E-ISSN No : 2581-6195 | Volume : 8 | Issue : 10 | October 2025

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

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Article DOI:
10.5281/zenodo.17855952

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How to Cite:
Prerana Shakti, & Ashutosh Kumar Pandey (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

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 ¬$PM_{2.5}$ 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 ¬$PM_{2.5}$ 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 60μg/m^3 and 100μg/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

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 ≤2.5 μm) and coarse particles (PM_{10}, with diameters ≤10 μm), 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

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$PM_{2.5}$ and PM_{10} (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 PM_{10} 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 PM_{10} 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 PM_{10} 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 PM_{10} 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 PM_{10}. 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 PM_{10} 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°55'19.4520"N, 75°46'43.9860"E) forms east-central part, and is situated at altitude distance from the ground of 431m above sea level, Ajmer (26°26'59.6256"N, 74°38'23.6940"E) western part of Rajasthan; Alwar (27°33'39.3552"N, 76°37'30.0540"E) northern part of Rajasthan, Bhiwadi (28o12'36.87"N 76o51'38.03"E), Jodhpur (26°14'20.2100"N, 73°01'27.5100"E), Udaipur (23°32'09.6800"N, 91°29'13.1500"E) located in the southernmost part of Rajasthan, Pali (25°46'16.7340"N, 73°19'25.2660"E) 70 km southeast of Jodhpur; Kota (25°09'46.7928"N, 75°50'43.1592"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.

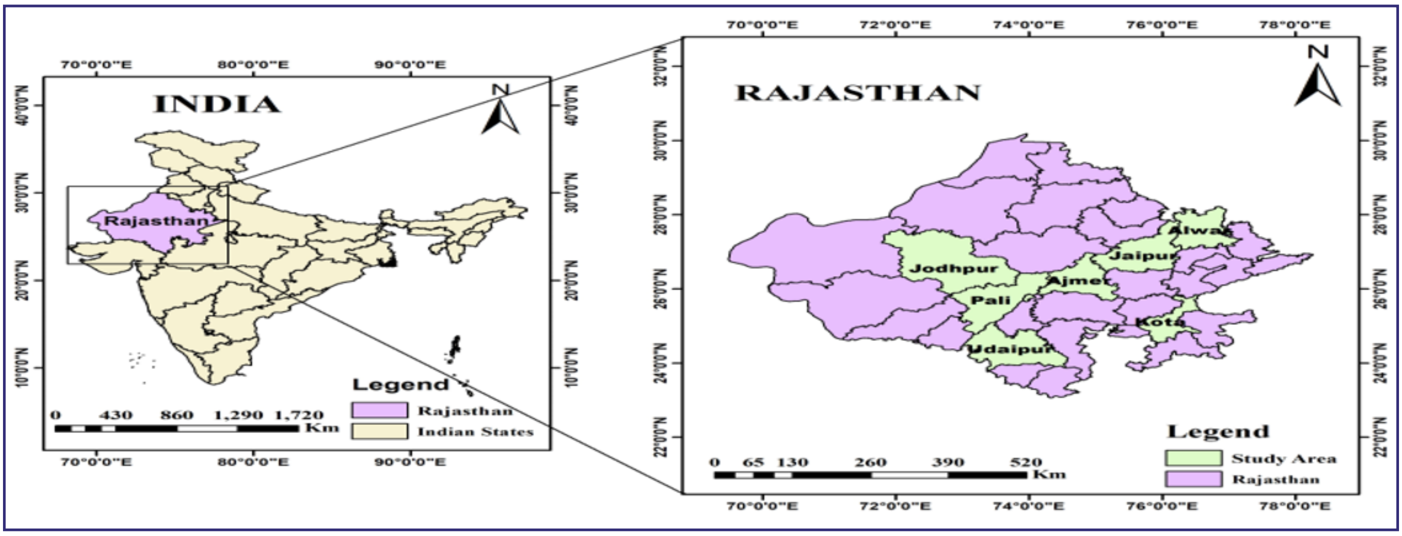


Fig. 1. The air quality monitoring station in Rajasthan state, India

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 PM_{10} 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 PM_{10} 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 PM_{10}) levels changed in eight selected Rajasthan cities in four phases of the sfirst 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, showing a 60.29% increase over lockdown and exceeding pre-lockdown levels. Pali exhibited highest reduction (63.74%) in $PM_{2.5}$ during lockdown, from 105.98 µg/m³ in 2019 to 38.43 µg/m³ in 2020. However, $PM_{2.5}$ rebounded to 70.72 µg/m³ 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 $PM_{2.5}$ only slightly dropping from 35.00 µg/m³ in 2019 to 29.51 µg/m³ in 2020. By 2022, concentrations increased sharply to 64.03 µg/m³, 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 µg/m³ in 2019 to 78.00 µg/m³ in 2020. However, in 2022, PM_{10} rebounded to 140.99 µg/m³, a 44.65% increase compared to lockdown, exceeding pre-lockdown levels. Alwar experienced a 51.32% reduction in PM10 during lockdown (from 109.85 µg/m³ in 2019 to 53.48 µg/m³ in 2020). By 2022, concentrations increased again to 111.80 µg/m³, reflecting a 52.16% increase compared to lockdown and slightly exceeding pre-lockdown levels. Bhiwadi, heavily industrialized region, had highest PM_{10} (260.97 µg/m³ in 2019). Lockdown measures reduced concentrations sharply by 112.09 µg/m³, resulting in a 57.06% reduction. However, in 2022, PM_{10} increased drastically to 274.27 µg/m³, 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 µg/m³ in 2019 to 87.30 µg/m³ in 2020). However, in 2022, concentrations increased to 167.12 µg/m³, 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 µg/m³ in 2019 to 114.03 µg/m³ in 2020. By 2022, concentrations increased to 211.60 µg/m³, a 46.09% rise over lockdown levels. Kota exhibited a 41.47% reduction in PM_{10} during lockdown (from 115.88 µg/m³ in 2019 to 67.82 µg/m³ in 2020). In post-lockdown, PM_{10} increased to 158.29 µg/m³ 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 µg/m³ in 2019 to 93.74 µg/m³ in 2020). In 2022, PM_{10} increased to 152.23 µg/m³, marking a 38.43% rise compared to lockdown. Udaipur recorded smallest decline in PM_{10} during lockdown (23.97%), dropping from 84.67 µg/m³ in 2019 to 64.35 µg/m³ in 2020. By 2022, however, PM_{10} surged to 153.46 µg/m³, representing a 58.07% increase compared to lockdown.

Therefore, concentration levels and percentage change in $PM_{2.5}$ 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 $PM_{2.5}$ 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 $PM_{2.5}$ 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 $PM_{2.5}$ (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 $PM_{2.5}$ 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 $PM_{2.5}$ and PM_{10} concentrations across multiple zones in Gujarat during lockdown as compared with pre-lockdown. In Zone 1 (Surat, Ankleshwar, Vadodara), $PM_{2.5}$ and PM_{10} decreased by 51% and 48%, respectively; in Zone 2 (Ahmedabad, Gandhinagar), reductions were 34% ($PM_{2.5}$) and 47% (PM_{10}); Zone 3 (Jamnagar, Rajkot) exhibited the highest reductions with 78% ($PM_{2.5}$) and 80%

(PM_{10}); and in Zone 4 (Bhuj, Palanpur), $PM_{2.5}$ and PM_{10} declined by 38% and 32%, respectively (Selvam et al. 2020). Similarly, at Peenya industrial monitoring station in Bengaluru, $PM_{2.5}$ and PM_{10} levels declined during lockdown phases but again started increasing gradually with easing of restrictions during unlock period (Navasakthi et al. 2023). During lockdown, drops PM_{10} concentrations ranged from 34.18 to 64.42μg/m³, and increased to 24.47–118.25μg/m³ during unlock period. $PM_{2.5}$ concentrations ranged from 30.12–42.49μg/m³ during lockdown and observed extremes of 14.82–63.67μg/m³ during unlock periods. This dropped in $PM_{2.5}$ and PM_{10} 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 PM_{10} levels was observed. These findings are consistent with several global investigations that recorded drop in $PM_{2.5}$ and PM_{10} 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).

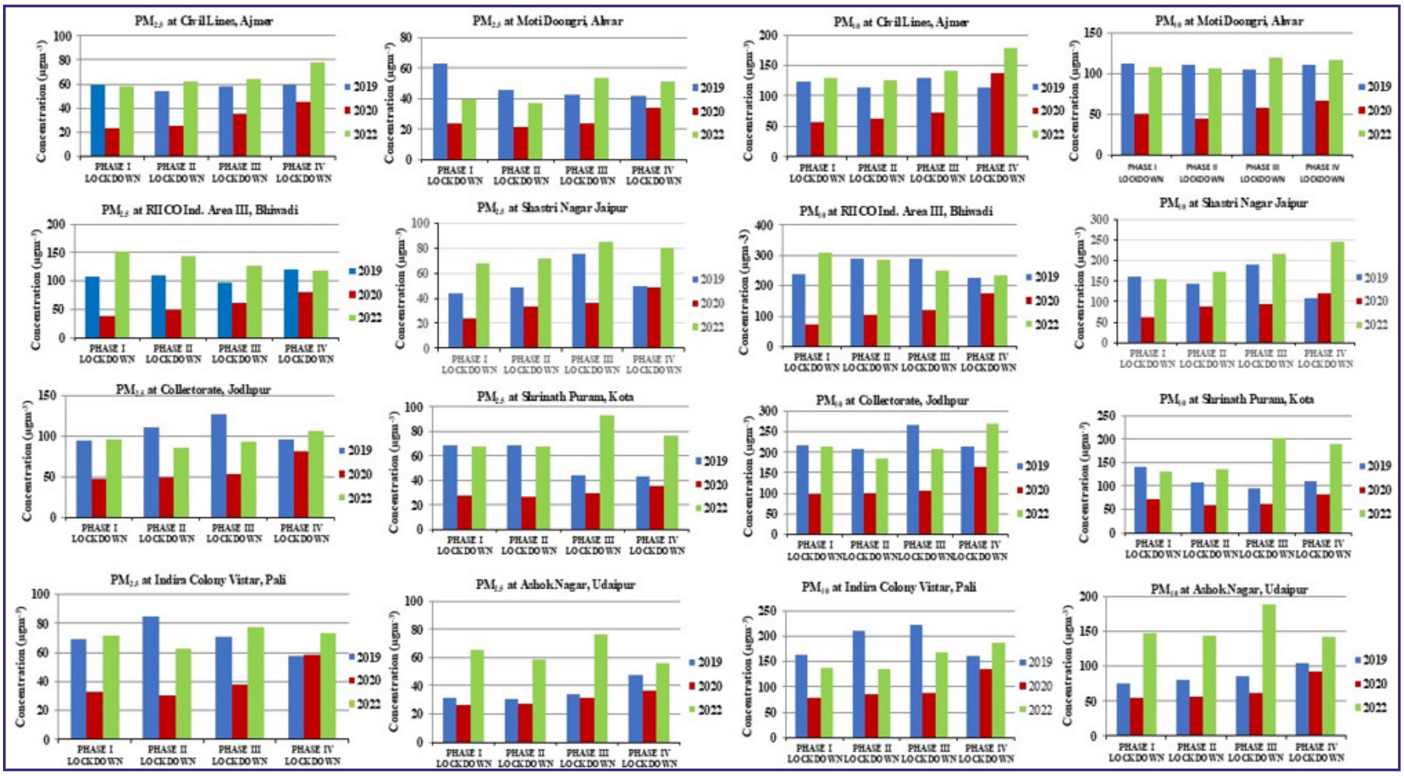


Fig. 2. Particulate matter ($PM_{2.5}$ and PM_{10}) in various preferred cities of Rajasthan before, during, and after lockdown (first wave of COVID-19)

Table 2: Percentage change in the $PM_{2.5}$ and PM_{10} 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 PM_{10} 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 PM_{10}) 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 PM_{10} variations in major cities of Rajasthan

In Ajmer, PM_{10} 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 PM_{10} 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 PM_{10} 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 PM_{10} decreasing from 152.89 μg/m³ to 103.55 μg/m³, a reduction of 32.27%. However, post-lockdown, PM_{10} enhanced to 200.47 μg/m³, an increase of 48.37% from lockdown. Jodhpur recorded a decrease in PM_{10} 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, PM_{10} 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 PM_{10} 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).

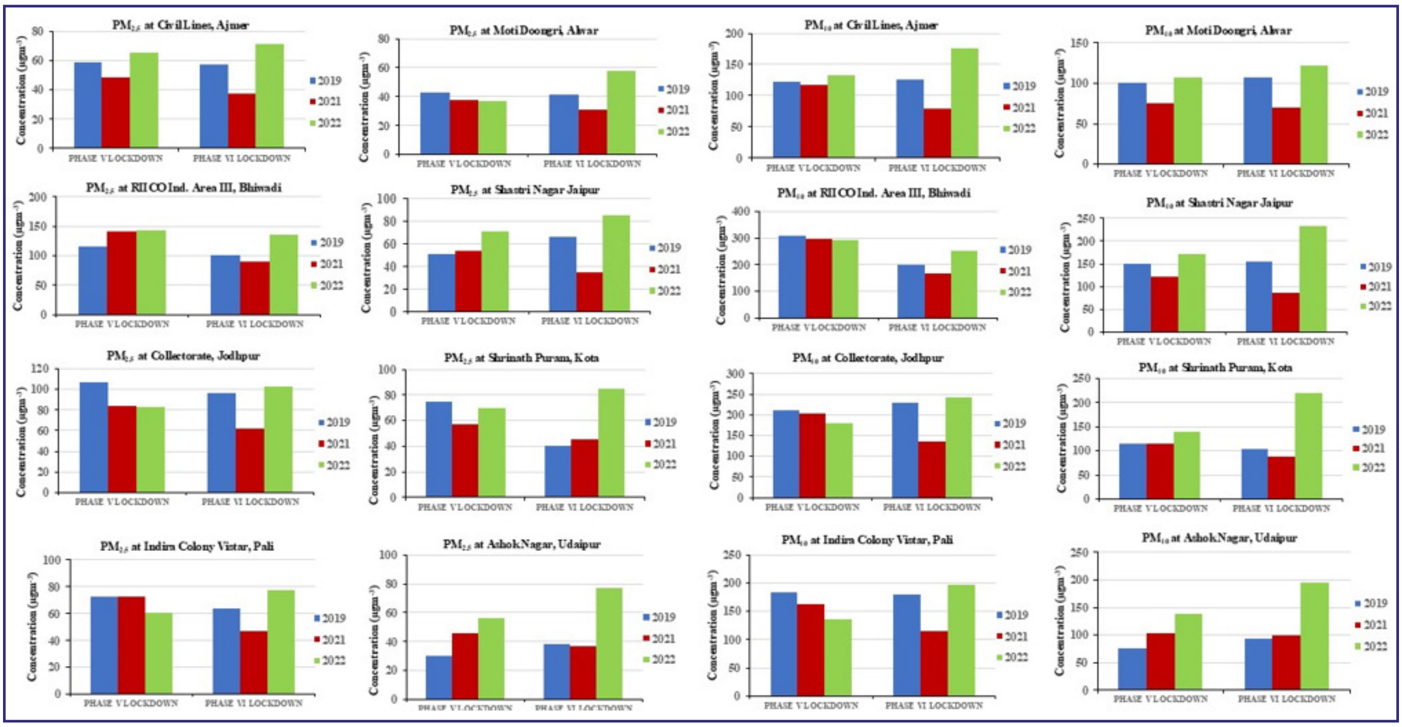


Fig. 3. Particulate matter ($PM_{2.5}$ and PM_{10}) in various preferred cities of Rajasthan before, during, and after lockdown (second wave of COVID-19)

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)

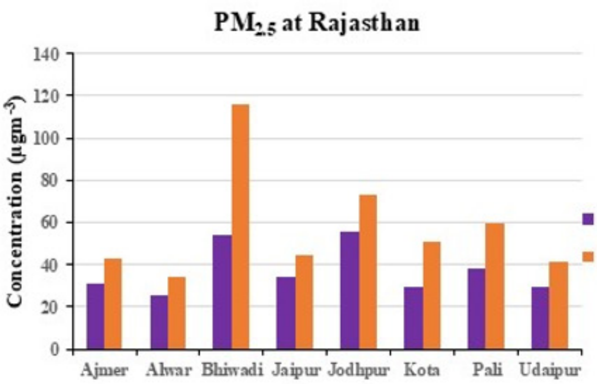
Cities	Percentage change in $PM_{2.5}$ (Before lockdown)	Percentage change in $PM_{2.5}$ (After lockdown)	Percentage change in PM_{10} (Before lockdown)	Percentage change in PM_{10} (After lockdown)
Ajmer	−26.05%	36.99%	−21.03%	36.64%
Alwar	−18.41%	26.83%	−30.16%	36.75%
Bhiwadi	7.28%	16.90%	−8.73%	14.67%
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 μg/m³ in 2020 to 43.15 μg/m³ in 2021, indicating an increase of 28.44%. Similarly, PM_{10} increased from 78.00 μg/m³ in 2020 to 98.14 μg/m³ in 2021, reflecting a rise of 20.52%. Alwar recorded an increase in $PM_{2.5}$ from 25.21 μg/m³ in 2020 to 34.43 μg/m³ in 2021, a 26.73% rise. PM_{10} increased from 53.48 μg/m³ to 72.64 μg/m³, showing a 26.38% rise. In Bhiwadi, $PM_{2.5}$ levels more than doubled, rising from 54.10 μg/m³ in 2020 to 116.16 μg/m³ in 2021, a sharp 53.44% increase. PM_{10} concentrations increased drastically from 112.09 μg/m³ to 232.01 μg/m³, a 51.70% rise. In Jaipur, $PM_{2.5}$ increased from 34.22 μg/m³ in 2020 to 44.49 μg/m³ in 2021, reflecting a 23.11% increase. PM10 levels increased from 87.30 μg/m³ to 103.54 μg/m³, indicating an increase of 15.68%. Jodhpur experienced an increase in $PM_{2.5}$ from 55.83 μg/m³ in 2020 to 73.13 μg/m³ in 2021, which is a 23.65% rise. PM_{10} showed a sharp increase from 114.03 μg/m³ to 169.10 μg/m³, a 32.55% increase. In Kota, $PM_{2.5}$ concentrations increased from 29.61 μg/m³ in 2020 to 50.99 μg/m³ in 2021, a 41.95% rise. PM_{10} increased from 67.82 μg/m³ to 101.63 μg/m³, a 33.27% rise. Pali showed an increase in $PM_{2.5}$ from 38.43 μg/m³ in 2020 to 59.75 μg/m³ in 2021, an increase of 35.72%. PM_{10} increased from 93.74 μg/m³ to 139.33 μg/m³, recording a 32.74% increase. In Udaipur, $PM_{2.5}$ increased from 29.51 μg/m³ in 2020 to 41.26 μg/m³ in 2021, a 28.47% rise. PM_{10} concentrations increased significantly from 64.35 μg/m³ to 100.59 μg/m³, 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.



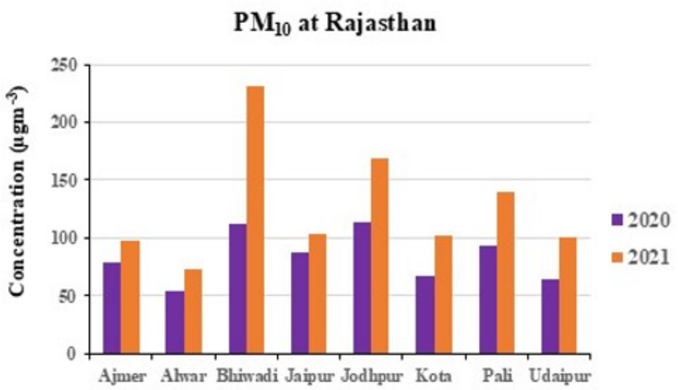


Fig. 4. $PM_{2.5}$ and PM_{10} in major metropolitan cities of Rajasthan throughout lockdown

Table 4. Percentage change in $PM_{2.5}$ and PM_{10} 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 PM_{10} 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 PM_{10} by 23–60%, attributed to restricted vehicular movement and industrial activities. Similarly, during 2021 partial lockdown, $PM_{2.5}$ and PM_{10} 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 PM_{10} 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.

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