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Spatio-Temporal and Seasonal Variation of Ambient Air Pollutants and their Relation to Meteorological Factors in Ajmer and Alwar of Rajasthan during 2018-2023

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Abstract

Urban air quality is deteriorating with increased pollutant concentrations due to anthropogenic activities. Meteorological conditions further influence spatial and seasonal distribution of these pollutants. This study investigated spatial and seasonal variations of Particulate Matter ($PM_{2.5}$ and PM_{10}), Nitrogen Dioxide (NO_2), Sulfur Dioxide (SO_2), and Ozone (O_3), and their relationships with meteorological parameters from 2018-2023 at Ajmer and Alwar monitoring stations. Monthly and annual mean concentrations of all pollutants, except O_3, peaked during winter, followed by pre-monsoon, post-monsoon, and lower during monsoon across both cities, attributed to rapid industrialization and urbanization. In Ajmer and Alwar, highest mean concentrations of $PM_{2.5}$ (55.71 and 31.2µg/m^3), PM_{10} (210 and 178µg/m^3), NO_2 (52 and 45µg/m^3), SO_2 (69.20 and 20.49µg/m^3), and O_3 (46.94 and 49.93µg/m^3) exceeded National Ambient Air Quality Standards (NAAQS) by 2.2-4.2 times, indicating severe air pollution. NO_2 and SO_2 concentrations positive correlated with temperature (T) (r = 0.52-0.68) and negative correlated with relative humidity (RH) (r = –0.40 to –0.55), whereas O_3 strong positive correlated with T (r = 0.61), reflecting photochemical formation under high solar radiation. Regression analysis indicated that Wind Speed (WS) and Direction (WD) explained 60% of pollutant variability (R^2 = 0.61-0.72), being the strongest influences on pollutant concentrations as compared to T and RH. Overall, Ajmer recorded higher pollution levels due to dense traffic, and construction activity, while Alwar showed strong meteorological variation. The findings emphasize the need for region-specific and season-adaptive mitigation strategies, and highlight implications for public and occupational health protection in semi-arid urban environments. Implementation of precautionary measures is essential to minimize public exposure to pollutants and reduce emissions at the source. This investigation further suggests the need for comprehensive studies on adverse impacts of air pollution on human health using appropriate environmental risk assessment techniques, which can support evidence-based air quality management at the regional scale.

Major Findings: Study found $PM_{2.5}$, PM_{10}, NO_2, and SO_2 levels in Ajmer and Alwar consistently exceeded NAAQS limits, peaking during winter and pre-monsoon due to emissions and unfavorable meteorological conditions, while O_3 levels were highest in summer from photochemical formation. Overall, findings emphasize the need for season-specific, site-based mitigation and occupational health measures to manage pollution in semi-arid urban regions.

Keywords: Air Pollutants, Gaseous Pollutants (NO_2, SO_2, O_3), Meteorological Parameters, Particulate Matter ($PM_{2.5}$ and PM_{10}), Seasonal Variations

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1. Introduction

Air pollution shows a critical and growing global public health concern, contributing significantly to the worldwide burden of disease from environmental factors[1-3]. According to the World Health Organization's (WHO's) latest urban air quality database, more than 80% of the urban populations worldwide are exposed to pollutant levels exceeding the recommended limits[3,4]. In developing countries, rapid industrialization, population growth, and vehicular expansion have further worsened air quality[5-7]. Globally, ambient air pollution is estimated to cause approximately 4.2 million premature deaths each year, largely due to exposure to fine and coarse Particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and ozone (O_3)[8-15].

Among atmospheric pollutants, $PM_{2.5}$, PM_{10}, NO_x, SO_2, and O_3 are the most extensively studied and commonly used as indicators of urban air quality[16-17]. These pollutants originate from diverse anthropogenic sources, including industrial activities, urban construction, and vehicular emissions. Increased vehicular traffic and rapid industrialization result in substantial emissions of air pollutants that are capable of inducing toxic effects on human health[18]. In addition to emission sources, meteorological parameters such as temperature (T), Relative Humidity (RH), Wind Speed (WS), and Wind Direction (WD) play a vital role in pollutant dispersion and accumulation[19-22]. Seasonal variation, particularly between monsoon and non-monsoon periods, further modulates pollution dynamics in tropical regions[23-24]. Seasonal variability, industrial emissions, and vehicular activity further aggravate urban air quality degradation. However, despite growing awareness, research addressing the combined influence of meteorological factors and air pollutants across the Indian subcontinent remains limited and region-specific.

India faces a persistent air pollution crisis and consistently ranks among the top three most polluted globally[25,26]. Industrial development and rapid urbanization have led to elevated concentration levels of PM, NO_2, and SO_2 in urban environments[7]. Major Indian cities, including Delhi, Kanpur, and Jaipur, consistently record hazardous pollution levels, primarily due to vehicular emissions, biomass burning, industrial discharges, and construction activities[7]. To mitigate and control air pollution, India enacted the Air (Prevention and Control of Pollution) Act in 1981 and subsequently established the National Ambient Air Quality Standards (NAAQS)[27] in 2009 to regulate emissions of twelve key pollutants.

Rajasthan's air quality is regionally significant due to its semi-arid climate, proximity to the Thar Desert, and frequent dust storms, which contribute to elevated levels of $PM_{2.5}$ and PM_{10}, particularly during pre-monsoon and summer months[28]. Furthermore, northeastern districts such as Alwar are influenced by transboundary pollution from the National Capital Region (Delhi and surrounding industrial hubs), where dense vehicular traffic and industrial emissions exacerbate particulate and gaseous pollutant levels[7]. These regional factors, combined with local industrial and traffic emissions, make Rajasthan a unique case for studying the interactions between meteorology, urbanization, and air pollution.

Although several studies have assessed air quality in Indian cities using CPCB datasets, most have been limited to short-term periods, single pollutants, or individual monitoring sites. In contrast, this study provides a comprehensive analysis of multiple pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3) over a longer temporal span (2018-2023) across two urbanizing districts (Ajmer and Alwar) and quantifies the influence of key meteorological parameters (T, RH, WS, WD) on pollutant variations, offering integrated insights into the combined effects of emissions and climatic factors on regional air quality. This approach distinguishes the study from previous CPCB-based analyses and provides region-specific knowledge for air quality management and occupational health planning.

However, in India, most studies focus on metropolitan areas, with relatively less attention paid to medium-sized cities and semi-arid regions where climatic variability can substantially alter air quality patterns. To tackle the air pollution problems, regional assessments are required, particularly in countries such as India, where substantial health and environmental disparities exist[29]. Considering a few variables and limited monitoring sites, there is a lack of understanding of air quality in Indian cities. Yet, localized and long-term studies remain essential for effective mitigation planning, as pollutant levels and meteorological influences vary significantly across regions.

Moreover, the implications of elevated air pollution levels extend beyond environmental degradation, posing serious risks to occupational health. Outdoor workers, including construction laborers, street vendors,

industrial employees, and traffic police, experience continuous exposure to high pollutant concentrations, especially during winter and pre-monsoon periods when $PM_{2.5}$, PM_{10}, NO_2, and SO_2 concentration levels peak. Such exposures have been associated with increased risks of respiratory ailments, cardiovascular conditions, and reduced work efficiency. Assessing pollutant levels in Ajmer and Alwar cities provides insights into potential occupational exposure risks and supports the development of mitigation strategies for outdoor workers. Therefore, understanding spatio-temporal pollution patterns is not only vital for environmental assessment but also for developing targeted occupational health and safety interventions.

The present study was undertaken to fill this research gap by evaluating seasonal variations in ambient air quality and associated meteorological influences in Ajmer and Alwar, two rapidly urbanizing districts of Rajasthan, India. These locations were selected due to their contrasting urban profiles, Ajmer being a pilgrimage and educational hub with growing traffic emissions, while Alwar represents an industrially active region within the NCR influence zone. Rajasthan's semi-arid climate, frequent dust resuspension, and increasing urban expansion provide an ideal setting to investigate how meteorological conditions interact with air pollutants. This study aims to provide a comprehensive assessment of the spatiotemporal dynamics of air pollutants in this specific part of Rajasthan, contributing region-specific insights for future air quality management and policy formulation. Accordingly, the present study aimed to evaluate ambient air parameters across different seasons and locations, and to examine the influence of meteorological factors on urban air quality in Ajmer and Alwar, Rajasthan, India.

2. Materials and Methods

The largest state of India i.e., Rajasthan, covers an 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[30]. Rajasthan has a prosperous history and rich cultural heritage, famous for its majestic beautiful forts, beautiful decorative Havelis, ornamented temples and distinctive architectural monuments. The geographical features of Rajasthan include the Aravalli Range. Rajasthan lies in the northwestern part of India and is characterized by a dry, hot semi-arid climate, famous as the "Thar Desert", marked by scorching summers, short monsoon seasons, and cool winters. The present study was conducted in two prominent districts of Rajasthan: Ajmer and Alwar, which represent distinct environmental and urban settings. Each of these regions has unique geographical features: Ajmer is located in the center of Rajasthan and surrounded by the Aravalli Range, is known for its pilgrimage, educational centers, and it also has a significant industrial presence. While Alwar lies in the northeastern part of the state, close to NCR, New Delhi, is an emerging industrial hub. Its terrain is varied, with flat plains and craggy hills. 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 two major ambient air quality monitoring locations of Rajasthan were selected, Civil Lines, Ajmer (26°26'59.6256"N, 74°38'23.6940"E), and Moti Doongri, Alwar (27°33'39.3552"N, 76°37'30.0540"E) (Figure. 1), based on the availability of continuous monitoring data, and their representation of urban residential and mixed land-use areas. It gives a comprehensive understanding of air pollution concentration levels in major urban centers of Rajasthan. These sites are part of the Continuous Ambient Air Quality Monitoring Stations (CAAQMS) network operated by the Central Pollution Control Board (CPCB), New Delhi. Air quality data for key pollutants, including $PM_{2.5}$, PM_{10}, NO_2, SO_2, and O_3, were obtained from the CPCB's online air quality data portal[31]. The data span from January 2018 to December 2023, covering multiple seasons (summer, monsoon, post-monsoon, and winter). For each site, hourly data were downloaded and used to compute daily and seasonal averages for subsequent analysis.

2.1 Data Quality Control

The CPCB ensures data quality through standard protocols, including routine calibration, instrument maintenance, and comprehensive Quality Assurance/ Quality Control (QA/QC) procedures. The selected monitoring locations and the study period (2018-2023) enabled a robust assessment of spatial and temporal variations in major air pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2, and O_3) and their relationship with meteorological parameters across contrasting urban environments in

Rajasthan. All CPCB datasets were screened for missing, negative, or anomalous values before analysis. Monthly averages were computed only when ≥75% of daily data were available to maintain statistical reliability. Outliers beyond the 1st and 99th percentiles were examined and excluded if found to result from instrument malfunction or data transmission errors. Data processing, cleaning, and quality validation were conducted using OriginPro and Microsoft Excel, following CPCB QA/QC guidelines.

2.2 Study Area Selection

Rajasthan, with its varied geographic and socio-economic landscape, presents unique challenges and opportunities for studying the interaction between urban development, industrial activities, and environmental health. The cities selected are Ajmer and Alwar, were chosen based on secondary data availability of air pollution concentration in 2018-2023 and multifaceted criterion that reflects the objectives of the study. The selection of these cities aligns closely with the study's objectives to explore the spatio-temporal variations in air pollutant concentrations across two selected study sites spanning the years 2018 to 2023. Additionally, these stations monitor key meteorological factors such as WS, WD, T, and RH. By including cities with varying pollution levels, industrial activities, and climatic conditions, the study is well-poised to address how urbanization and industrialization affect environmental health in Rajasthan. The Rajasthan State diligently monitors Ambient Air Quality utilizing a network of two CAAQMS, overseen by the Rajasthan State Pollution Control Board (RSPCB). This comprehensive monitoring effort is part of the National Air Quality Monitoring Programme (NAMP). Under the NAMP framework, the monitoring stations ensure round-the-clock surveillance of air pollutant concentrations. This continuous monitoring enables authorities to track fluctuations in air quality in real-time and to assess efficacy of pollution control measures over time.

2.3 Statistical Analysis

Correlation and regression were calculated between the criteria pollutants and meteorological parameters in order to investigate their relationship. These analyses were performed seasonally to assess the role of meteorological conditions in pollutant dispersion and accumulation at Ajmer and Alwar. Statistical analyses (Correlation and regression) were performed by using statistical software SPSS and OriginPro. WS and WD were statistically analyzed using Wind Rose (WRPlot) diagrams generated in (software name, WRPLOT View).

3. Results

3.1 Data Interpretation in Air pollution in Ajmer and Alwar

In our studies AQI values of $PM_{2.5}$, PM_{10}, NO_2, SO_2, and O_3 concentration levels were discussed for 2018 to 2023 during four seasons: Winter (December to February), pre-monsoon (March to May), monsoon (June to September), and post-monsoon (October to November), highlighting the highest and lowest recorded AQI in each

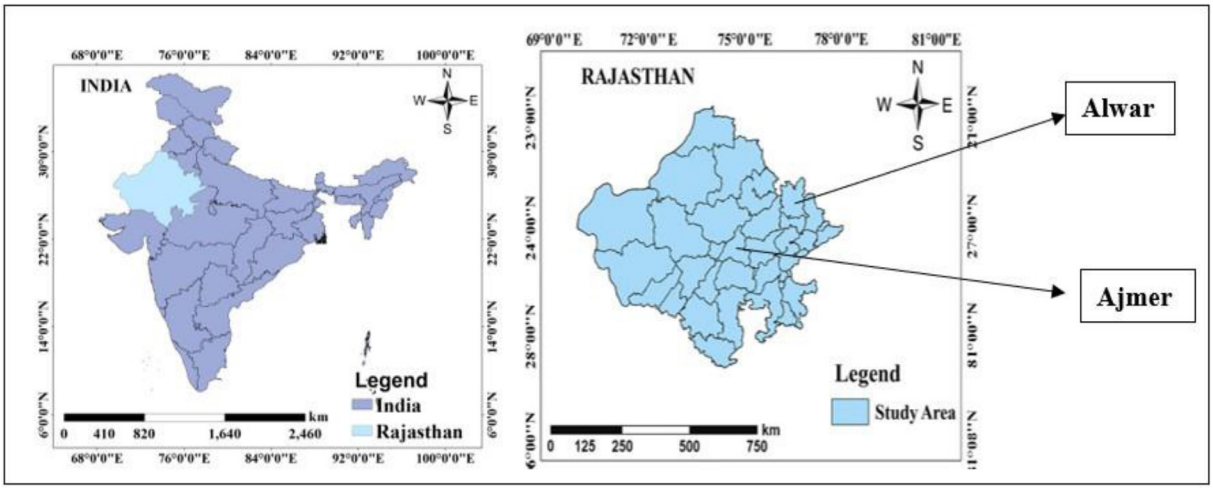


Figure 1. The air quality and meteorological monitoring station in Rajasthan state, India .

city along with scientific reasoning for these variations in Ajmer and Alwar monitoring stations, Rajasthan, India (Figure 2(a-j)).

3.1.1 Quantifying Air Quality Index (AQI) $PM_{2.5}$ Across the Cities of Ajmer and Alwar in Various Seasons of the Years 2018 to 2023

Generally, the $PM_{2.5}$ levels show seasonal variability with higher values in the cooler months and lower values during monsoon season. $PM_{2.5}$ levels in 2020 were generally lower compared to other years, possibly due to reduced activities during COVID-19 lockdowns. Levels appear to be slightly increasing in 2023 across several months. November generally has the highest $PM_{2.5}$, while the months of July and August typically have the lowest as shown in Figure 2a.

Similar to Ajmer, there's a seasonal pattern with higher pollution in winter months and lower in monsoon and summer in Alwar. The year 2020 again shows a dip, likely reflecting lockdown effects. The year 2023 shows a notable increase in January, November, and December. November 2023 shows exceptionally high levels, the highest across the analysed period as shown in Figure 2b. Both of the cities show higher $PM_{2.5}$ levels in colder months, possibly due to increased heating requirements and atmospheric conditions that trap pollutants closer to the ground. There is a notable decrease in $PM_{2.5}$ levels during 2020 across all cities, likely due to reduced human, vehicular and industrial activity during COVID-19 lockdowns. Recently, a general uptick in pollution levels in 2023 could indicate a rebound in industrial, vehicular, and other human activities post-lockdown.

3.1.2 Quantifying Air Quality Index (AQI) PM_{10} Across the Cities of Ajmer and Alwar in Various Seasons of the Years 2018 to 2023

In Ajmer, the highest recorded AQI stood at 180µg/m³ in January 2020, attributed to escalated domestic heating and stable atmospheric conditions impeding pollutant dispersion. Conversely, the lowest recorded AQI of 70µg/m³ in December 2018 was facilitated by favourable winds that effectively dispersed pollutants, as shown in Figure 2c. In May 2019, AQI peaked at 160µg/m³ due to escalating T and heightened dust movement. Whereas, April 2021 saw lowest AQI at 60µg/m³, attributed to the onset of seasonal rains, facilitating the settling of dust particles as shown in Figure 2c. July 2020 witnessed highest AQI at 95µg/m³, owing to sporadic dry spells and construction-related dust. In August 2019, reported lowest AQI at 30µg/m³, as regular monsoon rains significantly diminished airborne dust and particulate matter as shown in Figure 2c. October 2021 recorded highest AQI at 150µg/m³, attributable to residue burning in nearby regions and the resumption of industrial activities. Conversely, November 2018 saw lowest AQI at 45µg/m³, owing to improved meteorological conditions aiding in pollutant dispersion as shown in Figure 2c.

In Alwar, during winter, highest recorded AQI soared to 195µg/m³ in January 2021, primarily attributed to cold T and elevated RH levels, which trapped pollutants near the surface. Conversely, the lowest AQI of 80µg/m³ in December 2019 was experienced due to the presence of strong post-monsoon winds that provided enhanced dispersion conditions as shown in Figure 2d. Moving to the pre-monsoon season, April 2020 witnessed the highest AQI at 170µg/m³, driven by heightened vehicular emissions and intensified industrial activities. In contrast, March 2022 reported lowest AQI at 65µg/m³, as stricter pollution control measures were enforced as shown in Figure 2d. Transitioning into the monsoon season, July 2018 recorded highest AQI at 100µg/m³, with humid conditions exacerbating particle coagulation. Conversely, June 2021 saw lowest AQI at 25µg/m³, owing to consistent and heavy rainfall effectively cleansing the air as shown in Figure 2d. Finally, during post-monsoon, October 2019 registered the highest AQI at 160µg/m³, primarily due to agricultural stubble burning in neighbouring states impacting local air quality. Conversely, November 2020 reported lowest AQI at 50µg/m³, with reduced agricultural burning activities and improved weather conditions as shown in Figure 2d.

Seasonal and site-wise variation of $PM_{2.5}$ and PM_{10}-based AQI (2018-2023): In Ajmer (Figure 2a and 2c), AQI-$PM_{2.5}$ ranged between 90-180µg/m³, while AQI-PM_{10} varied between 80-170µg/m³ during 2018-2023. Winter showed highest levels of both $PM_{2.5}$ and PM_{10} ($PM_{2.5}$: 150-180µg/m³; PM_{10}: 140-170µg/m³) due to stagnant atmospheric conditions, reduced WS, and high local emissions from industry and traffic. During pre-monsoon, levels remained moderate ($PM_{2.5}$: 110-150µg/m³; PM_{10}: 120-160µg/m³) owing to biomass burning, dust resuspension and vehicular emissions. The monsoon season experienced lowest AQI values ($PM_{2.5}$: 70-100µg/m³; PM_{10}: 80-110µg/m³) because of rainfall-induced pollutant washout. Post-monsoon months exhibited a rising trend ($PM_{2.5}$: 100-140µg/m³; PM_{10}:

120-150μg/m³) leading up to winter accumulation. Yearly comparison indicated elevated levels in 2019 and 2021, while 2020 reflected a marked decline linked to restricted anthropogenic activities. In Alwar (Figure 2b and 2d), AQI-$PM_{2.5}$ values fluctuated between 100-200μg/m³, whereas AQI-PM_{10} ranged from 110-220μg/m³. Winter months recorded highest values ($PM_{2.5}$: 160-200μg/m³; PM_{10}: 180-220μg/m³), attributed to calm winds and high atmospheric stability. During pre-monsoon, moderate levels were observed ($PM_{2.5}$: 130-170μg/m³; PM_{10}: 150-190μg/m³) due to dry, dusty conditions. Monsoon brought a significant reduction ($PM_{2.5}$: 70-110μg/m³; PM_{10}: 90-130μg/m³). Post-monsoon levels rose again ($PM_{2.5}$: 120-160μg/m³; PM_{10}: 130-180μg/m³) before winter buildup. The highest concentrations occurred in 2019 and 2023, while 2020 remained comparatively cleaner. Yearly variations mirror Ajmer's pattern, with 2020 showing significantly lower PM due to pandemic-induced activity reductions, and 2023 demonstrating a resurgence in pollutant levels corresponding to resumed industrial, vehicular, and commercial activity.

3.1.3 Quantifying Air Quality Index (AQI) NO_2 Across the Cities of Ajmer and Alwar in Various Seasons of the Years 2018 to 2023

Ajmer in December, the NO_2 levels start to rise during winter, with a recorded average of 42.3μg/m³. This increase could be attributed to the increased usage of heating appliances and vehicles in colder weather. In January, the peak of winter shows a further increase in NO_2 levels, with an average of 47.6μg/m³. This could be due to stagnant air conditions that trap pollutants closer to the ground. In February, as winter starts to recede, there is a slight decrease in NO_2 levels, averaging around 39.8μg/m³. This may be due to improving weather conditions, allowing for better dispersion of pollutants. The average NO_2 level in winter is approximately 43.2μg/m³. Winter months show the highest concentrations of NO_2 in Ajmer, which could be largely due to heating and limited atmospheric dispersion as shown in Figure 2e. During pre-monsoon, in March, with the onset of warmer weather, NO_2 levels show a slight decrease to around 35.4μg/m³. The increase in T and sunlight may start to disperse the pollutants. In April, the levels further dropped to about 31.7μg/m³, possibly due to continued increase in T and possibly more mixing in the atmosphere. In May, before the monsoon, the levels reach their lowest pre-monsoon point at about 29.1μg/m³. The average NO_2 level in the pre-monsoon season is around 32.1μg/m³. This season experiences a steady decrease in NO_2 levels, likely due to better atmospheric conditions for dispersion and the absence of heating requirements, as shown in Figure 2e. During monsoon, in June, the onset of the monsoon brings further relief, reducing NO_2 levels to about 27.8μg/m³. The rains help in washing away the pollutants. In July, during peak monsoon, the levels further decrease to around 24.5μg/m³. In August, sustained monsoon conditions keep the levels low, at about 23.6μg/m³. In September, as the monsoon starts to withdraw, there is a slight increase in NO_2 levels to 25.4μg/m³. The average NO_2 level during the monsoon is around 25.3μg/m³. The monsoon season typically records the lowest levels of NO_2 due to rain and strong winds that help in dispersing air pollutants as shown in Figure 2e. During post-monsoon, in October, leads to a slight increase in NO_2 levels to about 30.2μg/m³ as the rain reduces and stagnant conditions begin to appear. In November, with the onset of cooler T, NO_2 levels rise to about 36.5μg/m³. The average NO_2 level in post-monsoon season is approximately 33.4μg/m³. This season sees a rise in NO_2 levels as the weather conditions start to favour the accumulation of pollutants as shown in Figure 2e.

In Alwar, during Winter, in December, average NO_2 Level is found to be 44μg/m³, Winter in Alwar, as in many north Indian cities, starts with moderate levels of NO_2 due to colder T and higher usage of fossil fuels for heating, leading to poor dispersion of air pollutants. In January, average NO_2 Level is recorded to be 50μg/m³: The NO_2 levels peak during January, potentially due to increased vehicular and industrial activity alongside adverse meteorological conditions that trap pollutants near the surface. In February, NO_2 Level is observed to be 42μg/m³. There is a slight decline in NO_2 levels as the season transitions towards spring, with improved dispersion conditions. The average NO_2 concentration is around 45.3μg/m³. Winter typically records the highest levels due to increased heating requirements and stagnant atmospheric conditions as shown in Figure 2f. During pre-monsoon, in March, NO_2 Level: 38μg/m³. As T begins to rise, the heating-related emissions decrease, and atmospheric mixing increases, resulting in lower NO_2 concentrations. In April, average NO_2 level: 35μg/m³. Continued improvement in weather conditions aids the dispersal of NO_2, slightly lowering the concentrations further. In May, average NO_2 level: 33μg/

m^3. The lowest pre-monsoon NO_2 levels are seen in May, just before the onset of the monsoon rains. The average NO_2 concentration during this season is approximately 35.3μg/m^3, reflecting a trend of decreasing NO_2 levels due to better dispersion and reduced heating usage as shown in Figure 2f. During monsoon, in June, average NO_2 Level: 30μg/m^3. The onset of the monsoon with its rains significantly helps in washing out the atmospheric pollutants, including NO_2. In July, average NO_2 level: 27μg/m^3. Peak monsoon conditions lead to lowest NO_2 levels, due to persistent rains and reduced outdoor activities. In August, average NO_2 level: 28μg/m^3. Similar conditions persist through August with slight variations due to the intensity of monsoonal rains. In September, average NO_2 level: 29μg/m^3. As the monsoon starts retreating, there's a minor increase in NO_2 levels, yet they remain significantly lower than other months. The monsoon season exhibits the lowest NO_2 levels with an average around 28.5μg/m^3, benefiting from rain-induced scavenging of pollutants as shown in Figure 2f. During post-monsoon, In October, average NO_2 level: 34μg/m^3. Post-monsoon, there is a gradual increase in NO_2 as the atmospheric conditions start to stabilize and agricultural and festive activities potentially increase. In November, average NO_2 level: 37μg/m^3 with the approach of winter, the levels increase slightly, influenced by crop residue burning in surrounding areas and preparation for colder T. The average NO_2 concentration is around 35.5μg/m^3, marking a transition phase where levels start to climb again due to seasonal human activities and changing weather patterns as shown in Figure 2f.

Seasonal and Site-wise Variation of NO_2 and SO_2-based AQI (2018-2023): In Ajmer (Figure 2e), AQI-NO_2 varied between 20-55μg/m^3 during 2018-2023. Winter months showed the highest NO_2 levels (45-55μg/m^3) due to increased fossil fuel combustion, low boundary layer height, and limited dispersion. During pre-monsoon, moderate levels (30-40μg/m^3) were observed, influenced by traffic and resuspension emissions. The monsoon season displayed the lowest concentrations (20-30μg/m^3) owing to rainfall scavenging and enhanced dilution. Post-monsoon months exhibited a sharp rise (35-50μg/m^3). Yearly analysis revealed higher NO_2 values in 2019 and 2022, while 2020 showed a distinct decline during the lockdown. In Alwar (Figure 2f), AQI-NO_2 ranged from 25-60μg/m^3. Winter displayed the highest concentrations (45-60μg/m^3), likely due to stagnant meteorological conditions and heavy vehicular activity. The pre-monsoon levels were moderate (30-45μg/m^3), while monsoon values dropped considerably (20-30μg/m^3). The post-monsoon rise (40-55μg/m^3) corresponded to resumed anthropogenic emissions. Yearly variation showed peaks in 2018 and 2021, whereas 2020 recorded reduced NO_2.

3.1.4 Quantifying Air Quality Index (AQI) SO_2 Across the Cities of Ajmer and Alwar in Various Seasons of the Years 2018 to 2023

The winter season in Ajmer city, spanning January to February, witnessed notable fluctuations in SO_2 levels over the past six years. In 2018, the average SO_2 concentration was alarmingly high at 44.91μg/m^3, indicating significant air pollution. However, there was a remarkable improvement in 2019, with levels dropping substantially to an average of 6.58μg/m^3, suggesting effective mitigation measures or environmental factors contributing to cleaner air. Despite this, there was a slight increase in 2020, averaging at 6.08μg/m^3, followed by a further marginal rise in 2021 to 7.99μg/m^3. However, the trend took a concerning turn in 2022, with a noticeable rise in SO_2 levels, averaging at 12.42μg/m^3, indicating a potential deterioration in air quality. This upward trajectory continued in 2023, recording the highest average SO_2 level in recent years at 18.12μg/m^3, signifying a significant escalation in air pollution during the winter months. Such fluctuations underscore the importance of continuous monitoring and targeted interventions to address air quality challenges in Ajmer city during the winter season, as shown in Figure 2g. In pre-monsoon, Ajmer city experienced notable variations in SO_2 levels. In May 2018, exceptionally high levels significantly skewed the average to 30.18μg/m^3. Subsequent years, however, showed lower and more consistent levels, with averages of 6.29μg/m^3 in 2019 and 7.32μg/m^3 in 2020. Levels saw an increment in 2021 (10.02μg/m^3) and a further increase in 2022 (16.40μg/m^3). However, 2023 saw a slight decrease compared to 2022, with an average of 14.29μg/m^3. as shown in Figure 2g. During monsoon, Ajmer city witnessed fluctuations in SO_2 levels. In 2018, initial high levels gradually decreased, averaging at 34.79μg/m^3. However, there was a significant drop in 2019, with an average of 6.09μg/m^3, followed by a slight increase in 2020 to 8.15μg/m^3. In 2021, there was a notable surge in levels, particularly in August, reaching an average of 18.09μg/m^3. The year 2022 exhibited high variation, with a peak in July averaging at 21.05μg/m^3. However, 2023

saw a reduction compared to 2022, with an average of 13.35μg/m³ as shown in Figure 2g. In post-monsoon, Ajmer city experienced fluctuations in SO_2 levels. In 2018, levels remained consistently high, averaging at 43.10μg/m³. However, there was a significant drop in 2019, with an average of 6.56μg/m³. Subsequently, in 2020, there was a slight increase to 8.86μg/m³. This trend continued in 2021, with a further increase to 14.17μg/m³. However, in 2022, levels were lower than in 2021, averaging at 15.55μg/m³. Finally, in 2023, there was a slight decrease compared to 2022, with an average of 11.54μg/m³ as shown in Figure 2g.

In Alwar city, the analysis of SO_2 levels during winter reveals consistent patterns over the years. In 2018, levels remained moderate, averaging at 12.21μg/m³. There was a slight increase observed in 2019, with levels peaking in February at an average of 13.83μg/m³. The year 2020 witnessed a marked increase, particularly in February, with significant spikes observed, averaging at 17.63μg/m³. However, in 2021, levels slightly decreased compared to 2020, stabilizing at an average of 11.19μg/m³. Subsequently, in 2022 and 2023, SO_2 levels remained relatively similar to the previous years, maintaining stability with averages of 12.76μg/m³ and 12.09μg/m³, respectively, as shown in Figure 2h. During pre-monsoon season in Alwar, SO_2 levels displayed varying trends over the years. In 2018, the season started with low levels in March but peaked in May, averaging at 9.87μg/m³. Subsequently, in 2019, levels were notably higher, particularly pronounced in March and May, averaging at 15.54μg/m³. The year 2020 recorded the highest levels in this season, with May showing a slight decrease compared to other months, averaging at 15.97μg/m³. In 2021, there was a slight reduction in SO_2 levels, although a consistent rise was observed into May, averaging at 11.83μg/m³. Similarly, in 2022, the profile resembled that of 2021, with a slight increase in May, averaging at 13.50μg/m³. Notably, in 2023, SO_2 levels were significantly higher, especially in May, averaging at 15.34μg/m³, indicating a possible environmental concern during this period, as shown in Figure 2h. During monsoon in Alwar, SO_2 levels exhibited diverse trends across different years. In 2018, levels ranged from moderate to high, peaking in July with an average of 13.89μg/m³. The subsequent year, 2019, saw higher levels overall, with a peak in September at an average of 14.06μg/m³. Conversely, 2020 experienced generally lower SO_2 levels, although a slight increase was observed towards September, averaging at 11.54μg/m³. In 2021, a similar pattern to 2020 emerged, albeit with slightly higher levels averaging at 11.98μg/m³. However, 2022 marked an increase in SO_2 levels, notably high in July and August, averaging at 15.06μg/m³. Remarkably, 2023 witnessed elevated levels throughout the season, peaking in October with an average of 18.08μg/m³, suggesting potential environmental concerns during this period as shown in Figure 2h. Post-monsoon in Alwar witnessed variable SO_2 levels annually. In 2018, they ranged from low to moderate, with a slight uptick in December. Conversely, 2019 saw an increasing trend, notably peaking in December. This pattern persisted in 2020, with a peak in October. However, 2021 showed slightly lower levels overall. In contrast, 2022 recorded slightly higher levels, trending upward towards December. Notably, 2023 exhibited a significant increase, particularly in October and November as shown in Figure 2h.

In Ajmer (Figure 2g), AQI-SO_2 varied between 5-25μg/m³. Winter showed slightly elevated concentrations (15-25μg/m³) due to domestic fuel use and low dispersion. Pre-monsoon levels were moderate (10-15μg/m³), while monsoon showed the lowest values (5-10μg/m³) due to rainfall washout. Post-monsoon displayed a marginal increase (10-20μg/m³). Yearly, 2019 and 2023 showed slight increases, while 2020 reflected the cleanest air. In Alwar (Figure 2h), SO_2 concentrations ranged between 10–30μg/m³. Winter values peaked (20-30μg/m³), pre-monsoon remained moderate (15-25μg/m³), and monsoon exhibited minima (10–15μg/m³). A small post-monsoon rise (20-25μg/m³) was observed. The highest yearly levels occurred in 2018 and 2021, while 2020 declined significantly.

3.1.5 Quantifying Air Quality Index (AQI) O_3 Across the Cities of Ajmer and Alwar in Various Seasons of the Years 2018 to 2023

In Ajmer, the ozone levels during winter are generally lower compared to other seasons. The highest recorded level in this period from 2018 to 2023 was 52.094μg/m³ in February 2018, and the lowest was 19.637μg/m³ in December 2022. The average ozone density tends to decrease over the years, indicating possible improvements in emissions control or changes in meteorological conditions that suppress O_3 formation, such as lower sunlight and colder T. The impact of the COVID-19 lockdowns during winters of 2020 and 2021 is noticeable with generally lower O_3 levels, reflecting reduced vehicular and industrial activities as shown in Figure 2i. This season typically experiences the highest ozone levels

in Ajmer. The peak concentration was 73.190μg/m³ in May 2018, while the lowest was 31.523μg/m³ in March 2022. The high levels during this season can be attributed to increased solar radiation and higher T which facilitate the photochemical production of ozone. However, during the lockdowns in 2020 and 2021, there was a slight dip in the typical annual increase, suggesting a reduction in precursor emissions from traffic and industry during these months as shown in Figure 2i. Ozone levels during the monsoon are naturally lower due to increased cloud cover and rainfall, which reduce solar radiation and wash out pollutants. The highest level recorded in this season was 55.917μg/m³ in June 2020, and the lowest was 19.104μg/m³ in August 2023. The average ozone concentration typically dips during this period. The monsoon's natural dampening effect on ozone was further enhanced by the lockdowns, which drastically reduced emissions from urban and industrial sources as shown in Figure 2i. Post-monsoon ozone levels in Ajmer show moderate values. The highest concentration was 46.878μg/m³ in October 2018, and the lowest was 21.591μg/m³ in September 2023. Post-monsoon T and reduced rainfall contribute to moderate ozone formation. Moreover, the resumption of normal activities post-lockdown could have influenced the slight increases or stability in O_3 levels observed in late 2020 and 2021 compared to the sharp falls during the lockdowns. However, overall, the trend does not show drastic fluctuations, suggesting a balance between meteorological influences and emission sources as shown in Figure 2i. These observations reflect the complex interplay between meteorological conditions, emission sources, and regulatory actions such as lockdowns, influencing ozone levels in Ajmer across different seasons and years.

In Alwar, ozone levels during winter months tend to be lower than other seasons. The highest recorded level was 49.781μg/m³ in December 2020, while the lowest was 13.604μg/m³ in January 2022. The average density has shown a decreasing trend, especially noticeable post-2020, reflecting the impacts of reduced human and industrial activities during the COVID-19 lockdowns. Cooler T and reduced sunlight during these months also contribute to lower O_3 production as shown in Figure 2j. Ozone concentrations are typically highest during the pre-monsoon season in Alwar, peaking at 76.396μg/m³ in May 2018. The lowest concentration was 19.121μg/m³ in March 2022. This season experiences increased solar radiation and rising T, which enhance ozone formation. The sharp drop in levels in 2020 and 2021 can be attributed to reduced emissions during the lockdowns, affecting the typical seasonal spike in O_3 levels as shown in Figure 2j. During the monsoon, the natural conditions of increased rainfall and cloud cover help lower the ozone levels by washing out pollutants and reducing solar irradiance. The highest level observed was 53.911μg/m³ in June 2019, with the lowest being 13.62μg/m³ in July 2022. The consistent decline in average O_3 levels during the monsoon over the years might also reflect ongoing improvements in emissions controls, alongside the seasonal weather impact as shown in Figure 2j. Post-monsoon O_3 levels show moderate readings with the highest being 42.001μg/m³ in November 2019 and the lowest at 14.348μg/m³ in September 2023. This season is characterized by reducing T and residual moisture, which moderately impacts O_3 formation. The notable decrease in levels post-2020 suggests that the residual impacts of reduced anthropogenic activities during the pandemic may still be influencing lower emissions, though the levels have begun stabilizing as activities resume to normal as shown in Figure 2j. Alwar's O_3 data from 2018 to 2023 indicates a trend of higher concentrations during the warmer pre-monsoon months and lower during the monsoon and winter, impacted by both meteorological conditions and anthropogenic factors. The significant drops during the pandemic years highlight the substantial role that human activities play in influencing air quality. As activities resumed, a gradual normalization of levels was observed, though they remain generally lower than pre-pandemic years, possibly due to ongoing emissions management and environmental policies.

Seasonal and Site-wise Variations in AQI-O_3 (2018-2023): Ajmer (Figure 2i), During pre-monsoon, exhibited elevated O_3 concentrations (60-80μg/m³) due to intense solar radiation and enhanced photochemical oxidation of precursors (NO_x and VOCs). The monsoon season recorded a sharp decline to 30-45μg/m³, resulting from increased humidity, wet scavenging, and reduced sunlight. In the post-monsoon months, O_3 levels rebounded to 50-70μg/m³, while winter concentrations were moderate, ranging between 40-55μg/m³. Yearly analysis showed a gradual rise in average O_3 values, with notable peaks in 2021 and 2023, suggesting an increase in photochemical smog formation due to growing vehicular density and urban activities. Alwar (Figure. 2j), showed high O_3 levels (70-90μg/m³) during the pre-monsoon, influenced by intense photochemical activity and traffic

emissions. The monsoon season marked a significant reduction to 35-50µg/m³, while post-monsoon months exhibited renewed elevation (60-80µg/m³) due to dry, sunny conditions favoring O_3 accumulation. Winter levels remained moderate (45-60µg/m³). Interannual patterns revealed relatively higher concentrations during 2019 and 2022, reflecting meteorological variability and increased precursor emissions from industrial and vehicular sources.

3.2 Annual Variation of Air Pollutants at selected sites of Ajmer and Alwar

Figure 3(a_1 – e_1) compares the annual mean concentrations of five criteria air pollutants in Ajmer during the study period from 2018 to 2023. The highest annual $PM_{2.5}$ and NO_2 mean concentration was recorded in 2018 with approximately 54.22 µg/m³, 30.54 µg/m³, whereas the highest annual mean concentration of PM_{10} (113.38 µg/m³), SO_2 (12.78 µg/m³) and O_3 (46.56 µg/m³) was found in 2022, 2021, and 2020 respectively. Also, the lowest annual mean concentration of $PM_{2.5}$, PM_{10}, NO_2, SO_2, and O_3 was observed in 2020, 2020, 2020, 2019, and 2022 with approximately 39.60 µg/m³, 84.14 µg/m³, 21.00µg/m³, 6.27µg/m³, and 29.33µg/m³ respectively. Unfortunately, the mean yearly values of $PM_{2.5}$, PM_{10}, and NO_2 exceeded the WHO air quality guidelines (20 and 10µg/m³ for PM_{10} and $PM_{2.5}$, and 22µg/m³ for NO_2) throughout the study period. A glance at the Figure. $3b_1$ provided reveals that the annual mean PM_{10} concentrations fluctuated between approximately 84.14µg/m³ and 113.38µg/m³ and had no constant downward or upward trend over the entire study period (2018-2023). The PM_{10} concentration had maximum decreased to 84.14µg/m³ due to COVID-19 lockdown restrictions in 2020. Compared to PM_{10}, annual averages of ambient $PM_{2.5}$ decreased from about 54.22µg/m³ to 39.60µg/m³; a decline of 26.96 percent from 2018 to 2023 and had maximum decreased to 39.60 µg/m³ due to COVID-19 lockdown restrictions in 2020. During the period from 2018 to 2023, among all ambient gaseous air pollutants, only the annual mean concentrations of NO_2 and SO_2 revealed a constant downward and upward trend, respectively (Figure $3c_1$ – d_1). Annual mean NO_2 concentrations declined from approximately 30.54 and 21.00µg/m³ between 2018 and 2023; a sharp fall of 31.23 percent (Figure $3c_1$), and a large decrease of NO_2 (21.00µg/m³) in 2020 due to the COVID-19 lockdown. By contrast, annual SO_2 displayed a considerable upward trend. Its annual mean concentrations increased to approximately 17.92 µg/m³ in 2022, an overall increase of 65.01 percent between 2018 and 2023. O_3 (Figure $3e_1$) had an annual mean concentration fluctuating trend somewhere between 29.33 and 46.56 ppm during the study period from 2018 to 2023.

Figure 4(a_2 - e_2) compares the annual mean concentrations of five criteria air pollutants in Alwar during the study period from 2018 to 2023. The highest annual $PM_{2.5}$, and PM_{10} mean concentration was recorded in 2018, with approximately 52.09µg/m³, and 100.93µg/m³, whereas the highest annual mean concentration of NO_2 (39.90 µg/m³), SO_2 (17.38 µg/m³) and O_3 (44.53 µg/m³) was found in 2023, 2023, and 2019 respectively. Also, the lowest annual mean concentration of $PM_{2.5}$, PM_{10}, NO_2, SO_2, and O_3 was observed in 2020, 2020, 2022, 2021, and 2022 with approximately 40.94 µg/m³, 77.50 µg/m³, 21.43 µg/m³, 11.73 µg/m³, and 20.01 µg/m³ respectively. Unfortunately, the mean yearly values of $PM_{2.5}$, PM_{10}, and NO_2 exceeded the WHO air quality guidelines (20 and 10µg/m³ for PM_{10} and $PM_{2.5}$, and 22 µg/m³ for NO_2) throughout the study period. A glance at Figure 4(a_2 - e_2) provided reveals that the annual mean PM_{10} concentrations fluctuated between

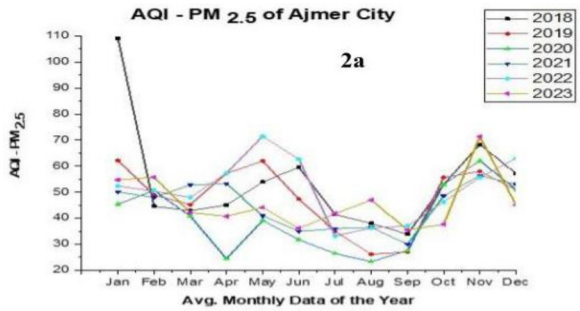


Figure 2a. Average monthly data of AQI-$PM_{2.5}$ of Ajmer City from 2018 to 2023

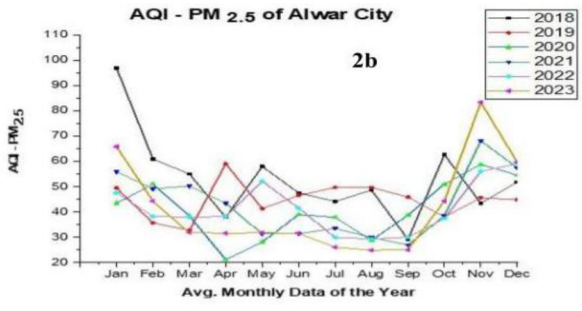


Figure 2b. Average monthly data of AQI-$PM_{2.5}$ of Alwar City from 2018 to 2023

Figure 2(a-j). Quantifying air pollutants at Ajmer and Alwar in various seasons of 2018 to 2023.

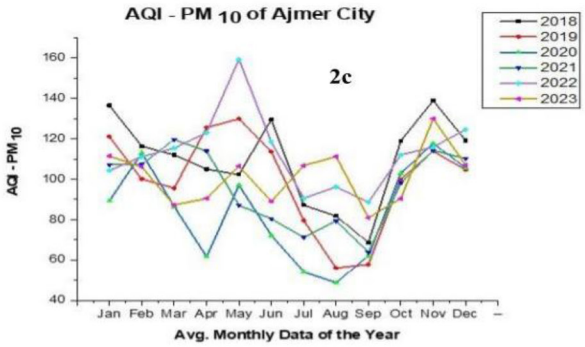


Figure 2c. Average monthly data of AQI-PM_{10} of Ajmer City from 2018 to 2023

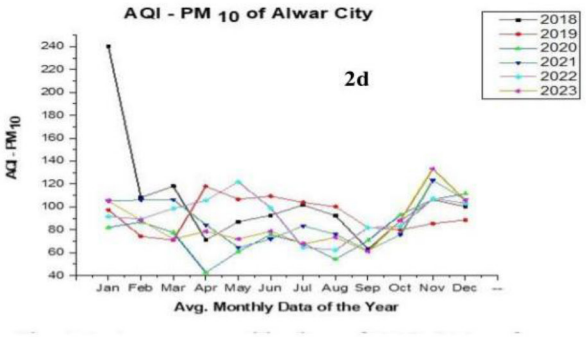


Figure 2d. Average monthly data of AQI-PM_{10} of Alwar City from 2018 to 2023

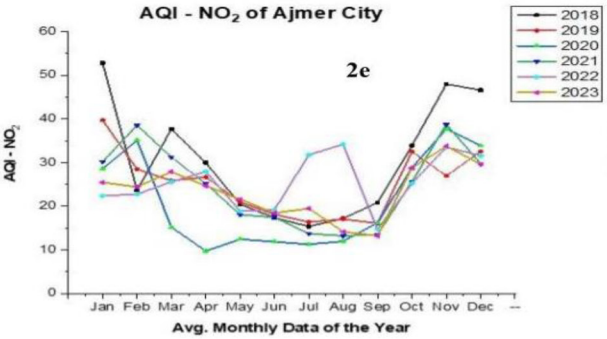


Figure 2e. Average monthly data of AQI-NO_2 of Ajmer City from 2018 to 2023

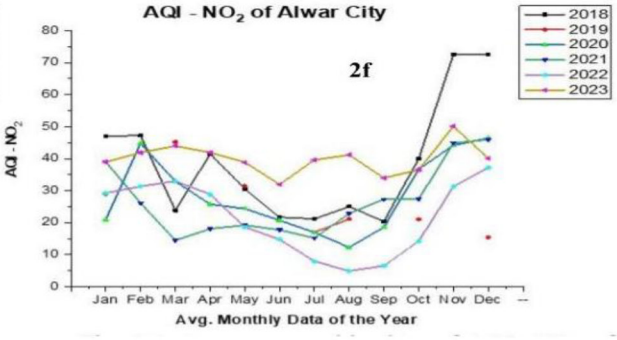


Figure 2f. Average monthly data of AQI-NO_2 of Alwar City from 2018 to 2023

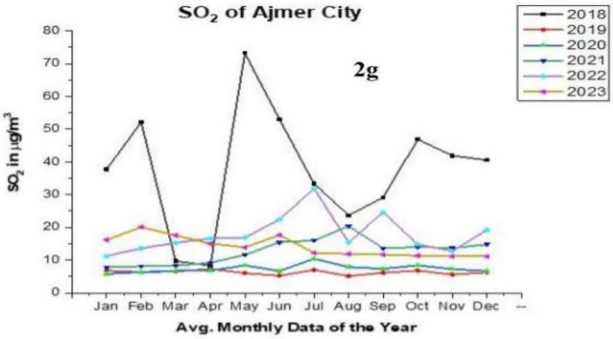


Figure 2g. Average monthly data of AQI-SO_2 of Ajmer City from 2018 to 2023



Figure 2h. Average monthly data of AQI-SO_2 of Alwar City from 2018 to 2023

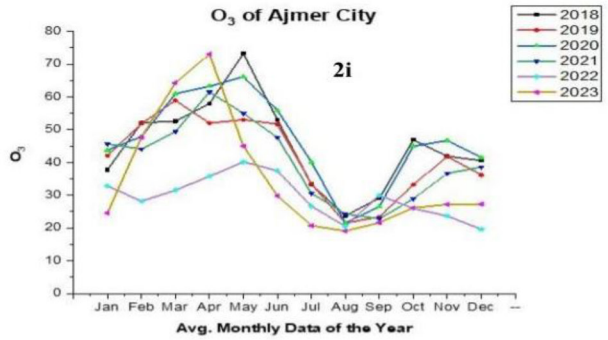


Figure 2i. Average monthly data of AQI-O_3 of Ajmer City from 2018 to 2023

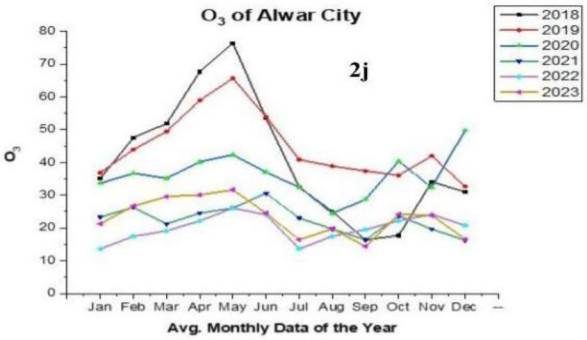


Figure 2j. Average monthly data of AQI-O_3 of Alwar City from 2018 to 2023

Figure 2(a-j). Continued....

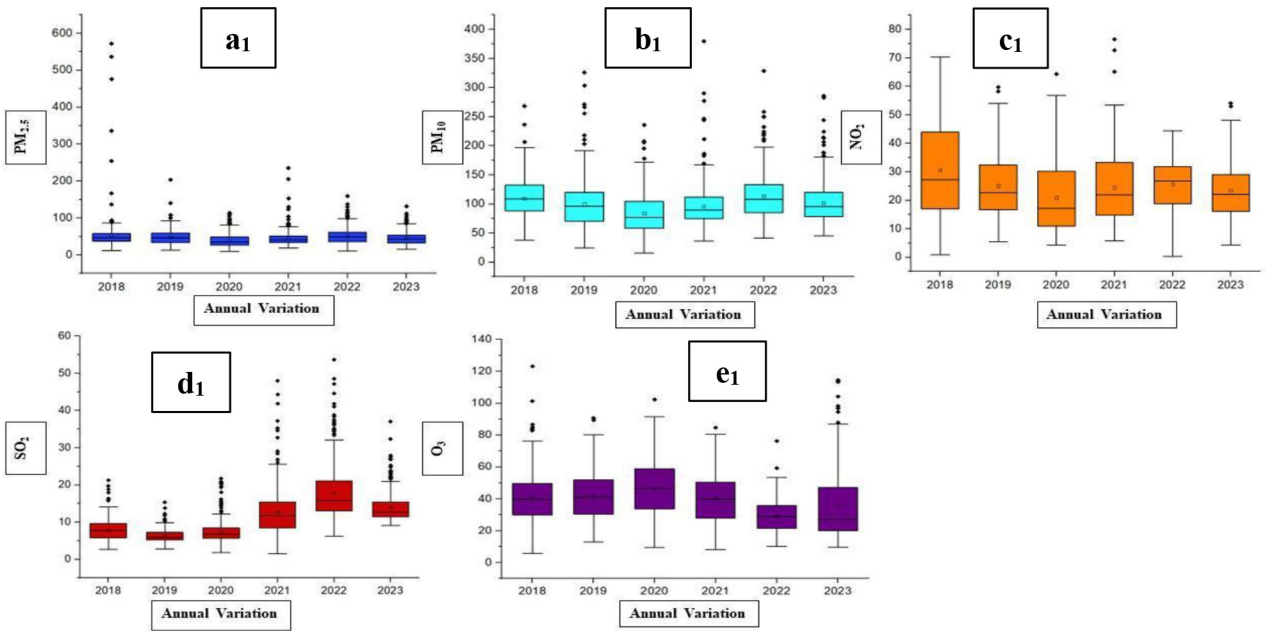


Figure 3(a_1 – e_1). The annual year-boxplot of $PM_{2.5}$, PM_{10}, NO_2, and SO_2, based on 24-hours concentrations, and O_3 based on 8 hours concentrations in Ajmer from 2018-2023.

approximately 100.93 and 77.50 µg/m³; a decline of 23.21 percent from 2018 and 2023 and had constant downward trend over the entire study period (2018-2023). The PM_{10} concentration had maximum decreased to 77.50 µg/m³ due to COVID-19 lockdown restrictions in 2020. Similarly, an annual averages of ambient $PM_{2.5}$ decreased from about 52.09 µg/m³ and 40.94 µg/m³; a decline of 21.40 percent from 2018 and 2023 and had constant downward trend over the entire period (2018-2023). The maximum decreased to 40.94 µg/m³ due to COVID-19 lockdown restrictions in 2020. During the period from 2018 to 2023, among all ambient gaseous air pollutants, only the annual mean concentrations of NO_2 and SO_2 revealed a downward and upward trend, respectively (Figure 4(c_2 and d_2)). Annual mean NO_2 concentrations declined from approximately 38.09 and 21.43 µg/m³ between 2018 and 2022; a sharp fall of 43.74 percent (Figure 4d_2), and an increment approximately 39.90 µg/m³ in 2023, an overall increase of 46.29 percent between 2022 and 2023. By contrast, annual SO_2 displayed a considerable upward trend. Its annual mean concentrations increased to approximately 17.38 µg/m³ in 2023, an overall increase of 32.52 percent between 2018 and 2023. O_3 (Figure 4e_2) had an annual mean concentration fluctuating trend somewhere between 20.01 and 44.53 ppm during the study period from 2018 to 2023, an overall increase of 55.08 percent, respectively.

3.3 Spatial Variation of Air Pollutant Concentration Trends at Ajmer and Alwar

The spatial variation of air pollutant concentrations for the year of 2018-2023 are shown in Figure 5(i-v). The overall year average $PM_{2.5}$ concentration is 47.26 µg/m³ in Ajmer and 44.16 µg/m³ in Alwar, respectively (Figure 5i). In six-years average, the higher PM_{10} concentration was observed in Ajmer (100.64 µg/m³) and Alwar (89.53 µg/m³) which remained above the standard value (Figure 5ii). Over this period (2018-2023), the average NO_2 concentration in Ajmer (25.014 µg/m³) and Alwar (30.43 µg/m³), respectively (Figure 5iii). During 2018-2023, the average SO_2 concentration is 15.36 µg/m³ in Ajmer and 13.79 µg/m³ in Alwar, respectively (Figure 5iv). The average concentration of O_3 (39.41 µg/m³ in Ajmer and 31.02 µg/m³ in Alwar (Figure 5v). During 2018-2023, average concentrations of air pollutants exceeded the Ambient Air Quality Standard (CAAQS), over both the monitoring cities as shown in Figure 5(i-v).

The boxplot was used to evaluate the annual fluctuation of criteria air pollutants at selected sites of Ajmer and Alwar during 2018-2023. In each plot, the lower and upper whisker lines represent the minimum and maximum values, the central box spans from the 25th percentile (lower quartile) to the 75th percentile (upper quartile), and the middle solid line indicates the median. The vertical line extends from the 10th to 90th

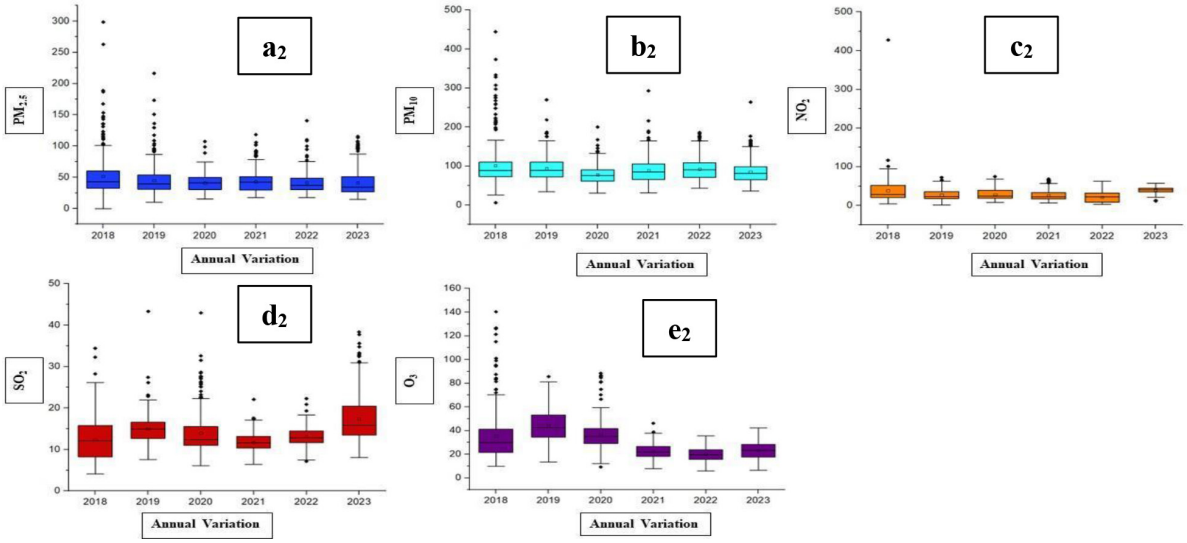


Figure 4(a_2 - e_2). The annual year-boxplot of $PM_{2.5}$, PM_{10}, NO_2, and SO_2, based on 24-hours concentrations, and O_3 based on 8 hours concentrations in Alwar from 2018-2023.

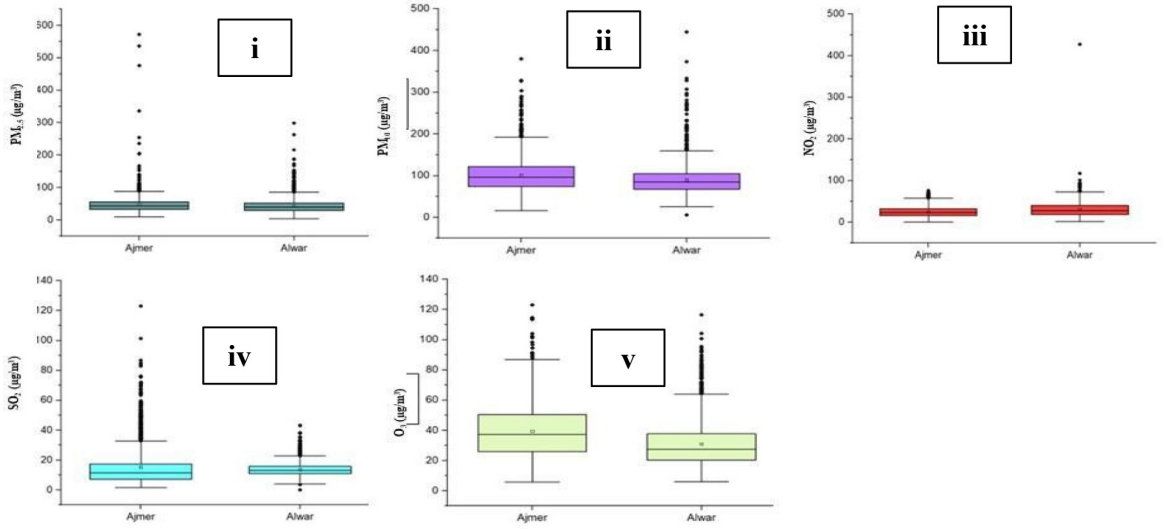


Figure 5(i-v). Spatial variation of air pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2, and O_3, concentrations are expressed inµg/m^3) in Ajmer and Alwar from 2018 to 2023.

percentile, and outliers beyond these limits are shown as dots, indicating isolated high concentration events.

3.4 Data Interpretation of Meteorological Parameters in Ajmer and Alwar

3.4.1 Quantifying Atmospheric Temperature Across the Cities of Ajmer and Alwar in Various Seasons of the Years 2018 to 2023

In winter, T in Ajmer are generally mild, with noticeable variations across the years. January T remained relatively consistent, with 2023 showing a typical T of 14.944°C. February T, however, experienced a rise in 2021 and 2023, peaking at 21.879°C in both years, possibly due to a warmer winter phase as shown in Figure 6a. During pre-monsoon, it sees a significant rise in T, leading into the pre-monsoon heat. March 2021 recorded an especially high average of 28.481°C, indicating an early onset of warmer weather that year. April and May continue this warming trend, with May 2022 reaching up to 35.146°C, showing the typical increase as summer approaches, as shown in Figure 6a. The monsoon months, although still

warm, often have slightly moderated T due to cloud cover and rainfall. July T hover around the 30°C mark, with 2021 showing a typical monsoon T of 30.652°C. August sees a slight decrease, with 2023 recording an average of 28.720°C as shown in Figure 6a. Post-monsoon T in Ajmer showed a gradual cooling, though conditions remain warm in September. September 2023 saw an average T close to that of the monsoon months at 29.154°C. October T are stable around 26°C, with 2023 slightly warmer at 26.941°C. November T gently dip into the lower twenties, marking the transition into winter, with November 2023 averaging 21.220°C as shown in Figure 6a. The atmospheric T in Ajmer displays a clear pattern of seasonal fluctuations, with the highest T observed during the late spring and lowest during winter. Yearly variations such as the particularly warm March in 2021 and the cooler April in 2023 suggest the influence of broader climatic patterns, possibly linked to regional climatic shifts or specific atmospheric phenomena. The consistency in seasonal transitions underscores the predictable climatic cycle in Ajmer, but ongoing monitoring is essential to understand longer-term trends and their implications on local and regional climates.

In Alwar, during December a noticeably colder T was observed, with a slight increase over the years from 15.22°C in 2021 to 16.25°C in 2023. In January, the T remain stable around 13-14°C, with 2023 observing a mild average of 13.18°C. In February, the T fluctuates over the years but shows a notable increase in 2023 to 21.19°C, indicating a significantly warmer late winter compared to other years as shown in Figure 6b. During pre-monsoon, a notable warming trend is visible, particularly in 2022 when T reaches 27.15°C, reflecting an early onset of warmer weather in March. The T averages remain consistently high, peaking in 2022 at 34.13°C. 2023 shows a decrease to 28.53°C, which might indicate variable spring conditions in April. T in May are consistently high, with the highest average T recorded in 2022 at 35.21°C. The year 2023 shows a cooler average of 30.72°C, but still quite warm in May as shown in Figure 6b. During monsoon, high T persists, with a slight decrease observed in 2023 (31.56°C) in June. T remains stable around 30°C, indicating consistent monsoon conditions. 2023 slightly lowers to 29.50°C in July. The T are stable in the high 20s to low 30s, with 2023 recording 30.49°C, suggesting a warm end to the monsoon season in August, as shown in Figure 6b. During post-monsoon, there's an observed increase across the years, peaking in 2023 at 29.86°C in September. T are relatively consistent around the mid-20s, with 2023 slightly warmer at 25.90°C in October. The T in November gradually decreases, averaging around 20-21°C across the years, fitting for the onset of cooler weather in November as shown in Figure 6b.

Alwar experiences a warm climate most of the year, with significant heat during the spring and early monsoon months. The gradual increase in T from winter to spring and a decrease towards the end of the year mark distinct seasonal changes. The highest T typically occur in May and June, while the coldest T are observed in January. Notably, 2022 appears to be a particularly warm year across several months, which may be indicative of broader climatic patterns affecting the region. The variability in spring T, especially noted in 2023, can impact the onset of summer, potentially affecting agriculture and water resources in the region. Regular monitoring and analysis of such data are essential for understanding long-term climate trends and planning accordingly for future environmental and resource management challenges.

3.4.2. Quantifying Relative Humidity across the Cities of Ajmer and Alwar in Various Seasons of the Years 2018 to 2023

During winter, RH levels in Ajmer varied, with the highest recorded in January 2022 at 66.3%, and the lowest in February 2021 at 30.2%. The average humidity across these winters generally increased over the years, potentially due to climatic changes that could be influencing higher moisture retention in the colder months. The significant drop in humidity in February 2021 could be related to unusual meteorological conditions or reduced water vapor emissions due to lesser industrial activity during the ongoing pandemic as shown in Figure 6c. The pre-monsoon months showed an increasing trend in humidity, setting the stage for the monsoon season. The lowest recorded humidity was 17.8% in April 2022, while the highest was in May 2021 at 47.1%. The pre-monsoon months are typically characterized by rising T which can lead to variable humidity levels depending on local weather systems and evaporative sources. The spike in May 2021 could be attributed to the lockdown effects, where reduced pollution may have led to more pronounced nighttime cooling, thereby increasing morning humidity levels as shown in Figure 6c. Monsoon months naturally displayed the highest humidity levels, peaking at 86.8% in July 2023. The lowest during this season was 37.4%

in June 2019. The intensity and onset of the monsoon significantly influence these figures, as southwest monsoon winds bring considerable moisture from the Arabian Sea. The variability, particularly the low in 2019, could be attributed to a delayed or weaker monsoon. The lockdown in 2020 and its lingering effects into 2021 might have also influenced patterns by reducing heat-island effects in urban areas, potentially allowing for more efficient moisture accumulation as shown in Figure 6c. The post-monsoon season observed moderate humidity levels, with a high of 63.2% in November 2019 and a low of 36.9% in October 2018. This period is characterized by the withdrawal of the monsoon and gradually decreasing T. The variations seen across the years could be due to the staggered retreat of the monsoon and varying local weather conditions. Post-monsoon humidity can also be influenced by residual moisture left from the monsoon and the cooling T which affect the dew point and moisture retention in the air as shown in Figure 6c.

In Alwar, winter season shows significant fluctuations in RH. The highest humidity observed was 96.37% in January 2022, indicative of an exceptionally moist winter month, potentially influenced by unusual climatic patterns or increased local moisture sources. The lowest was 47.68% in February 2018. On average, the RH levels in the winter months have been increasing year by year, which could be tied to broader climatic shifts affecting the region. The notably high humidity in 2020 and beyond could also reflect the reduction in pollution and urban heat due to reduced industrial activities during the COVID-19 lockdowns as shown in Figure 6d. The pre-monsoon months are generally drier in Alwar, with the lowest RH recorded at 22.83% in May 2018. However, there has been a gradual increase over the years, reaching a high of 42.47% in April 2020. This increase could be associated with changing meteorological conditions and possibly enhanced evaporation rates as the region warms up before monsoon. The lockdown effects in 2020, leading to reduced atmospheric pollutants, may have allowed for more solar radiation and hence higher evaporation rates, contributing to increased humidity as shown in Figure 6d. Monsoon months are most humid, with August 2022 seeing an unprecedented high of 111.52%. The increase in RH during these months is expected due to the heavy rainfall brought by the monsoon. However, the extraordinary highs in recent years could be influenced by intensified monsoon patterns and possibly the urban sprawl that prevents efficient water drainage, leading to higher local RH. The lockdown period, with its drastic reduction in human activity, might have allowed for more pronounced local climate effects to manifest, such as reduced urban heating, enhancing monsoon intensity as shown in Figure 6d. Post-monsoon humidity remains relatively high as the moisture from the monsoon lingers. September 2022 and 2023 consistently saw humidity levels around 111%, decreasing gradually towards November. The post-monsoon period typically experiences a reduction in humidity as the T starts to drop, but recent years have shown sustained high levels, potentially due to lingering monsoon effects and increased water retention in the environment. This could be further influenced by ongoing climate change effects, which alter the traditional patterns of the seasons as shown in Figure 6d.

3.4.3 Quantifying Wind Speed Across the Cities of Ajmer and Alwar in Various Seasons of the Years 2018 to 2023

During winter months in Ajmer, WS tend to be higher compared to other seasons. The highest recorded speed was in February 2018 at 2.94 m/sec, with January 2019 following at 2.20 m/sec. The lowest speeds were noted during lockdown period in 2021, influenced by a drastic reduction in human activities and possibly less atmospheric turbulence due to reduced heat emissions from urban activities. Average speeds ranged around 1.0 m/sec to 2.0 m/sec. The 2020-2021 lockdown likely contributed to lower atmospheric disturbances, resulting in reduced WS as shown in Figure 6e. Pre-monsoon season in Ajmer shows a progressive increase in WS, reaching their peak in May 2018 at 3.39 m/sec, which could be attributed to the increasing T gradients during these months. The lowest speeds were observed in 2021 during lockdown, particularly in May at 1.05 m/sec, underscoring the impact of reduced anthropogenic activities and possibly altered meteorological conditions. On average, WS in these months were moderate, generally staying above 1.5 m/sec as shown in Figure 6e. Monsoon months see fluctuating WS due to changing weather patterns, with the highest WS in June 2018 at 4.16 m/sec, which drops significantly in subsequent years, especially in 2020 and 2021, potentially due to global meteorological changes and the lockdown effect. The lowest WS during monsoon was in August 2020 at 0.95 m/sec. The average WS during these months tended to hover around 2.0 m/sec, influenced by seasonal storms

and varying rainfall patterns as shown in Figure 6e. Post-monsoon winds in Ajmer are generally lower than other seasons. The highest speed in this period was recorded in September 2019 at 2.47 m/sec, whereas the lowest was in November 2020 at 0.37 m/sec during the pandemic's impact phase. The average WS during this period are relatively subdued, often around 1.0 m/sec to 1.5 m/sec. This can be attributed to the settling down of monsoon activities and the beginning of the colder, calmer winter conditions as shown in Figure 6e. Throughout 2018 to 2023, Ajmer's WS demonstrate a clear influence from seasonal meteorological conditions, emission sources, and significant impacts from the 2020-2021 lockdowns. These factors combined have led to variations in wind behavior, showcasing higher speeds in pre-monsoon and generally lower during lockdown periods, reflecting the complex interplay of human activities and natural weather dynamics in urban environments.

In Alwar, WS during winter show variability with some years exhibiting slight increases. The highest recorded speed during these months was in February 2019 at 1.85 m/sec, possibly influenced by seasonal climatic changes such as Western Disturbances which are common in northern India during winter. The lowest speed was recorded in January

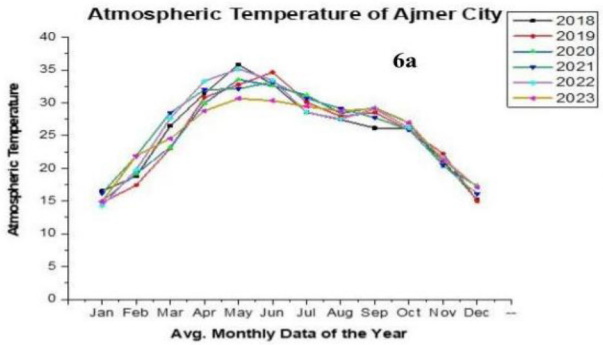


Figure 6a. Average monthly data of Atmospheric Temperature of Ajmer City from 2018 to 2023

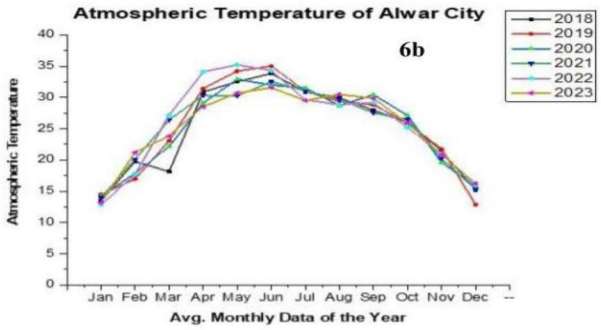


Figure 6b. Average monthly data of Atmospheric Temperature of Alwar City from 2018 to 2023

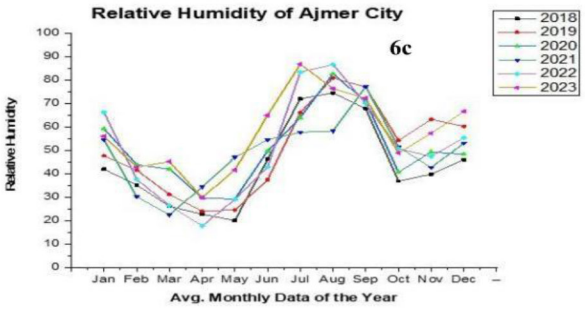


Figure 6c. Average monthly data of Relative Humidity of Ajmer City from 2018 to 2023

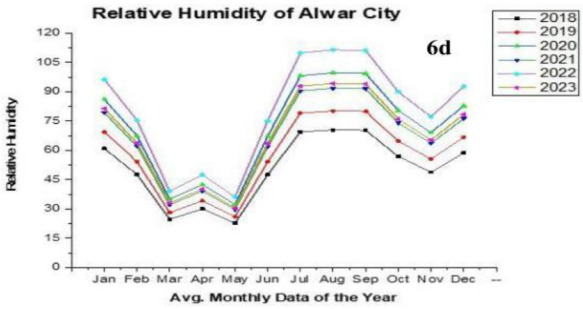


Figure 6d. Average monthly data of Relative Humidity of Alwar City from 2018 to 2023

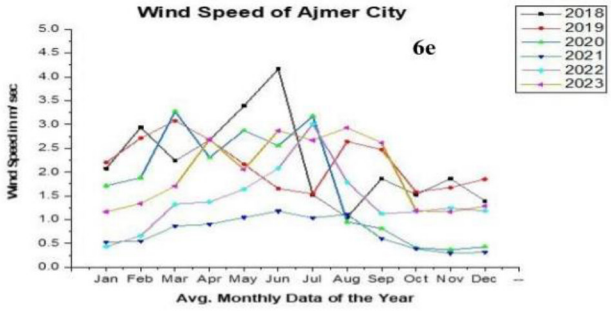


Figure 6e. Average monthly data of Wind Speed of Ajmer City from 2018 to 2023

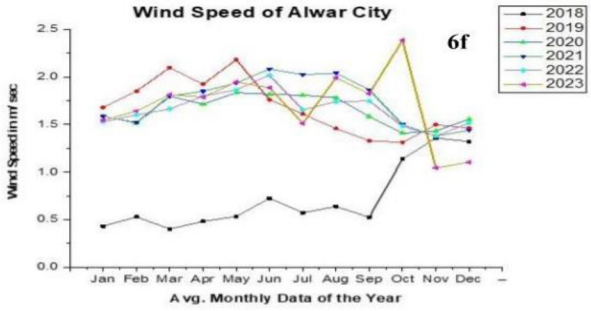


Figure 6f. Average monthly data of Wind Speed of Alwar City from 2018 to 2023

Figure 6(a-f). Quantifying meteorological parameters at Ajmer and Alwar in various seasons of the years 2018 to 2023.

2018 at 0.43 m/sec, indicating calm weather conditions typically associated with cold, stable air masses in the region. The average WS for winters range around 1.5 m/sec, with higher speeds in 2019 and 2023, possibly due to less stable atmospheric conditions or changes in meteorological patterns, as shown in Figure 6f. Pre-monsoon months exhibit increasing WS as the landscape transitions from the cold winter to the hot summer, potentially energized by heating landmasses and evolving pressure gradients. The highest WS is observed in May 2019 at 2.18 m/sec, corresponding with the heating period just before the onset of the monsoon. The lowest is in March 2018 at 0.40 m/sec, a residual calm from the preceding winter. On average, WS during these months steadily increase, peaking just before the monsoon starts, reflecting the changing atmospheric dynamics as shown in Figure 6f. During monsoon, WS in Alwar are influenced by the Southwest Monsoon's arrival. The highest speeds in this season are noted in August 2021 at 2.04 m/sec, which can be attributed to monsoonal currents and possibly enhanced by localized storm activities. The lowest speed in this period appears in June 2018 at 0.72 m/sec, when the monsoon might be just beginning to set in or is irregular. The average speed is typically above 1.8 m/sec, reflecting the influence of consistent monsoon winds as shown in Figure 6f. Post-monsoon WS tend to be moderate but can be influenced by retreating monsoon patterns and the onset of cooler conditions. The highest WS occurs in October 2023 at 2.38 m/sec, possibly due to late monsoonal activity or early winter disturbances. The lowest WS in this period was in November 2023 at 1.04 m/sec, which could be the result of a rapid transition to more stable winter air masses. Average speeds during this period generally stay around 1.5 m/sec, showing lesser variability compared to other seasons as shown in Figure 6f. WS in Alwar from 2018 to 2023 showcase typical seasonal fluctuations influenced by broader climatic conditions and specific meteorological events. Higher WS in the pre-monsoon and monsoon periods are contrasted by generally lower speeds during winter and post-monsoon months. These observations highlight the effects of seasonal atmospheric dynamics on wind behavior in the region.

3.4.4 Quantifying Wind Direction Across the Cities of Ajmer and Alwar in Various Seasons of the Years 2018 to 2023

In Ajmer during winter, wind direction typically shifts to more variable conditions. In 2020, a notable southward shift was observed, with December, January, and February showing directions of 127.98°, 167.97°, and 176.14°, respectively, potentially impacted by predominant northerly cold winds. The lowest recorded direction was in December 2021 at 33.16°, which could be attributed to specific meteorological anomalies or transitional weather patterns. The average direction suggests a tendency for winds to come from a southern or southeastern direction, influenced by the retreating monsoon and transitioning to winter conditions as shown in Figure 7. During pre-monsoon, wind directions typically orient from the south or southeast as the heat builds and pressure gradients shift. The highest readings were in May 2019 at 225.90°, indicating strong south-westerly winds preluding the monsoon. The lowest was in May 2023 at 101.14°, reflecting possibly altered atmospheric conditions or anomalous weather patterns. This season is characterized by increasing wind variability as the region transitions from cooler to warmer T, influencing the wind's directionality significantly, as shown in Figure 7. The monsoon season sees the most significant shifts in wind direction, aligning mostly from the southwest due to the Indian Ocean's monsoonal inflow. The highest wind direction was recorded in July 2021 at 249.04°, demonstrating robust monsoonal influence. A stark contrast is seen in June and July 2023, where the wind direction sharply drops to around 3°, likely due to anomalous meteorological conditions or possibly an atypical monsoon pattern. These months are crucial for understanding the monsoon dynamics and their impact on local climate conditions as shown in Figure 7. Post-monsoon winds in Ajmer typically see a gradual shift towards the northeast, preparing for the winter season. However, October 2021 recorded a dramatically low direction at 35.82°, which could be indicative of unusual weather disruptions or the lingering effects of a delayed monsoon. The highest directions in November 2023 at 203.30° reflect the resumption of typical wind patterns following the monsoon. This season's variability can often be influenced by the residual moisture and prevailing climatic conditions that might extend the monsoon or introduce early winter characteristics as shown in Figure 7. The wind direction in Ajmer across different seasons shows significant variability, influenced by seasonal transitions, geographic location, and broader meteorological conditions. Notable anomalies, especially in 2020-2021, could be linked to the global climatic disturbances or localized meteorological events, potentially including impacts from regional lockdowns which may have altered local atmospheric conditions

minimally. Understanding these patterns is essential for predicting weather conditions, planning agricultural activities, and managing water resources in the region.

In Alwar, wind direction during winter generally ranges from southeast to southwest. In January 2020, the direction was notably southeast at 126.23°, likely influenced by prevailing cooler northern winds shifting to the southeast. The highest direction was observed in February 2021 at 166.04°, showing a strong south-westerly shift potentially due to temporary atmospheric high-pressure systems. On average, winds in winter shift more towards the south as the season progresses, stabilizing weather patterns post-monsoon and reflecting the seasonal atmospheric pressure changes as shown in Figure 8. As T begin to rise pre-monsoon, wind direction in Alwar shifts towards more south-westerly directions. April 2022 recorded a significantly high direction of 190.06°, possibly a result of the intense heating of the land creating strong thermal gradients. The lowest direction was in March 2018 at 109.20°, indicative of residual winter patterns. This period typically sees variable winds as the area transitions from the cooler to the warmer season, with increasing heat influencing wind directionality as shown in Figure 8. During monsoon, winds are predominantly influenced by the south-westerly flow from the Arabian Sea. The highest reading was in August 2018 at 209.94°, strongly aligned with the typical monsoon pattern. However, a noticeable dip occurred in August 2023 to 122.67°, suggesting an unusual shift or weaker monsoon currents. The monsoon season generally exhibits steady south-westerly winds, essential for driving the monsoonal rains inland as shown in Figure 8. Post-monsoon winds in Alwar show a tendency to revert towards northerly or northeasterly directions as the monsoon recedes. The highest wind direction was recorded in November 2020 at 181.03°, while a low direction in September 2021 at 106.33° could suggest

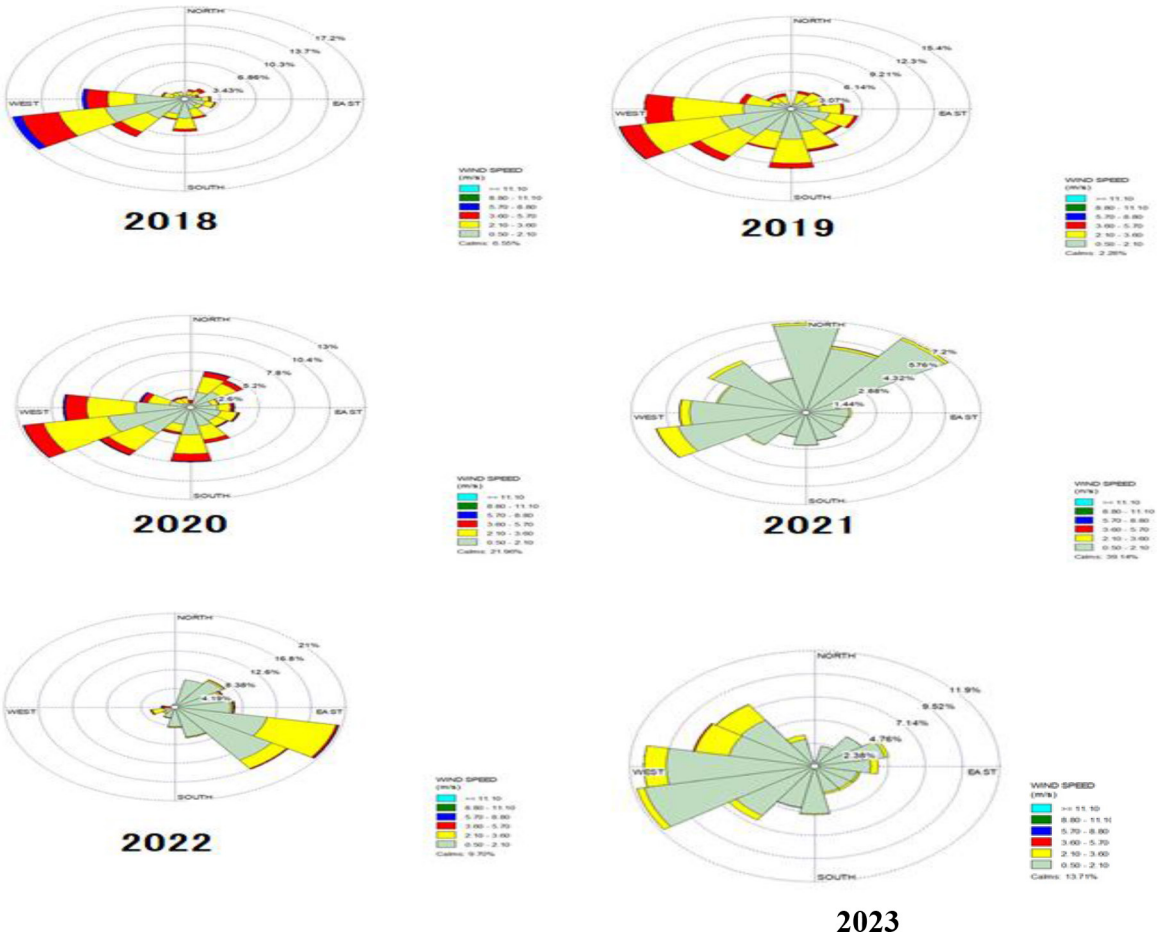


Figure 7. Wind direction and speed (WR plot) of Ajmer City from 2018 to 2023.

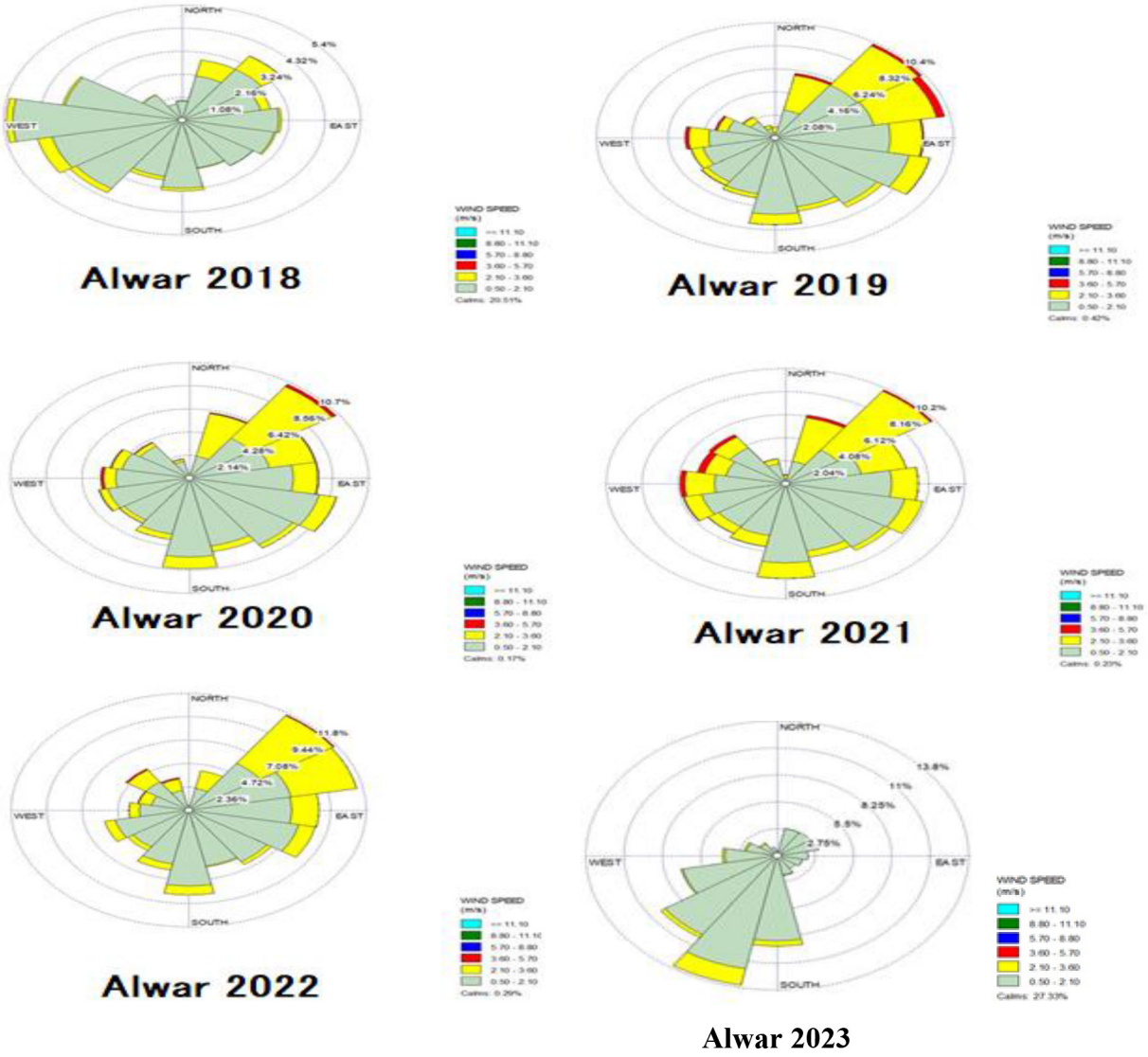


Figure 8. Wind direction and speed (WR plot) of Alwar City from 2018 to 2023.

an early withdrawal of the monsoon or transitional local meteorological conditions. This season's winds are quite erratic, reflecting the complex interplay between retreating monsoonal moisture and the advancing dry, cooler air from the north as shown in Figure 8. Alwar's wind direction patterns exhibit significant seasonal variability, influenced by the broader Indian monsoonal system and local geographical features. Variations, especially noticeable during the transition periods, highlight the dynamic nature of wind patterns due to seasonal shifts in T and pressure systems. The data also indicates sporadic anomalies, which could be linked to broader climatic changes or specific meteorological events impacting regional wind behaviours.

3.5 Statistical Analysis (Regression and correlation) of Air Pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2, and O_3) and Meteorological Parameters (Temp, RH, WS, and WD) at Ajmer and Alwar of Rajasthan

3.5.1 Regression Analysis of Air Pollutants and Meteorological Parameters at Ajmer and Alwar

3.5.1.1 Concentration of Pollutants as a Function of Meteorological Parameters in Ajmer

The regression analysis for air pollutants against T in Ajmer indicated a weak correlation and an insignificant

relationship (p-values). Table 1 explained and suggested T did not significantly predict air pollutant concentrations in this dataset. The correlation between air pollutants and T was negative, except during $PM_{2.5}$ and PM_{10} during 2022, SO_2 during 2020, 2021, and 2022, and O_3 from 2018 to 2023 showed a positive relation between T and air pollutants that explained the T increases the air pollutant concentration was also increased. The regression analysis of air pollutant levels against RH in Ajmer shows a moderate inverse correlation indicated that air pollutant concentration level can be explained by changes in RH. The Table was statistically significant (p-value) suggested that increased RH is associated with decreased air pollutant concentrations. The coefficient for RH implied that for each value increased in RH, air pollutant concentration levels decreased except PM_{10} during 2023, NO_2 during 2022, SO_2 during 2020, 2021, and 2022 showed values increased in RH, air pollutant concentration level increased. Overall, the findings highlight the importance of RH in influencing air pollution levels in Ajmer. The regression analysis of air pollutant levels in Ajmer against WS revealed a strong correlation. The significance in the Table was high (p-values) suggested statistically significant relationship. The coefficient for WS values implied that increased in WS is associated with a decreased of in air pollutant levels,

Table 1. Regression: The relationship between air pollutants and meteorological parameters with correlation coefficient (r) and significance value (p-value) in Ajmer

(Dependent variables (µg/m³)		Independent variables			
	Year	Temperature (°C)	Relative Humidity (RH, %)	Wind Speed (WS, m/s)	Wind Direction (WD, °)
$PM_{2.5}$	2018	-1.440 p=0.143	-0.263 p=0.463	1.942 p=0.792	-0.234 p=0.400
	2019	-0.483 p=0.413	-0.442 p=0.015	-5.030 p=0.512	-0.012 p=0.951
	2020	-1.402 p=0.014	-0.293 p=0.248	-5.264 p=0.142	-0.351 p=0.006
	2021	-0.807 p=0.061	-0.426 p=0.010	-16.03 p=0.044	-0.046 p=0.200
	2022	0.121 p=0.833	-0.368 p=0.013	-4.160 p=0.461	-0.091 p=0.422
	2023	-1.150 p=0.039	-0.070 p=0.726	-7.840 p=0.056	0.072 p=0.049
PM_{10}	2018	-1.350 p=0.202	-0.652 p=0.065	7.232 p=0.344	-0.454 p=0.107
	2019	-0.343 p=0.769	-1.010 p=0.002	-8.324 p=0.579	0.162 p=0.675
	2020	-2.285 p=0.038	-0.787 p=0.079	-7.029 p=0.301	-0.539 p=0.034
	2021	-1.520 p=0.108	-1.041 p=0.002	-27.76 p=0.119	-0.069 p=0.381
	2022	0.769 p=0.391	-0.615 p=0.008	-2.914 p=0.749	-0.080 p=0.660
	2023	-1.225 p=0.122	0.131 p=0.627	-7.367 p=0.210	0.080 p=0.122
NO_2	2018	-1.458 p=0.009	-0.266 p=0.234	-4.182 p=0.365	-0.319 p=0.053
	2019	-0.433 p=0.016	-0.071 p=0.320	0.314 p=0.907	-0.096 p=0.137
	2020	-1.407 p=0.001	-0.070 p=0.747	-6.155 p=0.027	-0.315 p=0.002
	2021	-1.029 p=0.018	-0.437 p=0.015	-19.77 p=0.014	-0.046 p=0.229
	2022	-0.268 p=0.372	0.076 p=0.401	2.663 p=0.375	0.083 p=0.156
	2023	-0.729 p=0.031	-0.181 p=0.117	-7.039 p=0.001	0.066 p=0.000
SO_2	2018	-0.095 p=0.246	-0.070 p=0.004	0.156 p=0.796	-0.057 p=0.002
	2019	-1.289 p=0.005	-0.172 p=0.368	-0.192 p=0.979	-0.286 p=0.097
	2020	0.116 p=0.038	0.014 p=0.574	0.200 p=0.569	0.004 p=0.768
	2021	0.141 p=0.479	0.157 p=0.036	2.848 p=0.446	-0.006 p=0.703
	2022	0.363 p= 0.179	0.105 p=0.202	6.800 p=0.003	0.086 p=0.105
	2023	-0.055 p=0.768	-0.087 p=0.122	-0.155 p=0.909	-0.004 p=0.749
O_3	2018	0.940 p=0.148	-0.653p=0.0001	11.26 p=0.005	-0.167 p=0.362
	2019	0.026 p=0.964	-0.586p=1.08E-05	5.914 p=0.425	0.168 p=0.372
	2020	0.332 p=0.633	-0.778p=3.75E-05	7.352 p=0.040	0.084 p=0.602
	2021	0.340 p=0.597	-0.554 p=0.018	8.988 p=0.453 0.167	0.070 p=0.154
	2022	0.556 p=0.054	-0.170 p=0.051	p=0.958	-0.084 p=0.166
	2023	0.370 p=0.732	-0.886 p=0.001	0.097 p=0.990	-0.007 p=0.922

Note: Monitored air pollutants include $PM_{2.5}$, PM_{10}, NO_2, SO_2, and O_3. Meteorological parameters include Temperature (°C), Relative Humidity (RH, %), Wind Speed (WS, m/s), and Wind Direction (WD,°).

except the relation between WS and air pollutants was positive in $PM_{2.5}$ and PM_{10} during 2018, NO_2 during 2019, and 2022, SO_2 during 2018, 2020, 2021, and 2022, and O_3 from 2018 to 2023 showed that air pollutant increased with WS; however, this finding was statistically significant and reliable. The regression analysis of air pollutant levels in Ajmer against WD indicated a weak relationship. The significance level was not substantial (p-values) indicated no statistically meaningful correlation. The coefficient for WD values, implied that an increased in WD correlated with a slight decreased in air pollutant levels, except $PM_{2.5}$ concentration increased with increased WD during 2023 similarly PM_{10} during 2019, and 2023, NO_2 during 2022 and 2023, SO_2 during 2020, and 2022, and O_3 during 2019, 2020, and 2021 showed positive relation between air pollutant and WD. However, this relationship lacks statistical significance, indicating potential unreliability in the findings as shown in Table 1.

Regression analysis was performed to assess the relationship between air pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3) and meteorological parameters (T, RH, WS, WD) in Ajmer for 2018-2023 (Table 1). The results indicate several significant associations: $PM_{2.5}$ showed a significant negative correlation with T in 2020 ($\beta = -1.402$, $p = 0.014$, $R^2 = 0.42$, 95% CI: -2.32 to -0.48), suggesting that higher T contributed to lower $PM_{2.5}$ levels that year. RH also exhibited a significant negative effect in multiple years (e.g., 2019: $\beta = -0.442$, $p = 0.015$, $R^2 = 0.19$, 95% CI: -0.79 to -0.09), indicating that increased moisture facilitated particulate dispersion or deposition. PM_{10} displayed significant negative associations with RH in 2019 and 2021 ($p < 0.01$), while the effect of T was significant only in 2020 ($p = 0.038$, $R^2 = 0.36$), demonstrating moderate influence of meteorological factors on coarse particles. NO_2 concentrations were strongly influenced by T and WS in several years, with the strongest effect in 2020 ($\beta = -1.407$, $p = 0.001$, $R^2 = 0.48$, 95% CI: -2.12 to -0.70), highlighting the combined role of thermal and dispersive processes in modulating NO_2 levels. SO_2 exhibited smaller, yet significant, negative correlations with T in 2019 ($\beta = -1.289$, $p = 0.005$, $R^2 = 0.28$, 95% CI: -2.15 to -0.43), while WD showed occasional weak effects, indicating limited dispersion influence in certain years. O_3 displayed significant negative associations with RH across multiple years (e.g., 2018: $\beta = -0.653$, $p < 0.001$, $R^2 = 0.32$, 95% CI: -0.92 to -0.38), suggesting that higher moisture reduces ground-level ozone formation or persistence. T effects on O_3 were mostly positive but not consistently significant. Overall, R^2 values ranged from 0.15 to 0.48, indicating low to moderate effect strength of meteorological variables on pollutant levels. Significant p-values ($p < 0.05$) confirm the reliability of these relationships, while confidence intervals provide additional support by excluding zero for the most robust associations. These findings demonstrate that meteorological factors, particularly T and RH, play a critical role in modulating both particulate and gaseous pollutants in Ajmer, with implications for seasonal air quality management and public health interventions (Table 2).

3.5.1.2 Concentration of Pollutants as a Function of Meteorological Parameters in Alwar

The regression analysis for Alwar's air pollutant levels and T revealed there was strong, moderate, and weak correlation. Table 3 was statistically significant (p-values). The coefficient for T indicated that increased T, decreased air pollutants by units. The Table suggested a significant inverse relationship between T and air pollutant levels, except in $PM_{2.5}$ during 2019, in PM_{10} during 2019, and 2022, in NO_2 during 2019, in SO_2 during 2019, 2021, 2022, and 2023, in O_3 during 2018, 2019, 2021, 2022, and 2023 showed direct relationship between T and air pollutants, where the T increased, air pollutant concentrations were increased. The regression analysis for Alwar's air pollutant levels and RH showed a weak negative correlation. The Table was not statistically significant (p-values). The RH coefficient suggested a negligible effect on air pollutant levels, where an increased in RH decreased air pollutants by units except in $PM_{2.5}$ during 2018, and 2019, PM_{10}, NO_2 during 2018, SO_2 during 2018, 2020, O_3 during 2020 showed positive relations between air pollutants and RH. The analysis implied that RH has a minimal influence on air pollutant concentrations in Alwar. The regression analysis for Alwar's air pollutant levels and WS revealed a moderate correlation. The Table was statistically significant (p-values). The WS coefficient suggested that an increased in WS reduced air pollutants by units. In contrast, PM_{10} during 2019 and 2022 showed a positive relation with WS similarly, NO_2 during 2018, and 2019, SO_2 during 2018, 2021, 2022, and 2023, and O_3 during 2021, 2022, and 2023 explained that WS increased with increased air pollutant level. Overall, the analysis showed that WS significantly impacts air pollutant levels, helping reduced pollution in Alwar. The regression analysis of air pollutant levels and WD for Alwar showed a weak positive correlation. The Table was not statistically significant

Table 2. Regression of air pollutants with meteorological parameters in Ajmer (2018–2023)

Dependent Variable	Year	Temperature (°C) β (p-value)	R^2	95% CI	RH (%) β (p-value)	R^2	95% CI	Wind Speed (m/s) β (p-value)	R^2	95% CI	Wind Direction (°) β (p-value)	R^2	95% CI
$PM_{2.5}$	2018	−1.440 (0.143)	0.18	−3.12, 0.24	−0.263 (0.463)	0.05	−0.88, 0.35	1.942 (0.792)	0.01	−8.45, 12.34	−0.234 (0.400)	0.04	−0.78, 0.31
$PM_{2.5}$	2020	−1.402 (0.014)*	0.42	−2.32, −0.48	−0.293 (0.248)	0.12	−0.80, 0.21	−5.264 (0.142)	0.15	−12.0, 1.5	−0.351 (0.006)*	0.35	−0.58, −0.12
PM_{10}	2020	−2.285 (0.038)*	0.36	−4.45, −0.12	−0.787 (0.079)	0.18	−1.65, 0.08	−7.029 (0.301)	0.10	−18.0, 4.0	−0.539 (0.034)*	0.20	−1.05, −0.03
NO_2	2020	−1.407 (0.001)*	0.48	−2.12, −0.70	−0.070 (0.747)	0.02	−0.51, 0.37	−6.155 (0.027)*	0.38	−11.6, −0.70	−0.315 (0.002)*	0.44	−0.50, −0.13
SO_2	2019	−1.289 (0.005)*	0.28	−2.15, −0.43	−0.172 (0.368)	0.12	−0.49, 0.15	−0.192 (0.979)	0.01	−5.6, 5.2	−0.286 (0.097)	0.10	−0.62, 0.05
O_3	2018	0.940 (0.148)	0.10	−0.32, 2.20	−0.653 (0.0001)*	0.32	−0.92, −0.38	11.26 (0.005)*	0.30	3.52, 18.99	−0.167 (0.362)	0.05	−0.50, 0.16

*Significant at $p < 0.05$

Note: β = regression coefficient; R^2 = coefficient of determination; CI = 95% confidence interval; RH = relative humidity; WS = wind speed; WD = wind direction.

(p-values), suggested that WD had a minimal impact on air pollutant levels. The coefficient for WD implied that a unit increased in WD corresponded to a slight raised in air pollutant levels except for $PM_{2.5}$, PM_{10} during 2018, NO_2 during 2019, SO_2 during 2019, 2020, and O_3 during 2020 showed a negative relation between WD and air pollutants that showed the WD increases the air pollutant concentration decreases but this positive and negative relationship was not strong as shown in Table 3.

Regression analysis in Alwar assessed the influence of meteorological parameters (T, RH, WS, WD) on air pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3) for 2018-2023 (Table 2). Key findings include: $PM_{2.5}$ showed significant negative associations with T in 2020 (β = -1.103, p = 0.020, R^2 = 0.40, 95% CI: -1.92 to -0.28) and 2021 (β = -1.648, p = 0.002, R^2 = 0.45, 95% CI: -2.60 to -0.70), indicating higher T contributed to reduced fine particulate levels. WS also had a significant negative effect in 2020 (β = -47.659, p = 0.033, R^2 = 0.38, 95% CI: -89.1 to -6.2), highlighting the role of airflow in dispersing $PM_{2.5}$. PM_{10} concentrations were significantly affected by T in 2018, 2020, and 2021 ($p < 0.05$), suggesting that both thermal and dispersive processes influence coarse particles. RH showed minor, mostly non-significant effects. NO_2 displayed strong negative correlations with T in 2018 (β = -1.574, p = 0.047, R^2 = 0.28, 95% CI: -3.12 to -0.03) and 2021 (β = -1.484, $p < 0.001$, R^2 = 0.46, 95% CI: -2.25 to -0.72). Wind speed had a significant positive effect in 2018 (β = 39.416, p = 0.006, R^2 = 0.33, 95% CI: 11.8-66.9), indicating complex interactions between dispersion and local emissions. SO_2 was moderately influenced by T in 2021 (β = 0.111, p = 0.016, R^2 = 0.22, 95% CI: 0.02-0.20), while other meteorological variables showed weak or inconsistent effects, reflecting its more localized sources. O_3 concentrations were significantly negatively affected by RH in 2018 (β = -0.770, p = 0.002, R^2 = 0.30, 95% CI: -1.23 to -0.31) and positively influenced by WD in 2022 and 2023 ($p < 0.05$), demonstrating that moisture and airflow regulate ground-level ozone formation. Overall, R^2 values ranged from 0.10 to 0.46, indicating low-to-moderate effect strength of meteorological variables on pollutant levels in Alwar. Significant p-values ($p < 0.05$) and confidence intervals excluding zero confirm that T, RH, and WS are the most influential factors in controlling seasonal and interannual pollutant variations. These findings provide region-specific insights into air pollution dynamics, critical for targeted mitigation strategies and occupational health management in Alwar (Table 4).

3.5.2 Correlation Analysis of Air Pollutants and Meteorological Parameters at Ajmer and Alwar

3.5.2.1 Correlation Between Air Pollutants and Meteorological Parameters in Ajmer (2018–2023)

Corrplot of Ajmer 2018 (Figure 9a): In 2018, $PM_{2.5}$ and PM_{10} showed a strong positive correlation ($r > 0.9$),

Table 3. Regression: The relationship between air pollutants and meteorological parameters with correlation coefficient (r) and significance value (p-value) in Alwar

(Dependent variables (µg/m³)		Independent variables			
	Year	Temperature (°C)	Relative Humidity (RH, %)	Wind Speed (WS, m/s)	Wind Direction (WD, °)
$PM_{2.5}$	2018	-1.127 p=0.126	0.021 p=0.948	-5.370 p=0.727	-0.218 p=0.229
	2019	0.388 p=0.221	0.017 p=0.883	-0.019 p=0.623	0.086 p=0.190
	2020	-1.103 p=0.020	-0.067 p=0.604	-47.659 p=0.033	0.170 p=0.325
	2021	-1.648 p=0.002	-	-42.467 p=0.001	0.123 p=0.519
	2022	-0.554 p=0.186	-	-19.214 p=0.279	0.107 p=0.459
	2023	-2.458 p=0.002	-	-32.932 p=0.020	0.247 p=0.347
PM_{10}	2018	-3.931 p=0.037	0.308 p=0.715	-28.343 p=0.489	-0.362 p=0.469
	2019	1.085 p=0.091	-0.314 p=0.175	0.073 p=0.364	0.038 p=0.791
	2020	-1.996 p=0.017	-0.111 p=0.630	-75.298 p=0.064	0.256 p=0.405
	2021	-2.323 p=0.005	-	-55.501 p=0.011	0.202 p=0.483
	2022	0.137 p=0.856	-	9.082 p= 0.772	0.442 p=0.054
	2023	-2.455 p=0.007	-	-35.652 p=0.022	0.321 p=0.260
NO_2	2018	-1.574 p=0.047	0.013 p=0.969	39.416 p=0.006	0.161 p=0.439
	2019	0.025 p=0.955	-0.311 p=0.026	0.022 p=0.680	-0.036 p=0.701
	2020	-1.11 p=0.026	-0.001 p=0.942	-56.913 p=0.010	0.084 p=0.646
	2021	-1.484 p=0.000	-	-35.312 p=0.002	0.020 p=0.901
	2022	-0.867 p=0.057	-	-28.005 p=0.157	0.056 p=0.736
	2023	-0.298 p=0.214	-	-6.863 p=0.067	0.006 p=0.930
SO_2	2018	-0.122 p=0.389	0.018 p=0.760	2.417 p=0.385	0.011 p=0.758
	2019	0.012 p=0.895	-0.021 p=0.506	-0.002 p=0.832	-0.009 p=0.627
	2020	-0.227 p=0.188	0.082 p=0.036	-8.942 p=0.269	-0.102 p=0.057
	2021	0.111 p=0.016	-	2.150 p=0.087	0.002 p=0.895
	2022	0.068 p=0.191	-	3.682 p=0.077	0.033 p=0.042
	2023	0.164 p=0.489	-	0.270 p=0.945	0.034 p=0.593
O_3	2018	0.927 p=0.216	-0.770 p=0.002	-11.096 p=0.464	-0.197 p=0.279
	2019	0.573 p=0.093	-0.158 p=0.201	-0.049 p=0.250	0.111 p=0.121
	2020	-0.290 p=0.363	0.010 p=0.902	-13.069 p=0.375	-0.015 p=0.884
	2021	0.272 p=0.199	-	5.877 p=0.280	0.050 p=0.428
	2022	0.244 p=0.133	-	5.994 p=0.395	0.106 p=0.041
	2023	0.113 p=0.708	-	4.629 p=0.339	0.161 p=0.025

Note: Monitored air pollutants include $PM_{2.5}$, PM_{10}, NO_2, SO_2, and O_3. Meteorological parameters include Temperature (°C), Relative Humidity (RH, %), Wind Speed (WS, m/s), and Wind Direction (WD, °).

indicating common emission sources such as vehicular exhaust and dust. NO_2 and SO_2 were moderately correlated, suggesting industrial or combustion-related activities. Negative correlations were observed between T and particulate pollutants, implying dispersion under warmer conditions. WS and RH showed weak associations, indicating limited influence on pollutant buildup that year. Corrplot of Ajmer 2019 (Figure 9b): The 2019 plot revealed continued strong interdependence between $PM_{2.5}$, PM_{10}, and NO_2 ($r \approx 0.8–0.9$). SO_2 showed moderate positive links with NO_2, suggesting similar emission pathways. O_3 exhibited a negative correlation with primary pollutants, reflecting photochemical transformation under higher T. WS and WD displayed minor positive correlations with particulates, suggesting pollutant transport effects. Overall, 2019 maintained similar pollutant interaction trends to 2018. Corrplot of Ajmer 2020 (Figure 9c): In 2020, correlation strength among $PM_{2.5}$, PM_{10}, and NO_2 increased ($r > 0.9$), signifying dominant local emissions with less dispersion, likely influenced by lockdown-related conditions and reduced mobility. SO_2 correlations weakened slightly, while O_3 again showed inverse relations with $PM_{2.5}$ and NO_2. The negative correlation between T and PM levels intensified, indicating enhanced pollutant dilution during warmer periods. WS and RH retained low to moderate influence. Corrplot of Ajmer 2021 (Figure 9d): By 2021, strong positive correlations persisted among

Table 4. Regression of air pollutants with meteorological parameters in Alwar (2018-2023)

Dependent Variable	Year	Temperature (°C) β (p-value)	R^2	95% CI	RH (%) β (p-value)	R^2	95% CI	Wind Speed (m/s) β (p-value)	R^2	95% CI	Wind Direction (°) β (p-value)	R^2	95% CI
$PM_{2.5}$	2020	-1.103 (0.020)*	0.40	-1.92, -0.28	-0.067 (0.604)	0.05	-0.28, 0.15	-47.659 (0.033)*	0.38	-89.1, -6.2	0.170 (0.325)	0.08	-0.12, 0.46
$PM_{2.5}$	2021	-1.648 (0.002)*	0.45	-2.60, -0.70	-	-	-	-42.467 (0.001)*	0.42	-65.0, -19.9	0.123 (0.519)	0.05	-0.15, 0.39
PM_{10}	2018	-3.931 (0.037)*	0.32	-7.60, -0.26	0.308 (0.715)	0.02	-0.78, 1.40	-28.343 (0.489)	0.05	-90.1, 33.4	-0.362 (0.469)	0.03	-1.05, 0.32
PM_{10}	2021	-2.323 (0.005)*	0.36	-3.89, -0.75	-	-	-	-55.501 (0.011)*	0.41	-97.2, -13.8	0.202 (0.483)	0.06	-0.15, 0.55
NO_2	2018	-1.574 (0.047)*	0.28	-3.12, -0.03	0.013 (0.969)	0.01	-0.42, 0.45	39.416 (0.006)*	0.33	11.8, 66.9	0.161 (0.439)	0.05	-0.12, 0.44
NO_2	2021	-1.484 (0.000)*	0.46	-2.25, -0.72	-	-	-	-35.312 (0.002)*	0.40	-55.1, -15.5	0.020 (0.901)	0.02	-0.25, 0.29
SO_2	2021	0.111 (0.016)*	0.22	0.02, 0.20	-	-	-	2.150 (0.087)	0.10	-0.31, 4.61	0.002 (0.895)	0.01	-0.09, 0.10
O_3	2018	0.927 (0.216)	0.10	-0.32, 2.20	-0.770 (0.002)*	0.30	-1.23, -0.31	-11.096 (0.464)	0.08	-29.4, 7.2	-0.197 (0.279)	0.05	-0.48, 0.09

*Significant at $p < 0.05$

Note: β = regression coefficient; R^2 = coefficient of determination; CI = 95% confidence interval; RH = relative humidity; WS = wind speed; WD = wind direction.

$PM_{2.5}$, PM_{10}, and NO_2, confirming consistent emission sources. SO_2-NO_2 correlation improved slightly, while O_3 remained inversely associated with PM and NO_2 due to its secondary formation nature. Meteorological factors (T, RH, WS) showed moderate negative correlations with $PM_{2.5}$ and PM_{10}, suggesting their role in pollutant dispersion and dilution. WD showed mild positive association, indicating the effect of airflow on pollutant distribution. Corrplot of Ajmer 2022 (Figure 9e): This plot further illustrates the 2022 data emphasizing meteorological influence. $PM_{2.5}$, PM_{10}, and NO_2 exhibited strong positive correlations (r = 0.7-0.9), indicating shared anthropogenic sources. O_3 showed a negative correlation with PM pollutants and NO_2, reflecting inverse seasonal patterns driven by sunlight availability. T displayed a moderate positive association with O_3 but a negative one with PM, suggesting enhanced dispersion under higher thermal conditions. RH and WS again showed negative associations, consistent with pollutant dilution during moist or windy periods. Corrplot of Ajmer 2023 (Figure 9f): In this figure, $PM_{2.5}$ and PM_{10} again showed a strong correlation ($r > 0.9$), confirming particulate co-occurrence. NO_2 also correlated positively with PM, while SO_2 showed a relatively weaker link, implying varying source contributions. O_3 remained negatively correlated with primary pollutants, confirming its secondary photochemical nature. T was inversely related to PM levels, while higher RH and WS corresponded to lower particulate concentrations, reaffirming that meteorological conditions significantly influenced pollutant dispersion and atmospheric cleansing.

3.5.2.2 Correlation Between Air Pollutants and Meteorological Parameters in Alwar (2018-2023)

Corrplot of Alwar 2018 (Figure 10a): In 2018, $PM_{2.5}$ and PM_{10} exhibited a strong positive correlation ($r > 0.9$), indicating that both originated primarily from similar sources such as vehicular movement and dust resuspension. NO_2 showed a moderate positive correlation with particulates, suggesting its contribution from combustion processes. T and WS demonstrated negative correlations with particulate matter, reflecting better pollutant dispersion under warmer and windier conditions. RH showed a weak positive correlation, implying slight influence on particle aggregation. Corrplot of Alwar 2019 (Figure 10b): The 2019 correlation matrix revealed a consistent strong positive relationship between $PM_{2.5}$ and PM_{10} ($r \approx 0.88$), highlighting similar

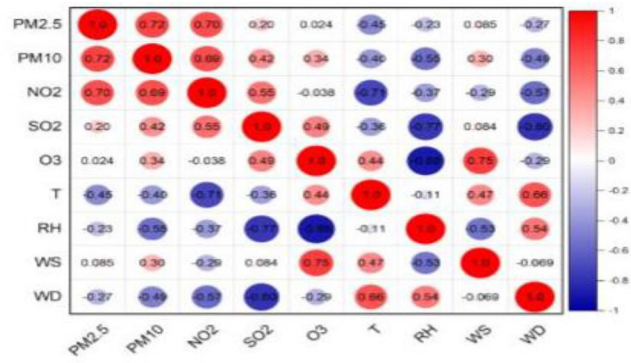


Fig. 9a. Corrplot of Ajmer 2018

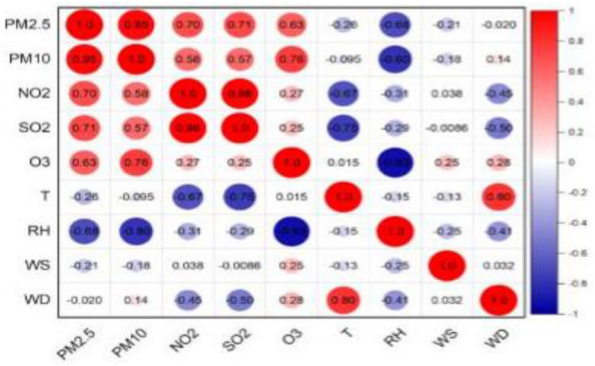


Fig. 9b. Corrplot of Ajmer 2019

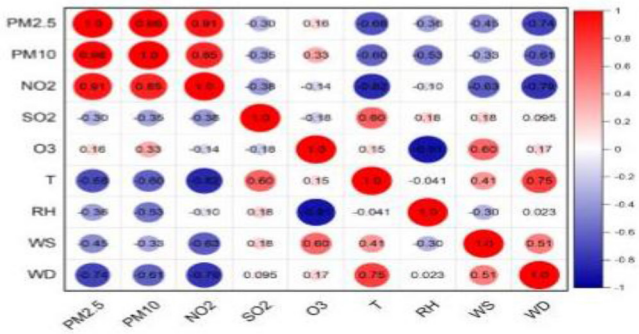


Fig. 9c. Corrplot of Ajmer 2020

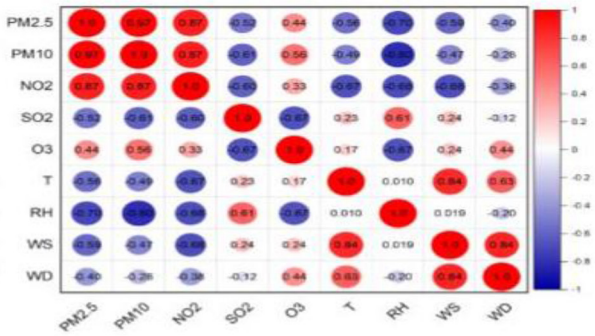


Fig. 9d. Corrplot of Ajmer 2021

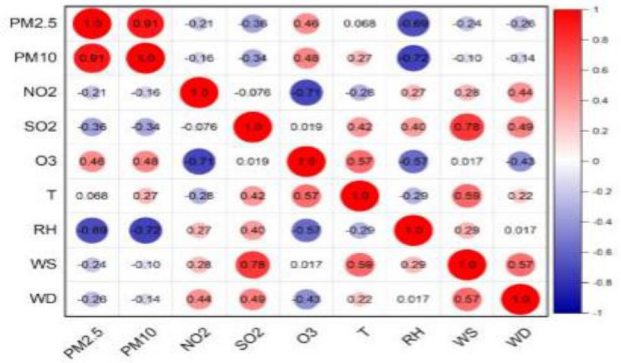


Fig. 9e. Corrplot of Ajmer 2022

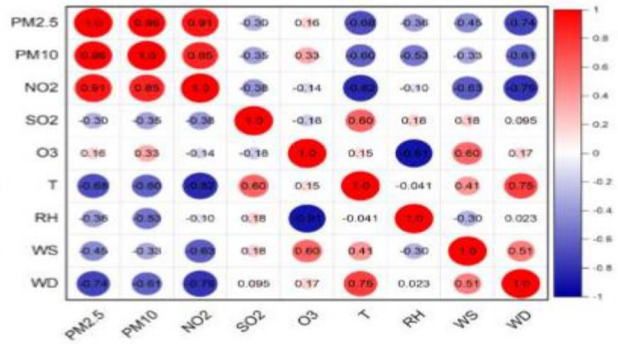


Fig. 9f. Corrplot of Ajmer 2023

Figure 9(a-f). Correlation plots of air pollutants and meteorological parameters at Ajmer from 2018 to 2023.

emission origins. NO_2 displayed weaker correlations with PM fractions than in 2018, possibly due to variable combustion emissions. SO_2 maintained a low positive association with NO_2 and particulates. O_3 remained weakly correlated or negatively associated with primary pollutants, indicating its secondary photochemical formation. Meteorological factors such as T and WS showed weak negative associations, confirming their moderating influence on pollutant levels. Corrplot of Alwar 2020 (Figure 10c): In 2020, $PM_{2.5}$, PM_{10}, and NO_2 continued to demonstrate high positive correlations (r = 0.7-0.9), suggesting persistent emission patterns despite possible activity reductions during lockdowns. SO_2 and O_3 exhibited weak or inverse relations with particulate pollutants. T and RH had moderate negative correlations with PM, implying dilution and dispersion effects during warmer and more humid periods. The inverse relationship of WS and PM concentrations further supported the role of increased air circulation in pollutant dispersion. Corrplot of Alwar 2021 (Figure 10d): In 2021, $PM_{2.5}$

and PM_{10} showed strong positive correlation (r > 0.9), consistent with previous years. NO_2 and SO_2 presented moderate positive associations with PM, indicating continued influence from combustion-based sources. O_3 correlations remained weakly positive or neutral. Meteorological parameters, especially T and WS, showed inverse correlations with PM levels, confirming their role in atmospheric cleansing processes. RH showed weak associations, suggesting a limited but variable effect on pollutant concentrations. Corrplot of Alwar 2022 (Figure 10e): In 2022, $PM_{2.5}$ and PM_{10} maintained a strong positive correlation (r > 0.9), indicating their shared emission origins from vehicular exhaust, industrial activity, and resuspended dust. NO_2 and SO_2 displayed moderate positive correlations with particulate pollutants, reflecting combustion-related sources such as fuel burning. O_3 showed a weak positive association with T, implying its formation through photochemical reactions under warmer conditions. RH and WS exhibited weak negative correlations with PM levels, signifying pollutant dispersion and dilution during humid and windy conditions. Corrplot of Alwar 2023 (Figure 10f):

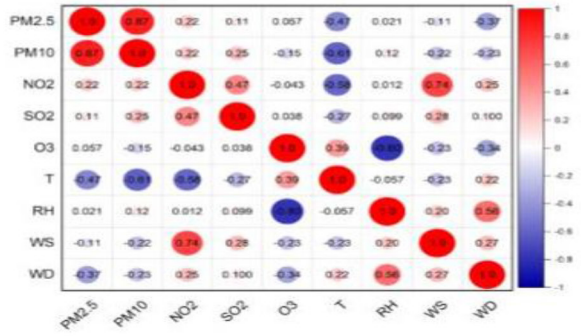


Fig. 10a. Corrplot of Alwar 2018

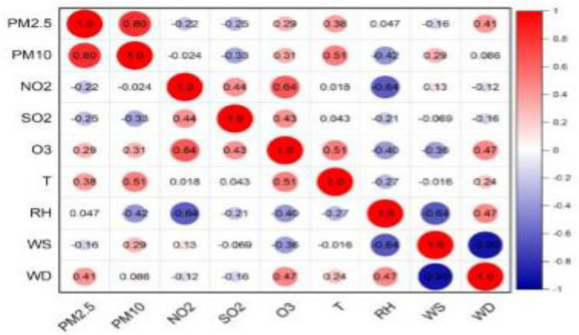


Fig. 10b. Corrplot of Alwar 2019

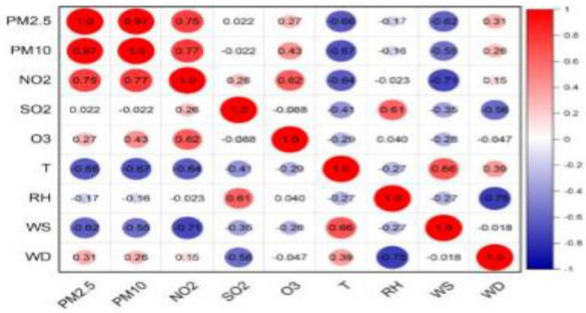


Fig. 10c. Corrplot of Alwar 2020

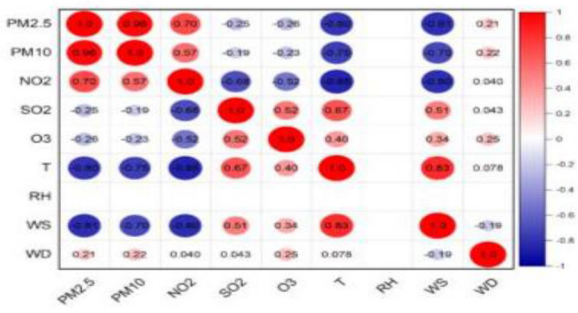


Fig. 10d. Corrplot of Alwar 2021

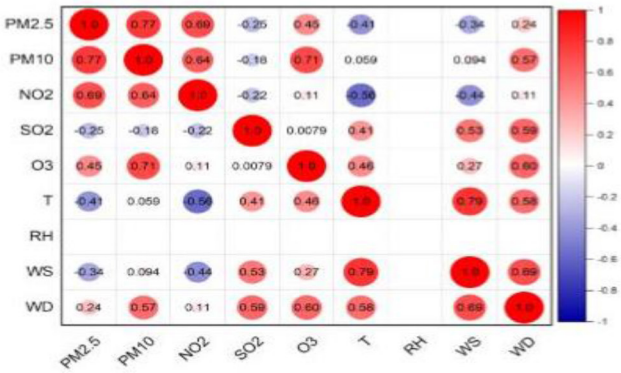


Fig. 10e. Corrplot of Alwar 2022

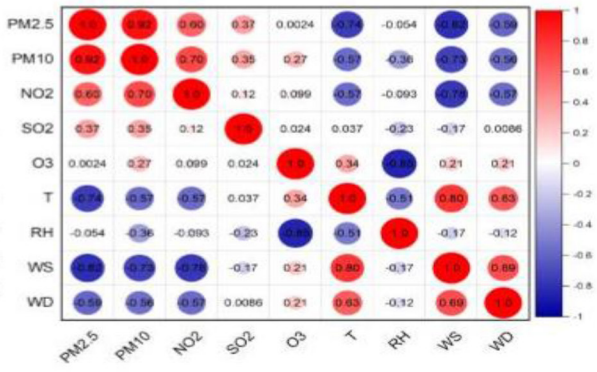


Fig. 10f. Corrplot of Alwar 2023

Figure 10(a-f). Correlation plots of air pollutants and meteorological parameters at Alwar from 2018 to 2023.

The 2023 correlation analysis again revealed a strong interdependence between $PM_{2.5}$ and PM_{10} ($r \approx 0.97$), consistent with prior years. NO_2 correlated moderately with PM fractions, confirming their co-emission from traffic and fossil fuel combustion. SO_2 displayed weaker correlations, suggesting reduced industrial contributions or effective emission control measures. O_3 remained weakly or negatively correlated with primary pollutants, supporting its secondary formation nature. T and WD had weak positive relations, while RH and WS showed inverse associations with PM concentrations, reaffirming their pollutant-scavenging effects.

4. Discussions

4.1 Data Interpretation in Air pollution

The monthly and spatio-temporal variations in air pollutant concentrations from 2018 to 2023 were observed in this study (Figure 2(a-j)) reflect the combined effects of anthropogenic activities and meteorological conditions on urban air quality. Our findings are consistent with several earlier studies[32-42], which similarly reported that air pollutant levels in urban areas exhibit strong temporal fluctuations and pronounced seasonal patterns. $PM_{2.5}$ and PM_{10} peaked in winter and pre-monsoon due to low T, calm winds, and industrial/vehicular emissions, while monsoon rainfall reduced concentrations through wet deposition. Ajmer and Alwar exhibited consistently higher particulate levels, highlighting the strong influence of traffic sources, corroborating other findings[37,38]. NO_2 concentrations were highest in winter and pre-monsoon, reflecting combustion activities, and decreased during monsoon due to washout[39,40]. SO_2 displayed a similar seasonal trend, with pre-monsoon maxima and monsoon minima driven by industrial emissions and rainfall-mediated removal[41,42]. O_3 peaked in pre-monsoon, with higher variability in Alwar due to elevated precursor emissions and photochemical activity. Positive correlations with T and negative correlations with NOx confirmed its secondary photochemical formation[43]. Meteorological parameters significantly influenced pollutant dispersion: low WS and stable layers during winter favored accumulation, while monsoonal rainfall and increased vertical mixing reduced pollution[44,45]. Overall, Ajmer air quality was primarily emission-driven, whereas Alwar's pollution was largely meteorologically modulated. Seasonal trends, industrial intensity, and other anthropogenic activity shaped the observed patterns, providing insights for targeted mitigation strategies, including industrial control, traffic and seasonal management in Ajmer and Alwar.

4.2 Annual Variation of Air Pollutant Concentration Trends

The annual spatio-temporal variations of air pollutants at Ajmer and Alwar (2018-2023, Figures $3(a_1 - e_1)$ and $4(a_2 - e_2)$) revealed distinct inter-city differences and seasonal dynamics, consistent with earlier studies[32,35,37-39,42]. In Ajmer and Alwar, $PM_{2.5}$ and PM_{10} showed consistently higher concentrations, particularly in winter and post-monsoon, reflecting intense industrial activity, vehicular emissions, and dust resuspension. Our study observed downward trend during 2020 corroborated the effects of COVID-19 lockdown, which were similar to other findings[38-39]. NO_2 and SO_2 also exhibited seasonal maxima in winter and pre-monsoon, driven by combustion and industrial emissions, while monsoon rainfall effectively reduced concentrations, consistent with other findings[37]. O_3 displayed pre-monsoon peaks, highlighting secondary photochemical formation enhanced by high solar radiation and elevated precursor gases, supporting observations by other findings[32,42]. In Ajmer and Alwar, higher pollutant levels were maintained with seasonal fluctuations primarily modulated by meteorological conditions. This emphasizes the combined role of emissions and local climate in shaping urban air quality. Overall, the results enhance understanding of pollutant dynamics in contrasting urban environments and inform targeted mitigation strategies tailored to emission intensity and meteorological influences.

4.3 Spatial Variation of Air Pollutant Concentration Trends

The observed spatial variability in annual mean air pollutant concentrations between Ajmer and Alwar (2018-2023, Figure 5(i-v)) highlights the influence of urbanization, industrialization, and vehicular density on air quality. Ajmer and Alwar consistently exhibited higher levels of $PM_{2.5}$, PM_{10}, NO_2, and SO_2, reflecting dense traffic and construction-related dust. These findings align with earlier studies reporting elevated pollutant concentrations in urban hotspots[46-50]. The presence of outliers in Ajmer

and Alwar indicates frequent pollution spikes due to fluctuating emissions and meteorological stagnation. Interestingly, O_3 levels were slightly higher in Ajmer and Alwar, likely due to stronger photochemical formation under cleaner conditions and reduced NOx titration, consistent with patterns[42]. Overall, the spatial comparison emphasizes the dominant role of local emission sources in shaping urban air quality and underscores the need for site-specific mitigation strategies tailored to industrial and vehicular impacts.

4.4 Data Interpretation of Meteorological Parameters

Meteorological parameters played a significant role in deciding the ambient air quality of the urban sites of Ajmer and Alwar during 2018 and 2023. Seasonal analyses revealed that T, RH, WS, and WD strongly influenced pollutant dispersion and accumulation. Numerous studies observed correlation and regression analyses between gaseous and air pollutant concentrations and meteorological parameters (Tables 1, 2a-j, and Figures 6(a-f), 7, 8, 9(a-f), 10(a-f))[35,37,39,40,44,45,51,52]. In our studies meteorological parameters were analyzed for 2018 to 2023 during four seasons: Winter (December to February), pre-monsoon (March to May), monsoon (June to September), and post-monsoon (October to November), highlighting the highest and lowest values recorded in each city along with scientific reasoning for these variations at Ajmer and Alwar monitoring stations, Rajasthan, India. During winter, low T and atmospheric stability contributed to pollutant build-up, especially in Ajmer, consistent with other findings[37,44]. Conversely, pre-monsoon and monsoon periods exhibited enhanced dispersion due to higher T, convective activity, and rainfall, leading to reduced particulate and gaseous concentrations, aligning with other observations[40,45]. Wind patterns were particularly influential in Ajmer, where higher speeds and favorable topography promoted pollutant transport and dilution, while Alwar's industrial and urban layout limited effective dispersion[35,51]. RH modulated particulate accumulation, with higher RH during monsoon facilitating wet deposition of $PM_{2.5}$ and PM_{10}. Overall, these findings underscore the critical interplay between meteorology and pollution dynamics, highlighting the necessity of integrating climatic variability into urban air quality management and predictive modeling.

4.5 Implications for Public and Occupational Health

The elevated levels of $PM_{2.5}$, PM_{10}, NO_2, and SO_2 observed in Ajmer and Alwar, particularly during winter and pre-monsoon seasons, have important implications for workers in outdoor occupations. Construction laborers, traffic police, street vendors, and industrial workers are continuously exposed to ambient pollutants and may experience increased respiratory and cardiovascular risks due to prolonged inhalation of particulate matter and gaseous pollutants. $PM_{2.5}$ exposure is associated with decreased lung function, chronic bronchitis, and cardiovascular morbidity, while NO_2 and SO_2 can exacerbate asthma and other respiratory conditions[53,54]. Traffic-related pollutants, especially in densely populated urban areas, exacerbate risks for outdoor workers who spend extended periods in high-exposure zones[55]. Seasonal peaks and stagnation periods imply that workers are at highest risk during winter and pre-monsoon, when dispersion is limited and pollutant accumulation is maximal. To mitigate these impacts, occupational health interventions are essential, including the use of personal protective equipment (masks), routine health screenings, and exposure monitoring of air quality, especially in urban and industrial zones. Additionally, season-adaptive strategies like adjusting work hours or providing indoor shelters during high-pollution days can reduce exposure. Policymakers should also integrate urban traffic management, emission reduction, and workplace safety standards into regional air quality plans. Overall, this study establishes a strong link between seasonal air quality dynamics and human health outcomes, emphasizing the urgent need for evidence-based environmental and occupational health policies tailored to semi-arid urban regions like Ajmer and Alwar.

5. Conclusion

This study revealed significant spatial, seasonal, and annual variations in air pollutant concentrations in Ajmer and Alwar, Rajasthan, highlighting the combined effects of emissions and meteorological conditions on urban air quality. $PM_{2.5}$, PM_{10}, NO_2, and SO_2 consistently exceeded NAAQS limits, particularly during winter and pre-monsoon, while O_3 concentrations were highest in industrial areas during summer due to favorable photochemical conditions. Regression and correlation

analyses confirmed that meteorological parameters, especially wind speed, wind direction, temperature, and relative humidity, strongly influenced pollutant dynamics. The study highlights several key actionable insights include:

1. Seasonal mitigation strategies: Elevated pollution during winter and pre-monsoon calls for season-specific measures, such as regulating traffic and industrial emissions, and scheduling outdoor work to minimize exposure.
2. Site-specific interventions: Ajmer's high pollution from dense traffic and construction versus Alwar's meteorologically modulated pollution highlights the need for localized management strategies, including monitoring hot-spots and deploying targeted controls.
3. Occupational health measures: Outdoor workers face elevated risks of respiratory and cardiovascular effects; interventions such as personal protective equipment, exposure monitoring, and health advisories are critical during high pollution periods.
4. Research and modeling recommendations: Continuous long-term monitoring, source apportionment, trajectory analysis, and advanced modeling are essential to understand pollutant transport, inform policy, and support evidence-based urban air quality management.

Overall, the findings underscore the importance of region-specific, seasonally adaptive air quality management to reduce human exposure, protect vulnerable populations, and improve environmental sustainability in semi-arid urban settings.

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Author Contribution

Both authors measured air pollutant emissions data, designed the research, analysed the data, generated the figures, wrote the original manuscript, and edited the manuscript. All authors reviewed the manuscript.

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