2(1). <http://dx.doi.org/10.2174/26669587-v2-e2203030>.
- Bhatti, U. A., Wu, G., Bazai, S. U., Nawaz, S. A., Baryalai, M., Bhatti, M. A., & Nizamani, M. M. (2022a). A Pre-to Post-COVID-19 Change of Air Quality Patterns in Anhui Province Using Path Analysis and Regression. *Polish Journal of Environmental Studies*, 31(5). <https://doi.org/10.15244/pjoes/148065>.
- Bhatti, U. A., Zeeshan, Z., Nizamani, M. M., Bazai, S., Yu, Z., & Yuan, L. (2022b). Assessing the change of ambient air quality patterns in Jiangsu Province of China pre-to post-COVID-19. *Chemosphere*, 288, 132569. <https://doi.org/10.1016/j.chemosphere.2021.132569>.
- Business Standard. 2020. India breathes easy as 88 cities

- record minimal pollution due to lockdown. https://www.business-standard.com/article/current-affairs/india-breathes-easy-as-88-cities-record-minimal-pollution-due-to-lockdown-120033101314_1.html.
10. Chai, G., He, H., Sha, Y., Zhai, G., & Zong, S. (2019). Effect of PM_{2.5} on daily outpatient visits for respiratory diseases in Lanzhou, China. *Science of the Total Environment*, 649, 1563-1572. <https://doi.org/10.1016/j.scitotenv.2018.08.384>.
 11. Chauhan, A., & Singh, R. P. (2020). Decline in PM_{2.5} concentrations over major cities around the world associated with COVID-19. *Environmental research*, 187, 109634. <https://doi.org/10.1016/j.envres.2020.109634>.
 12. Chen, J., Zhou, C., Wang, S., & Li, S. (2018a). Impacts of energy consumption structure, energy intensity, economic growth, urbanization on PM_{2.5} concentrations in countries globally. *Applied energy*, 230, 94-105. <https://doi.org/10.1016/j.apenergy.2018.08.089>.
 13. Chen, N., Zhou, M., Dong, X., Qu, J., Gong, F., Han, Y., & Zhang, L. (2020). Epidemiological and clinical characteristics of 99 cases of 2019 novel coronavirus pneumonia in Wuhan, China: a descriptive study. *The lancet*, 395(10223), 507-513. [https://doi.org/10.1016/S0140-6736\(20\)30211-7](https://doi.org/10.1016/S0140-6736(20)30211-7).
 14. Chen, X., Li, X., Yuan, X., Zeng, G., Liang, J., Li, X., & Chen, G. (2018b). Effects of human activities and climate change on the reduction of visibility in Beijing over the past 36 years. *Environment international*, 116, 92-100. <https://doi.org/10.1016/j.envint.2018.04.009>.
 15. Cortegiani, A., Ingoglia, G., Ippolito, M., Giarratano, A., & Einav, S. (2020). A systematic review on the efficacy and safety of chloroquine for the treatment of COVID-19. *Journal of critical care*, 57, 279-283. <https://doi.org/10.1016/j.jcrc.2020.03.005>.
 16. CPCB (2020) <https://app.cpcbcr.com/ccr/#/caaqm-dashboard-all/caaqm-landing>.
 17. Dangayach, R., Pandey, M., Gusain, D., Srivastav, A. L., Jain, R., Bairwa, B. M., & Pandey, A. K. (2023). Assessment of Air Quality Before and During COVID-19-Induced Lockdown in Jaipur, India. *Mapan*, 1-11. <https://doi.org/10.1007/s12647-022-00615-9>.
 18. Dantas, G., Siciliano, B., França, B. B., da Silva, C. M., & Arbilla, G. (2020). The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro, Brazil. *Science of the total environment*, 729, 139085. <https://doi.org/10.1016/j.scitotenv.2020.139085>.
 19. Das, M., Das, A., Sarkar, R., Mandal, P., Saha, S., & Ghosh, S. (2021). Exploring short term spatio-temporal pattern of PM_{2.5} and PM₁₀ and their relationship with meteorological parameters during COVID-19 in Delhi. *Urban Climate*, 39, 100944. <https://doi.org/10.1016/j.uclim.2021.100944>.
 20. Dong, J., Chi, Y., Ephraim, A., Nzihou, A., & Romero Millán, L. M. (2020). Particulate matter. *Handbook on Characterization of Biomass, Biowaste and Related By-products*, 1267-1306. https://doi.org/10.1007/978-3-030-35020-8_14.
 21. Ghude, S. D., Chate, D. M., Jena, C., Beig, G., Kumar, R., Barth, M. C., & Pithani, P. (2016). Premature mortality in India due to PM_{2.5} and ozone exposure. *Geophysical Research Letters*, 43(9), 4650-4658. <https://doi.org/10.1002/2016GL068949>.
 22. Government of Rajasthan. (2021). Implementation guidelines: Lockdown phases and state-level restrictions (Apr–Jun 2021). Home Department, Government of Rajasthan.
 23. Guo, H., Kota, S. H., Sahu, S. K., & Zhang, H. (2019). Contributions of local and regional sources to PM_{2.5} and its health effects in north India. *Atmospheric Environment*, 214, 116867. <https://doi.org/10.1016/j.atmosenv.2019.116867>.
 24. Guttikunda, S. K., Nishadh, K. A., Gota, S., Singh, P., Chanda, A., Jawahar, P., & Asundi, J. (2019). Air quality, emissions, and source contributions analysis for the Greater Bengaluru region of India. *Atmospheric Pollution Research*, 10(3), 941-953. <https://doi.org/10.1016/j.apr.2019.01.002>.
 25. Hasnain, A., Hashmi, M. Z., Bhatti, U. A., Nadeem, B., Wei, G., Zha, Y., & Sheng, Y. (2021). Assessment of Air Pollution before, during and after the COVID-19 Pandemic Lockdown in Nanjing, China. *Atmosphere*, 12(6), 743. <https://doi.org/10.3390/atmos12060743>.
 26. Hu, M., Chen, Z., Cui, H., Wang, T., Zhang, C., & Yun, K. (2021). Air pollution and critical air pollutant assessment during and after COVID-19 lockdowns: Evidence from pandemic hotspots in China, the Republic of Korea, Japan, and India. *Atmospheric pollution research*, 12(2), 316-329. <https://doi.org/10.1016/j.apr.2020.11.013>.
 27. Jain, S., & Mandowara, V. L. (2019). Study on particulate matter pollution in jaipur city. *International Journal of Applied Engineering Research*, 14(3), 637-645.
 28. Jain, S., & Sharma, T. (2020). Social and travel lockdown impact considering coronavirus disease (COVID-19) on air quality in megacities of India: present benefits, future challenges and way forward. *Aerosol and Air Quality Research*, 20(6), 1222-1236. <https://doi.org/10.4209/aaqr.2020.04.0171>.
 29. Kermani, M., Arfaeina, H., Masroor, K., Abdolahnejad, A., Fanaei, F., Shahsavani, A., & Vahidi, M. H. (2022). Health impacts and burden of disease attributed to long-term exposure to atmospheric PM₁₀/PM_{2.5} in Karaj, Iran: effect of meteorological factors. *International Journal of Environmental Analytical Chemistry*, 102(18), 6134-6150. <https://doi.org/10.1080/03067319.2020.1807534>.
 30. Khaniabadi, Y. O., Polosa, R., Chuturkova, R. Z., Daryanoosh, M., Goudarzi, G., Borgini, A., & Naserian, P. (2017). Human health risk assessment due to ambient PM₁₀ and SO₂ by an air quality modeling technique. *Process safety and environmental protection*, 111, 346-354. <https://doi.org/10.1016/j.psep.2017.07.018>.
 31. Kolluru, S. S. R., Nagendra, S. S., Patra, A. K., Gautam, S., Alshetty, V. D., & Kumar, P. (2023). Did unprecedented air pollution levels cause spike in Delhi's COVID cases during second wave?. *Stochastic Environmental Research and Risk Assessment*, 37(2), 795-810. <https://doi.org/10.1007/s00477-022-02308-w>.
 32. Kolluru, S. S. R., Patra, A. K., & Nagendra, S. S. (2021). Association of air pollution and meteorological variables with COVID-19 incidence: evidence from five megacities

- in India. *Environmental Research*, 195, 110854. DOI: <https://doi.org/10.1016/j.envres.2021.110854>.
33. Kota, S. H., Guo, H., Myllyvirta, L., Hu, J., Sahu, S. K., Garaga, R., & Zhang, H. (2018). Year-long simulation of gaseous and particulate air pollutants in India. *Atmospheric Environment*, 180, 244-255. <https://doi.org/10.1016/j.atmosenv.2018.03.003>.
 34. Krecl, P., Targino, A. C., Oukawa, G. Y., & Junior, R. P. C. (2020). Drop in urban air pollution from COVID-19 pandemic: Policy implications for the megacity of São Paulo. *Environmental Pollution* (Barking, Essex: 1987), 265, 114883.
 35. Lauer, S. A., Grantz, K. H., Bi, Q., Jones, F. K., Zheng, Q., Meredith, H. R., & Lessler, J. (2020). The incubation period of coronavirus disease 2019 (COVID-19) from publicly reported confirmed cases: estimation and application. *Annals of Internal Medicine*, 172(9), 577-582. <https://doi.org/10.7326/M20-0504>.
 36. Macías-Hernández, B. A., & Tello-Leal, E. (2022). Analysis of Particulate Matter Concentration Changes before, during, and Post COVID-19 Lockdown: A Case Study from Victoria, Mexico. *Atmosphere*, 13(5), 827. <https://doi.org/10.3390/atmos13050827>.
 37. Mahato, S., & Ghosh, K. G. (2020). Short-term exposure to ambient air quality of the most polluted Indian cities due to lockdown amid SARS-CoV-2. *Environmental Research*, 188, 109835. <https://doi.org/10.1016/j.envres.2020.109835>.
 38. Mahato, S., & Pal, S. (2022). Revisiting air quality during lockdown persuaded by second surge of COVID-19 of megacity Delhi, India. *Urban Climate*, 41, 101082. <https://doi.org/10.1016/j.uclim.2021.101082>.
 39. Mahato, S., Pal, S., & Ghosh, K. G. (2020). Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. *Science of the total environment*, 730, 139086. <https://doi.org/10.1016/j.scitotenv.2020.139086>.
 40. Ministry of Home Affairs. (2020). Extension of COVID 19 lockdown phases 1–4 (Mar–May 2020) [Order No.]. Government of India.
 41. Mohan, V., & Mishra, R. K. (2022). A picture of Delhi's regional air quality during diminished anthropogenic activities in the COVID-19 era. *Arabian Journal of Geosciences*, 15(15), 1331. <https://doi.org/10.1007/s12517-022-10567-8>.
 42. Mukherjee, A., & Agrawal, M. (2018). Air pollutant levels are 12 times higher than guidelines in Varanasi, India. Sources and transfer. *Environmental Chemistry Letters*, 16, 1009-1016. <https://doi.org/10.1007/s10311-018-0706-y>.
 43. Nandhini, C., Mirthul, E. S., & Dhurandher, B. K. (2022, July). An assessment on Air Quality in various Polluted Industrialized states of India due to COVID-19. In 2022 1st International Conference on Sustainable Technology for Power and Energy Systems (STPES) (pp. 1-6). IEEE. <https://doi.org/10.1109/STPES54845.2022.10006546>.
 44. Navasakthi, S., Pandey, A., Bhari, J. S., & Sharma, A. (2023). Significant variation in air quality in South Indian cities during COVID-19 lockdown and unlock phases. *Environmental Monitoring and Assessment*, 195(6), 772. <https://doi.org/10.1007/s10661-023-11375-7>.
 45. Nigam, R., Pandya, K., Luis, A. J., Sengupta, R., & Kotha, M. (2021). Positive effects of COVID-19 lockdown on air quality of industrial cities (Ankleshwar and Vapi) of Western India. *Scientific reports*, 11(1), 4285. <https://doi.org/10.1038/s41598-021-83393-9>.
 46. Otmani, A., Benchrif, A., Tahri, M., Bounakhla, M., El Bouch, M., & Krombi, M. H. (2020). Impact of Covid-19 lockdown on PM10, SO2 and NO2 concentrations in Salé City (Morocco). *Science of the total environment*, 735, 139541. <https://doi.org/10.1016/j.scitotenv.2020.139541>.
 47. Patel, K., & Singh, A. K. (2023). Consequences of pre and post confinement on the atmospheric air pollutants during spread of COVID-19 in India. *Indian Journal of Physics*, 97(2), 319-336. <https://doi.org/10.1007/s12648-022-02380-6>.
 48. Pratap, V., Tiwari, S., Kumar, A., & Singh, A. K. (2021). COVID-19 lockdown induced air pollution reduction over India: A lesson for future air pollution mitigation strategies. *Journal of Earth System Science*, 130, 1-16. <https://doi.org/10.1007/s12040-021-01722-y>.
 49. Ruhela, M., Maheshwari, V., Ahamad, F., & Kamboj, V. (2022). Air quality assessment of Jaipur city Rajasthan after the COVID-19 lockdown. *Spatial Information Research*, 30(5), 597-605. <https://doi.org/10.1007/s41324-022-00456-3>.
 50. Saha, J., Barman, B., & Chouhan, P. (2020). Lockdown for COVID-19 and its impact on community mobility in India: An analysis of the COVID-19 Community Mobility Reports, 2020. *Children and youth services review*, 116, 105160. <https://doi.org/10.1016/j.childyouth.2020.105160>.
 51. Saharan, U. S., Kumar, R., Tripathy, P., Sateesh, M., Garg, J., Sharma, S. K., & Mandal, T. K. (2022). Drivers of air pollution variability during second wave of COVID-19 in Delhi, India. *Urban Climate*, 41, 101059. <https://doi.org/10.1016/j.uclim.2021.101059>.
 52. Sahoo, P. K., Mangla, S., Pathak, A. K., Salāmao, G. N., & Sarkar, D. (2021). Pre-to-post lockdown impact on air quality and the role of environmental factors in spreading the COVID-19 cases-a study from a worst-hit state of India. *International journal of biometeorology*, 65, 205-222. <https://doi.org/10.1007/s00484-020-02019-3>.
 53. Selvam, S., Muthukumar, P., Venkatramanan, S., Roy, P. D., Bharath, K. M., & Jesuraja, K. (2020). SARS-CoV-2 pandemic lockdown: Effects on air quality in the industrialized Gujarat state of India. *Science of the Total Environment*, 737, 140391. <https://doi.org/10.1016/j.scitotenv.2020.140391>.
 54. Sharma, G. K., Tewani, A., & Gargava, P. (2022). Comprehensive analysis of ambient air quality during second lockdown in national capital territory of Delhi. *Journal of Hazardous Materials Advances*, 6, 100078. <https://doi.org/10.1016/j.hazadv.2022.100078>.
 55. Sharma, M., Jain, S., & Lamba, B. Y. (2020a). Epigrammatic study on the effect of lockdown amid Covid-19 pandemic on air quality of most polluted cities of Rajasthan (India). *Air Quality, Atmosphere & Health*, 13(10), 1157-1165. <https://doi.org/10.1007/s11869-020-00879-7>.
 56. Sharma, S., Zhang, M., Gao, J., Zhang, H., & Kota, S. H. (2020b). Effect of restricted emissions during COVID-19 on air quality in India. *Science of the total environment*, 728,

138878. <https://doi.org/10.1016/j.scitotenv.2020.138878>.
57. Shukla, A., Mishra, A., & Tandel, B. N. T. (2021). Is Exposure to PM_{2.5} and PM₁₀, a Factor of Surge of 2nd Wave of COVID-19-A Case Study of Delhi, India?. DOI: <https://doi.org/10.21203/rs.3.rs-808021/v1>.
 58. Singh, R. P., & Chauhan, A. (2020). Impact of lockdown on air quality in India during COVID-19 pandemic. *Air Quality, Atmosphere & Health*, 13, 921-928. <https://doi.org/10.1007/s11869-020-00863-1>.
 59. Singh, V., Singh, S., Biswal, A., Kesarkar, A. P., Mor, S., & Ravindra, K. (2020). Diurnal and temporal changes in air pollution during COVID-19 strict lockdown over different regions of India. *Environmental Pollution*, 266, 115368. <https://doi.org/10.1016/j.envpol.2020.115368>.
 60. Sohrabi, C., Alsafi, Z., O'Neill, N., Khan, M., Kerwan, A., Al-Jabir, A., & Agha, R. (2020). World Health Organization declares global emergency: A review of the 2019 novel coronavirus (COVID-19). *International journal of surgery*, 76, 71-76. <https://doi.org/10.1016/j.ijsu.2020.02.034>.
 61. Srivastava, S., Kumar, A., Baudh, K., Gautam, A.S., Kumar, S. (2020). 21-Day lockdown in India dramatically reduced air pollution indices in Lucknow and New Delhi, India. *Bull. Environ. Contam. Toxicol.* 1. <https://doi.org/10.1007/s00128-020-02895-w>.
 62. Sundarakumar, J. S., Menesgere, A. L., Hameed, S. K., SANSOCG & TLSA Study Teams, & Ravindranath, V. (2022). Depression and anxiety during the first and second waves of the COVID-19 pandemic in two large, prospective, aging cohorts in rural and urban India. *Health Science Reports*, 5(6), e901. <https://doi.org/10.1002/hsr2.901>.
 63. 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>.
 64. The Hindu. 2020a. Coronavirus live updates 19th March 2020. <https://www.thehindu.com/news/national/coronavirus-live-updates-march-19-2020/article31105138.ece> (accessed May 13, 2020).
 65. The Hindu. 2020b. PM Modi announces 21-day lockdown as COVID-19 toll touches 12. <https://www.thehindu.com/news/national/pm-announces-21-day-lockdown-as-covid-19-toll-touches-10/article31156691.ece> (accessed May 10, 2020).
 66. 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/covid-19-second-wave-heres-a-list-of-states-that-have-imposed-lockdowns-7306634/>.
 67. Thorpe, A., & Harrison, R. M. (2008). Sources and properties of non-exhaust particulate matter from road traffic: a review. *Science of the total environment*, 400(1-3), 270-282. <https://doi.org/10.1016/j.scitotenv.2008.06.007>.
 68. Tobías, A., Carnerero, C., Reche, C., Massagué, J., Via, M., Minguillón, M. C., & Querol, X. (2020). Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. *Science of the total environment*, 726, 138540. <https://doi.org/10.1016/j.scitotenv.2020.138540>.
 69. Wang, Y., Wen, Y., Wang, Y., Zhang, S., Zhang, K. M., Zheng, H., & Hao, J. (2020). Four-month changes in air quality during and after the COVID-19 lockdown in six megacities in China. *Environmental Science & Technology Letters*, 7(11), 802-808. <https://doi.org/10.1021/acs.estlett.0c00605>.
 70. World Health Organization. (2018). WHO global ambient air quality database (update 2018). World Health Organization: Geneva, Switzerland.
 71. World Health Organization. (2020). Coronavirus Disease 2019 (COVID-19) Situation Report–51. World Health Organization 2020; https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200311-sitrep-51-covid-19.pdf?sfvrsn=1ba62e57_10 accessed March 20, 2020).
 72. Xu, K., Cui, K., Young, L. H., Hsieh, Y. K., Wang, Y. F., Zhang, J., & Wan, S. (2020). Impact of the COVID-19 event on air quality in central China. *Aerosol Air Qual. Res.* 20, 915–929. <https://doi.org/10.4209/aaqr.2020.04.0150>.
 73. Yadav R, Sahu LK, Jaaffrey SNA, Beig G (2014) Temporal variation of Particulate matter (PM) and potential sources at an urban site of Udaipur in Western India. *Aerosol Air Qual Res* 14(6):1613–1629. DOI: <https://doi.org/10.4209/aaqr.2013.10.0310>.