



SPATIO-SEASONAL VARIATION OF AMBIENT AIR POLLUTANTS AND THEIR RELATION TO METEOROLOGICAL FACTORS IN BHIWADI AND UDAIPUR OF RAJASTHAN

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Abstract: Urban air quality is deteriorating with increased pollutant concentrations due to anthropogenic activities. The study examined spatial and seasonal variations of particulate matter (PM_{2.5} and PM₁₀), nitrogen dioxide, sulfur dioxide and ozone from 2018-2023 at Bhiwadi and Udaipur monitoring stations, and assessed their relationships with meteorological parameters. Results showed that monthly and annual mean concentrations of all pollutants, except O₃, consistently peaked in both cities, attributed to rapid industrialization and urbanization. Seasonal variations observed higher pollutant concentrations during winter, followed by pre-monsoon, post-monsoon, and lower in monsoon seasons. In Bhiwadi and Udaipur, highest mean concentrations of PM_{2.5} (55.71 and 31.2 µg/m³), PM₁₀ (210 and 178 µg/m³), NO₂ (52 and 45 µg/m³), SO₂ (69.20 and 20.49 µg/m³), and O₃ (46.94 and 49.93 µg/m³) were recorded, respectively. The wind speed and direction were the strongest influences on pollutant concentrations. Correlation and regression analyses indicated significant relationships between pollutants and meteorological parameters. These findings led in designing and implementing season-specific air pollution mitigation strategies at the regional scale. Implementation of precautionary measures is essential to reduce pollutant exposure to the public. This investigation further suggests that extensive studies on adverse impacts of air pollution on human health and environmental risk assessment are required.

Keywords: Air pollutants, Meteorological parameters, Particulate matter, Urban environment, Variation.

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INTRODUCTION

Air pollution shows a critical and growing global public health concern, being responsible for the global burden of disease from environmental factors (Cohen *et al.*, 2017; Orioli *et al.*, 2018). According to the World Health Organization's (WHO) urban air quality database, more than 80% of the population residing in urban areas are exposed to pollutant level exceeding these limits (WHO, 2016). The air quality continues to deteriorate in developing countries due to increased

vehicular traffic and rapid industrialization. Globally, atmospheric air pollutants contributed to 3.7 million premature deaths annually (WHO, 2018). Exposure to fine and coarse particulate matter (PM) with an aerodynamic diameter of less than 2.5 µm (PM_{2.5}) and less than 10 µm (PM₁₀) are responsible for deleterious effects on human and plant health (Finch and Conklin, 2016; WHO, 2016; Yang *et al.*, 2016; Fang *et al.*, 2017; Turner *et al.*, 2017; Dehghan *et al.*, 2018; Wang *et al.*, 2018; Singh and Tiwari, 2025).



Although numerous air pollutants have been associated with adverse health effects, nitrogen oxides (NO_x), ozone (O₃), sulfur dioxide (SO₂), and PM_{2.5} are most extensively studied and commonly used as proxy indicators of air pollution exposure (WHO, 2005). These air pollutants originate from diverse sources, including industrial activities, urban construction, biomass burning, and vehicular emissions. Increased vehicular traffic and rapid industrialization lead to substantial emissions of air pollutants that are capable of inducing toxic effects on human health (Sharma *et al.*, 2014; Singh and Tiwari, 2025). In addition to emission sources, meteorological parameters influence urban air pollution (Dey *et al.*, 2017; Zhan *et al.*, 2018; Niu *et al.*, 2024). Among these, relative humidity (RH), temperature (T), wind speed (WS), and wind direction (WD) are considered as major factors determining the pollution potential over a region (Goyal and Rao, 2007; Suthar *et al.*, 2024; Zhai *et al.*, 2024). However, the research regarding addressing the combined influence of meteorological factors on urban air pollution across the Indian subcontinent remains limited.

India continues to face a persistent air pollution crisis and consistently ranks among the top three most polluted globally (Dholakia *et al.*, 2014). Industrial development and rapid urbanization have led to elevated concentration levels of PM, NO₂, and SO₂ in urban environments (Guttikunda *et al.*, 2025). 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 (Guttikunda *et al.*, 2025). 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, 2009) to regulate emissions of twelve key pollutants. Despite these regulatory efforts, air pollution remains a major environmental and public health challenge.

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 (Tobollik *et al.*, 2015). 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.

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 PM₁₀, particularly during pre-monsoon and summer months (Singh *et al.*, 2025). Urban centres such as Bhiwadi and Udaipur are influenced by pollution from industrial activities and dense vehicular traffic emissions leading to exacerbate particulate and gaseous pollutant levels. These regional factors, climatic and anthropogenic factors make Rajasthan a unique case for studying the interactions between meteorology, urbanization, and air quality. Elevated pollution levels in these cities pose serious risks to human health, including respiratory, cardiovascular and other disorders, underscoring the need for region-focused air quality assessments to support effective mitigation strategies. Therefore, understanding spatio-temporal pollution patterns is not only vital for environmental assessment but also for developing targeted human health and safety interventions.

Although several studies have assessed air quality in Indian cities using Central Pollution Control Board (CPCB) datasets, most have been limited to short-term periods, single pollutants, or individual monitoring sites. In contrast, the present study provides a comprehensive analysis of multiple pollutants (PM_{2.5}, PM₁₀, NO₂, SO₂, O₃) over a longer temporal span (2018-2023) across two urbanizing districts (Bhiwadi and Udaipur) 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.

The present study was undertaken to fill this research gap by evaluating seasonal variations in ambient air quality and associated meteorological influences in Bhiwadi and Udaipur, two rapidly urbanizing districts of Rajasthan, India. 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 the spatio-temporal and seasonal variations of ambient air parameters across selected urban locations in Bhiwadi and Udaipur, Rajasthan, India and to examine the influence of meteorological factors on urban air quality. By focusing on rapidly urbanizing districts within a semi-arid climatic setting, this research provides region-specific insights that are critical for future air quality management, mitigation planning, and policy formulation.

MATERIALS AND METHODS

Study area

Rajasthan, the largest state of India, covers area of 342,239 square KM in area, which is about 10.4 % of total geographical area of India, has 33 districts, and is ranked seventh in terms of population. Rajasthan has a prosperous history and rich culture heritage, famous for its majestic beautiful forts, beautiful decorative Havelis, and ornamented temples. The geographical features of Rajasthan include the Aravalli Range. Rajasthan lies in northwestern part of India, which has a warm, dry, semiarid climate, famous as the 'Thar Desert'. Rajasthan has a hot semi-arid climate, and has a dry climate with scorching summers, cold winters, and short-lived monsoon season.

In Rajasthan, each city has its own industrial profile of which Bhiwadi is one of the most polluted industrial cities. Udaipur, known as the City of Lakes, is in southern Rajasthan; has a rich cultural background and is a popular tourist destination (Kalal *et al.*, 2021). Udaipur is well known for its history, attractive monuments, luxurious hotels, parks, and lakes, making it a tourist paradise. Unplanned urbanization and rapid industrial growth in Rajasthan have significantly transformed agricultural and wastelands into urban areas.

The prominent districts of Rajasthan (Bhiwadi and Udaipur) have monitoring stations to measure the ambient air quality. The geographical position of two major cities of Rajasthan is RIICO Ind. Area III, Bhiwadi (28°12'36.87"N 76°51'38.03"E), and Ashok Nagar, Udaipur (23°32'09.6800"N, 91°29'13.1500"E) located in the southernmost part of Rajasthan (Fig. 1). The study was conducted in these two major cities of Rajasthan, and selected them based on the availability of ample secondary data, geographical features, urbanization, and variable pollution levels, which give a comprehensive understanding of air pollution concentration levels in major urban centres of Rajasthan.

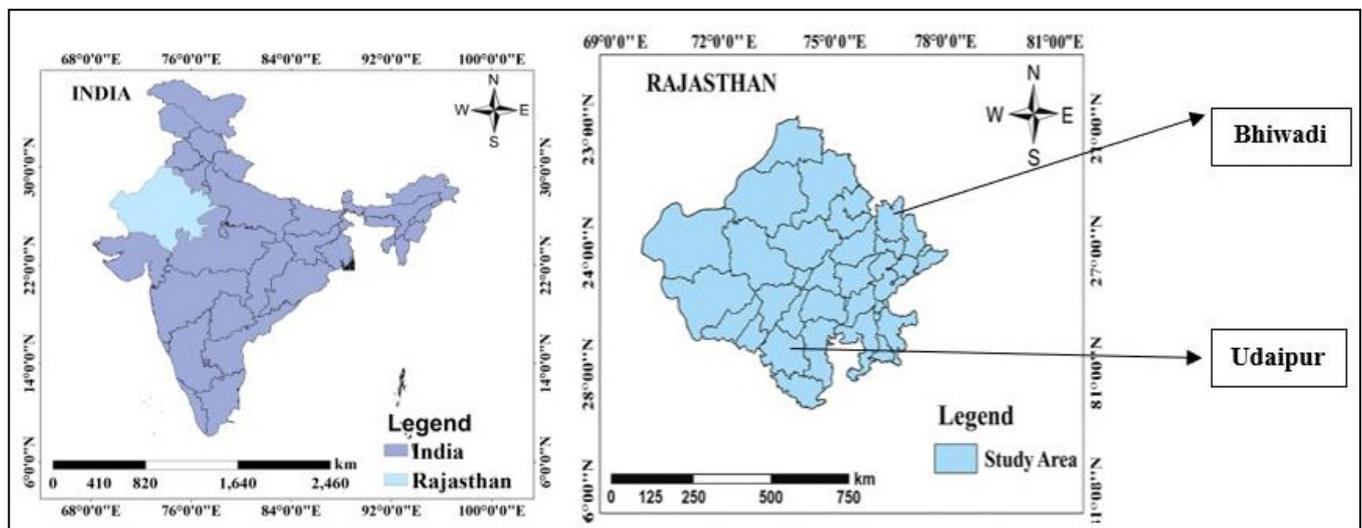


Fig. 1: Details of selected sites in cities of Rajasthan, India.

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 Bhiwadi and Udaipur. Statistical analyses (Correlation and regression) were performed by using statistical software SPSS and OriginPro. Wind speed and direction were statistically analyzed using Wind Rose (WRPlot) diagrams generated in (software name, WRPLOT View).

RESULTS AND DISCUSSION

1. Data Interpretation of Air pollution

In present studies, Air Quality Index (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 city along with scientific reasoning for these variations in Bhiwadi and Udaipur monitoring stations, Rajasthan, India (Fig. 2 and 3).

Quantifying AQI of air pollutants (PM_{2.5}, PM₁₀, NO₂, SO₂, O₃) in the city of Bhiwadi

The monthly variation of air pollutants-based AQI in Bhiwadi over six years (2018-2023) has been illustrated in Fig. 2. Bhiwadi consistently exhibited the highest AQI values among all sites, with PM_{2.5} ranging between 160 and 280 µg/m³ and PM₁₀ from 180-300 µg/m³. Winter recorded extreme levels (PM_{2.5}: 220-280 µg/m³; PM₁₀: 240-280 µg/m³), primarily due to industrial emissions, vehicular exhaust, and temperature inversion.

During pre-monsoon, values remained high (PM_{2.5}: 190–240 µg/m³; PM₁₀: 200–240 µg/m³) because of persistent emission sources and dust resuspension. Monsoon levels declined moderately (PM_{2.5}: 120-160 µg/m³; PM₁₀: 120-160 µg/m³) yet stayed elevated compared to other cities, reflecting continuous industrial activity. Post-monsoon concentrations increased again (PM_{2.5}: 180-230 µg/m³; PM₁₀: 180-230 µg/m³). Year-wise, 2019, 2021, and 2023 exhibited the most severe pollution episodes, while 2020 marked a temporary improvement. In Bhiwadi, AQI-NO₂ showed the highest overall values (50-120 µg/m³) among all sites due to intense industrialization and vehicular density. Winter peaks reached 100-120 µg/m³, exacerbated by temperature inversion and low WS. Pre-monsoon levels remained high (70-100 µg/m³)

from industrial and transport sources. The monsoon period recorded reduced NO₂ (40-60 µg/m³), while post-monsoon months again saw elevated values (80-100 µg/m³). Yearly maxima were noted in 2019, 2021, and 2023, with a dip during 2020. In Bhiwadi, SO₂ concentrations were highest among all cities (15-50 µg/m³). Winter recorded maximum values (35-50 µg/m³) due to industrial combustion and thermal plant emissions. Pre-monsoon values were also remained elevated (25-40 µg/m³), while monsoon values decreased sharply (10-20 µg/m³).

Post-monsoon months showed moderate increases (25-35 µg/m³). Yearly maxima appeared in 2019, 2021, and 2023, with a noticeable dip in 2020. Bhiwadi (Fig. 4.3.3), as a major industrial area, exhibited pronounced pre-monsoon O₃ peaks (80-100 µg/m³) due to high photochemical activity and emissions from industries and traffic. The monsoon period saw O₃ reduction to 40-55 µg/m³, attributable to washout and reduced solar radiation. A secondary increase occurred during post-monsoon (65-85 µg/m³), while winter values were lower (35-50 µg/m³) because of temperature inversion restricting vertical dispersion. Yearly analysis indicated high O₃ levels in 2020 and 2022, corresponding with post-lockdown industrial recovery and increased emission activities.

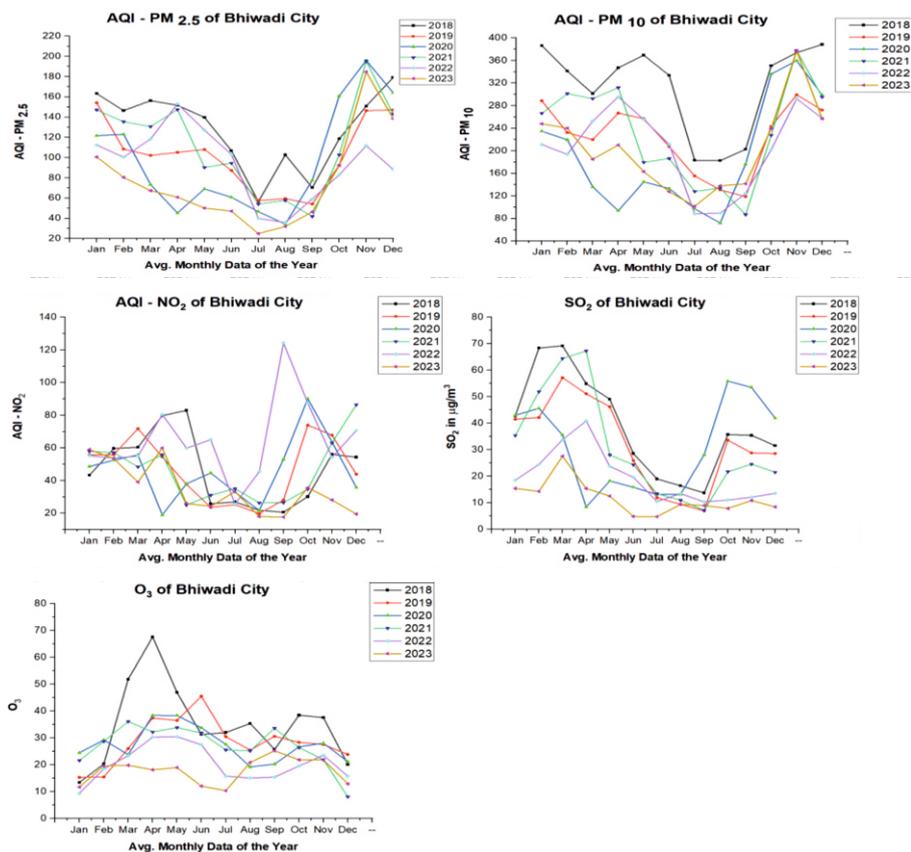


Fig. 2: Quantifying Air pollutants at Bhiwadi in various seasons of years 2018 to 2023.

Quantifying AQI of air pollutants (PM_{2.5}, PM₁₀, NO₂, SO₂, O₃) in the city of Udaipur

NO₂ concentrations in Udaipur ranged between 20 and 50 µg/m³, indicating relatively lower levels compared to particulate pollutants. Winter recorded the highest concentrations (40–50 µg/m³), whereas pre-monsoon and post-monsoon periods showed moderate levels (30–45 µg/m³). The monsoon season exhibited the lowest concentrations (20–30 µg/m³), reflecting improved atmospheric conditions.

Udaipur showed comparatively lower particulate concentrations, with AQI-PM_{2.5} between 90 and 170 µg/m³ and AQI-PM₁₀ from 100-180 µg/m³. Winter peaks were moderate (PM_{2.5}: 130-160 µg/m³; PM₁₀: 140-180 µg/m³). Pre-monsoon levels were similar (PM_{2.5}: 110-150 µg/m³; PM₁₀: 120-160 µg/m³). Monsoon displayed the lowest AQI (PM_{2.5}: 70-100 µg/m³; PM₁₀: 70-110 µg/m³). Post-monsoon showed a gradual rise (PM_{2.5}: 100-130 µg/m³; PM₁₀: 110-150 µg/m³). The year 2019 showed the highest particulate levels, while 2020 reflected a substantial decline due to reduced

emission activities. In Udaipur, NO₂ concentrations was comparatively low (20-50 µg/m³). Winter showed the highest AQI (40-50 µg/m³), while pre-monsoon and post-monsoon levels were moderate (30-45 µg/m³). Monsoon recorded the cleanest conditions (20-30 µg/m³). Year-wise, 2019 and 2022 showed slight increases, while 2020 reflected the lowest NO₂ levels. In Udaipur, SO₂ concentrations were lowest among all sites (5-20 µg/m³). Winter showed higher values (15-20 µg/m³), pre-monsoon moderate (10-15 µg/m³), monsoon lowest (5-10 µg/m³), and post-monsoon slightly increased (10-15 µg/m³). Udaipur, displayed distinct seasonal oscillations, with pre-monsoon O₂ levels around 65-85 µg/m³ and post-monsoon values (60-80 µg/m³) forming the two major peaks. The monsoon period exhibited reduced levels (35-45 µg/m³), while winter concentrations were moderate (40-60 µg/m³). Yearly variations indicated higher O₃ values in 2021 and 2023, suggesting enhanced photochemical activity due to urban expansion, vehicular emissions, and favorable meteorological conditions. The results are shown in Fig. 3.

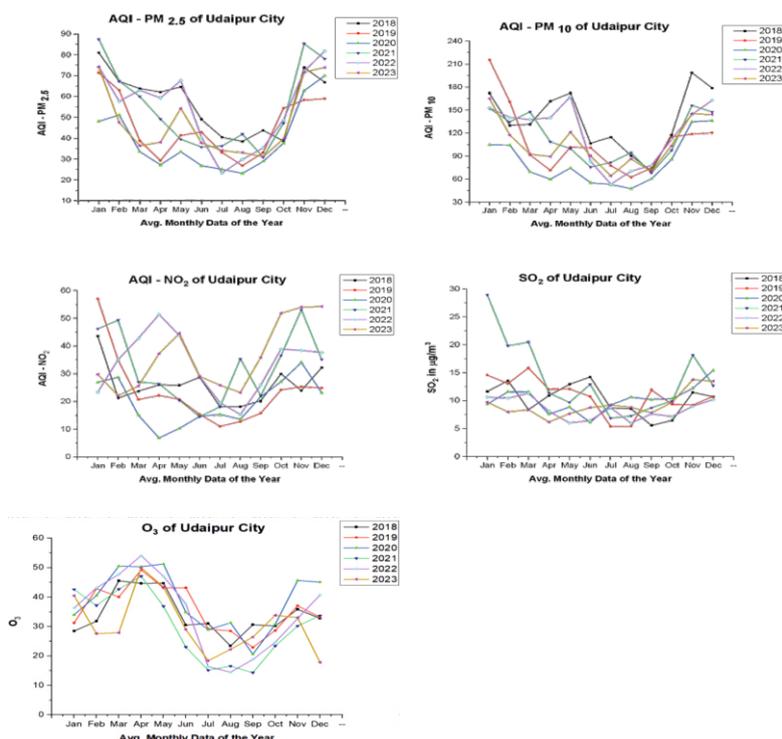


Fig. 3: Quantifying Air pollutants at Udaipur in various seasons of years 2018 to 2023.

Annual Variation of air pollutants in Bhiwadi city

A comparison among the annual mean concentrations of five criteria air pollutants in Bhiwadi during the study period from 2018 to 2023 is shown in Fig. 4. The highest annual mean concentrations of PM_{2.5}, PM₁₀, SO₂, and O₃ were recorded in 2018, with approximately 127.19 µg/m³, 311.79 µg/m³, 36.79 µg/m³, and 29.46 µg/m³, respectively, whereas the highest annual mean concentration of NO₂ (64.71

µg/m³) was found in 2022. The lowest annual mean concentrations of PM_{2.5}, PM₁₀, NO₂, SO₂, and O₃ were observed in 2023, 2020, 2023, 2023, and 2023, with approximately 76.99 µg/m³, 188.68 µg/m³, 34.38 µg/m³, 11.71 µg/m³, and 17.74 µg/m³, respectively. The mean yearly values of PM_{2.5}, PM₁₀, and NO₂ exceeded the WHO air quality guidelines (20 and 10 µg/m³ for PM₁₀ and PM_{2.5}, and 22 µg/m³ for NO₂) throughout the study period.

The data presented in Fig. 4 clearly showed that annual mean PM_{10} concentrations fluctuated between approximately 311.79 and 188.68 $\mu\text{g}/\text{m}^3$, marking a decline of 39.48% from 2018 to 2023, and followed a consistent downward trend over the entire period. The PM_{10} concentration decreased to a minimum of 188.68 $\mu\text{g}/\text{m}^3$, likely due to COVID-19 lockdown restrictions in 2020. Similarly, the annual average of ambient $PM_{2.5}$ declined from about 127.19 $\mu\text{g}/\text{m}^3$ to 76.99 $\mu\text{g}/\text{m}^3$, a reduction of 39.47% between 2018 and 2023, also showing a steady downward trend. During the period from 2018 to 2023, among all ambient gaseous air

pollutants, only the annual mean concentrations of NO_2 and SO_2 showed a downward trend (Fig. 3). Annual mean NO_2 concentrations declined approximately from 64.71 to 34.38 $\mu\text{g}/\text{m}^3$, representing a sharp fall of 46.87%. Similarly, annual SO_2 displayed a considerable downward trend, with mean concentrations decreasing from about 36.79 $\mu\text{g}/\text{m}^3$ to 11.71 $\mu\text{g}/\text{m}^3$ between 2018 and 2023, marking an overall decline of 68.17%. O_3 exhibited a fluctuating trend in its annual mean concentrations, ranging between 29.46 $\mu\text{g}/\text{m}^3$ and 17.74 $\mu\text{g}/\text{m}^3$ during the study period, with an overall increase of 39.78% (Fig. 4).

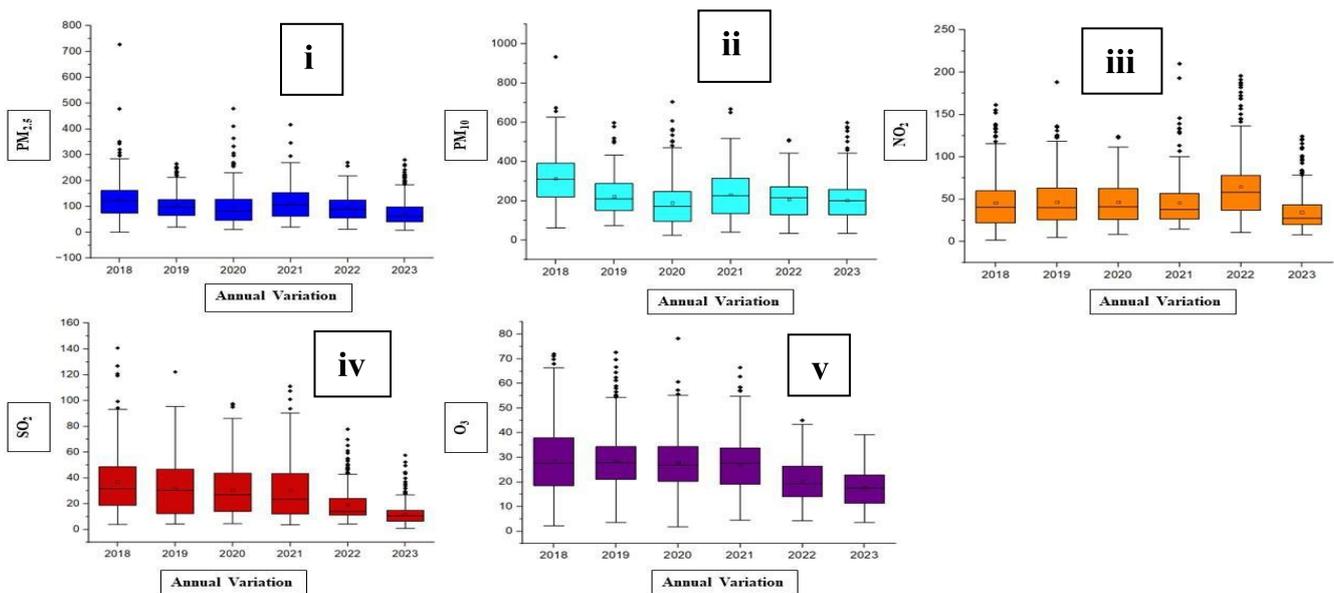


Fig. 4: Annual variation of Air Pollutants at Bhiwadi city from 2018 to 2023.

Annual Variation of air pollutants in Udaipur city

The data presented in Fig. 5 demonstrated a comparison among the annual mean concentrations of five criteria air pollutants in Udaipur during the study period from 2018 to 2023. The highest annual mean concentrations of $PM_{2.5}$ (57.25 $\mu\text{g}/\text{m}^3$) and PM_{10} (137.08 $\mu\text{g}/\text{m}^3$) were found in 2018, whereas the highest annual mean concentrations of NO_3 (36.23 $\mu\text{g}/\text{m}^3$), SO_2 (13.86 $\mu\text{g}/\text{m}^3$), and O_3 (38.55 $\mu\text{g}/\text{m}^3$) were recorded in 2023, 2021, and 2020, respectively. The lowest annual mean concentrations of $PM_{2.5}$, PM_{10} , NO_2 , SO_2 , and O_3 were observed in 2020, 2020, 2020, 2022, and 2021, with approximately 38.95 $\mu\text{g}/\text{m}^3$, 82.14 $\mu\text{g}/\text{m}^3$, 19.74 $\mu\text{g}/\text{m}^3$, 8.44 $\mu\text{g}/\text{m}^3$, and 30.13 $\mu\text{g}/\text{m}^3$, respectively. The mean yearly values of $PM_{2.5}$, PM_{10} , and NO_2 exceeded the WHO air quality guidelines (20 and 10 $\mu\text{g}/\text{m}^3$ for PM_{10} and $PM_{2.5}$, and 22 ppb for NO_2) throughout the study period. A glance at Fig. 5 showed that annual mean $PM_{2.5}$ concentrations fluctuated between 137.08 $\mu\text{g}/\text{m}^3$ and 82.14 $\mu\text{g}/\text{m}^3$, marking a decline of 40.08% from 2018 to 2023, and followed a consistent downward trend over the entire study period. The

PM_{10} concentration decreased to 82.14 $\mu\text{g}/\text{m}^3$ due to COVID-19 lockdown restrictions in 2020.

Similarly, the annual average of ambient $PM_{2.5}$ declined from 57.25 $\mu\text{g}/\text{m}^3$ to 38.95 $\mu\text{g}/\text{m}^3$, a reduction of 31.96% between 2018 and 2023, and showed a consistent downward trend across the years. The $PM_{2.5}$ concentration decreased to 38.95 $\mu\text{g}/\text{m}^3$ during the 2020 lockdown period. During the period from 2018 to 2023, among all ambient gaseous air pollutants, only the annual mean concentrations of NO_2 and SO_2 showed upward and downward trends, respectively (Fig. 5). Annual mean NO_2 concentrations increased from approximately 19.74 $\mu\text{g}/\text{m}^3$ to 36.23 $\mu\text{g}/\text{m}^3$ between 2018 and 2023, representing a sharp rise of 45.51%. In contrast, annual SO_2 displayed a considerable downward trend, with its annual mean concentrations decreasing from about 13.86 $\mu\text{g}/\text{m}^3$ to 8.44 $\mu\text{g}/\text{m}^3$ between 2018 and 2023, indicating an overall decline of 39.10%. O_3 exhibited a fluctuating annual trend, ranging between 30.13 $\mu\text{g}/\text{m}^3$ and 38.55 $\mu\text{g}/\text{m}^3$ during the study period, with an overall increase of 21.84% (Fig. 5).

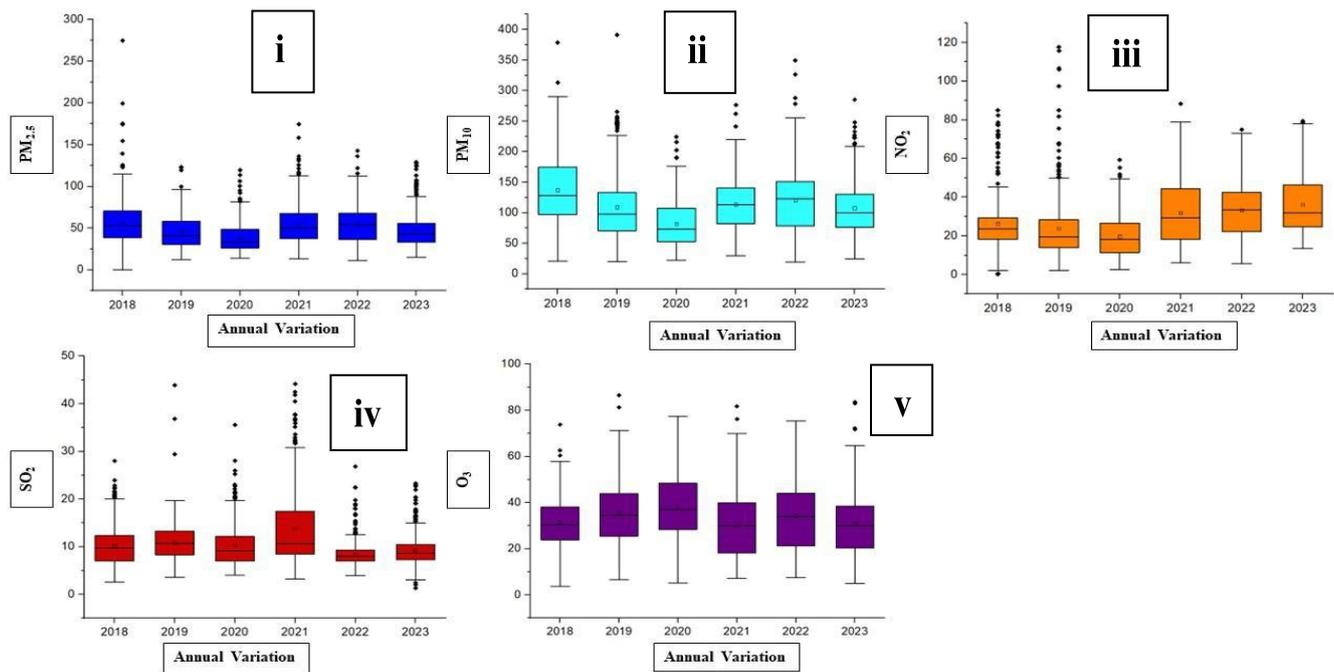


Fig. 5: Annual variation of Air Pollutants at Udaipur city from 2018 to 2023.

The annual spatio-temporal variations of air pollutants at Bhiwadi and Udaipur (2018-2023, Figs. 4i-v and 5i-v) revealed distinct inter-city differences and seasonal dynamics, consistent with earlier studies (İçağa and Sabah, 2009; Jiang and Bai, 2018; Manju *et al.*, 2018; Yousefian *et al.*, 2020; Shelton *et al.*, 2022; Suthar *et al.*, 2023). In Bhiwadi, $PM_{2.5}$ and PM_{10} showed consistently higher concentrations, particularly in winter and post-monsoon, reflecting intense industrial activity, vehicular emissions, and dust resuspension. The observed downward trend during 2020 corroborated the effects of COVID-19 lockdown, echoing similar reductions (Manju *et al.*, 2018; Suthar *et al.*, 2023). 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 findings of İçağa and Sabah (2009). O_3 displayed pre-monsoon peaks, highlighting secondary photochemical formation enhanced by high solar radiation and elevated precursor gases, supporting observations by Jiang and Bai (2018) and Yousefian *et al.* (2020).

In contrast, Udaipur maintained comparatively lower pollutant levels, with seasonal fluctuations primarily modulated by meteorological conditions rather than industrial intensity. This emphasizes the combined role of emissions and local climate in shaping urban air quality. Overall, the results enhance understanding of the pollutant dynamics in contrasting urban environments and inform targeted mitigation

strategies tailored to emission intensity and meteorological influences.

Spatial Variation of air pollutants at Bhiwadi and Udaipur cities

The box plots clearly illustrated the differences in pollutant concentrations across both cities. Overall, Bhiwadi exhibited significantly higher concentrations of $PM_{2.5}$, PM_{10} , NO_2 , and SO_2 compared to Udaipur, as indicated by the higher median values and wider interquartile ranges. This reflected the intense industrial activities, vehicular emissions, and construction-related dust prevalent in Bhiwadi, an established industrial hub. The presence of numerous outliers also indicated frequent pollution spikes due to emission fluctuations and stagnant atmospheric conditions.

In contrast, Udaipur demonstrated relatively lower pollutant levels, which were attributed to its tourism-oriented and less industrialized environment and better dispersion resulting from the favorable meteorological conditions. Interestingly, O_3 levels showed a slightly higher median in Udaipur than in Bhiwadi, which was linked to stronger photochemical activity and lower NO_x titration in the comparatively cleaner atmosphere of Udaipur. In summary, the spatial comparison underscored Bhiwadi's degraded air quality dominated by particulate and gaseous pollutants, while Udaipur maintained comparatively cleaner air, except for moderate ozone accumulation under high solar radiation conditions (Fig. 6i-v).

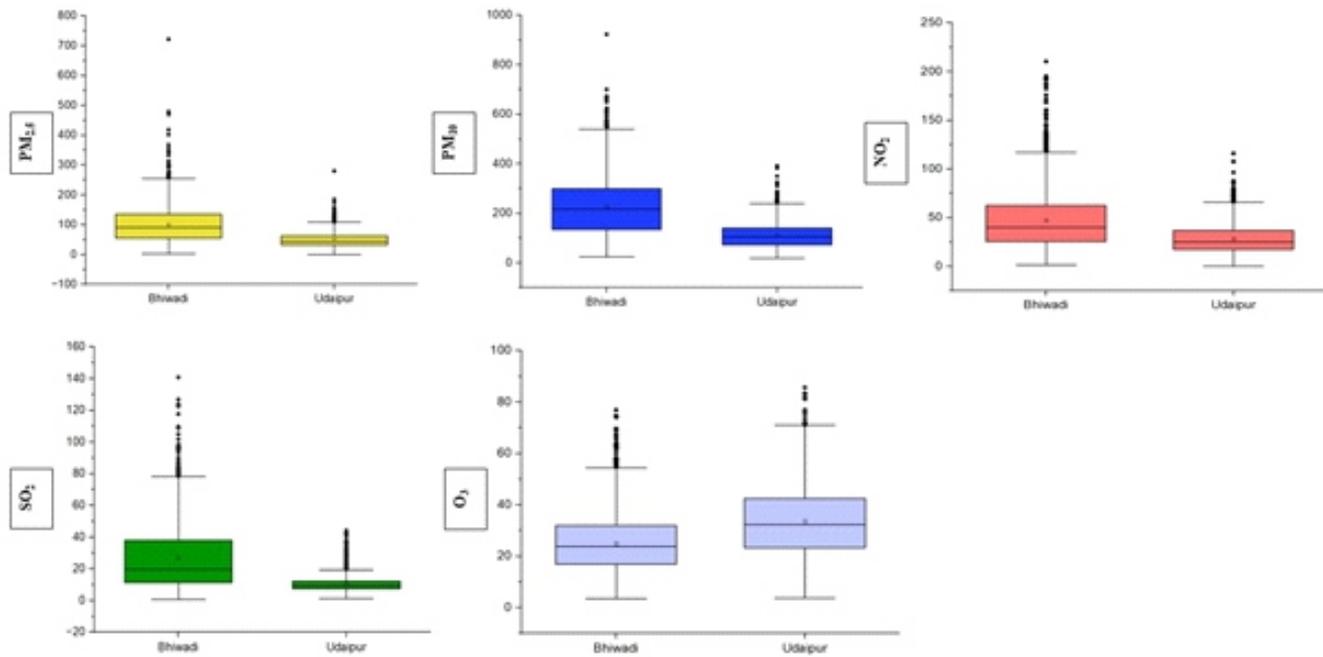


Fig. 6: Spatial variation of Air Pollutants at Bhiwadi and Udaipur from 2018 to 2023.

The observed spatial variability in annual mean air pollutant concentrations between Bhiwadi and Udaipur (2018-2023, Fig. 6i-v) highlights the influence of urbanization, industrialization, and vehicular density on air quality. Bhiwadi consistently exhibited higher levels of $PM_{2.5}$, PM_{10} , NO_2 , and SO_2 , reflecting intensive industrial operations, dense traffic, and construction-related dust. These findings align with earlier studies reporting elevated pollutant concentrations in industrial and urban hotspots (Dor *et al.*, 1995; Mayer, 1999; Morawska *et al.*, 2002; Azmi *et al.*, 2010; Dominick *et al.*, 2012). The presence of outliers in Bhiwadi indicates frequent pollution spikes due to fluctuating emissions and meteorological stagnation. In contrast, Udaipur maintained comparatively lower pollutant concentrations, attributable to its tourism-oriented, less industrialized environment, and favorable atmospheric dispersion. Interestingly, O_3 levels were slightly higher in Udaipur, likely due to stronger photochemical formation under cleaner conditions and reduced NO_x titration, consistent with patterns reported by Yousefian *et al.* (2020). 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.

2. Data Interpretation of Meteorological Parameters

Quantifying Atmospheric Temperature across the cities of Bhiwadi and Udaipur

The results presented in Fig.7 illustrated the seasonal variation of average monthly atmospheric temperature in Bhiwadi and Udaipur cities from 2018 to 2023. During winter, both cities exhibited the lowest

temperatures, ranging from 15-22°C in Bhiwadi and 17-23°C in Udaipur. The relatively lower temperature was attributed to reduced solar insolation and increased atmospheric stability, typical of northern India's winter climate. In pre-monsoon, a sharp rise in temperature was observed, marking the annual thermal peak. Bhiwadi recorded maximum temperature of 35-40°C, whereas Udaipur showed slightly moderate levels of 33-38°C. The rise corresponded to intensified solar heating, clear skies, and dry conditions, especially prominent in April and May. During monsoon, a decline in temperature was noted in both cities owing to cloud cover, rainfall, and high humidity. Average temperatures ranged from 28-33°C in Bhiwadi and 26-31°C in Udaipur, showing the cooling influence of monsoonal precipitation. In post-monsoon, temperatures gradually decreased as the rainfall subsided and skies cleared, resulting in mean values of 25-30°C in Bhiwadi and 24-29°C in Udaipur. Overall, both cities demonstrated a distinct seasonal thermal cycle, with pre-monsoon maxima and winter minima. However, Bhiwadi consistently experienced higher temperatures due to its industrial heat emissions and urban heat island effects, whereas Udaipur maintained relatively moderate temperatures influenced by its topography and presence of water.

Quantifying Relative Humidity (RH) across the cities of Bhiwadi and Udaipur

The seasonal variation in average monthly RH for Bhiwadi and Udaipur from 2018 to 2023 is shown in Fig. 7. During winter, both cities recorded moderately high relative humidity, typically ranging from 60 to 75% in Bhiwadi and 65 to 80% in Udaipur. The increased RH during this period was attributed to low temperatures and reduced evapotranspiration, which

promoted higher atmospheric moisture retention. In pre-monsoon, relative humidity declined sharply in both the locations, reaching 20-40% in Bhiwadi and 25-45% in Udaipur. This reduction corresponded to rising temperatures, clear skies, and dry winds, characteristic of the hot and arid pre-monsoon climate. During monsoon, a distinct rise in RH was observed, with peak values exceeding 75-85% in Bhiwadi and 80-90% in Udaipur, due to intense rainfall, high cloud cover, and enhanced atmospheric moisture. This marked the period of maximum humidity throughout the year. In post-monsoon, relative humidity values remained elevated but began to decline gradually as rainfall subsided and temperatures decreased, ranging between 55-70% in Bhiwadi and 60-75% in Udaipur. Overall, both cities displayed a distinct inverse relationship between temperature and humidity. RH was lowest during pre-monsoon and highest during monsoon. However, Udaipur consistently exhibited higher RH values compared to Bhiwadi, likely due to its lake-dominated landscape and semi-humid climatic conditions, while Bhiwadi's industrial and urban setting contributed to relatively lower atmospheric moisture.

monthly WS in Bhiwadi and Udaipur from 2018 to 2023. During winter, WS in both cities remained comparatively low, ranging from 0.6-0.9 m/s in Bhiwadi and 1.5-2.0 m/s in Udaipur. Calm conditions and stable atmospheric layers during winter limited air movement, leading to lower wind velocity and potential pollutant accumulation. In pre-monsoon, WS showed a gradual increase in locations, reaching 0.9-1.2 m/s in Bhiwadi and 2.0-2.5 m/s in Udaipur. This enhancement corresponded to rising temperatures and convective activity, which promoted stronger horizontal and vertical air movement. During monsoon, WS remained moderate, influenced by south-west monsoonal flows. Average speeds fluctuated around 0.8-1.1 m/s in Bhiwadi and 2.0-2.8 m/s in Udaipur, aiding better dispersion of atmospheric pollutants and increased ventilation. In post-monsoon, WS decreased gradually as the monsoon system retreated, stabilizing around 0.7-1.0 m/s in Bhiwadi and 1.8-2.2 m/s in Udaipur. Overall, Udaipur consistently exhibited higher wind speeds throughout the year as compared to Bhiwadi. This was attributed to topographical openness and local convective dynamics in Udaipur, whereas Bhiwadi's industrial-urban environment and denser infrastructure likely contributed to reduced wind circulation.

Quantifying Wind Speed (WS) across the cities of Bhiwadi and Udaipur

Fig. 7 illustrated the seasonal variation in average

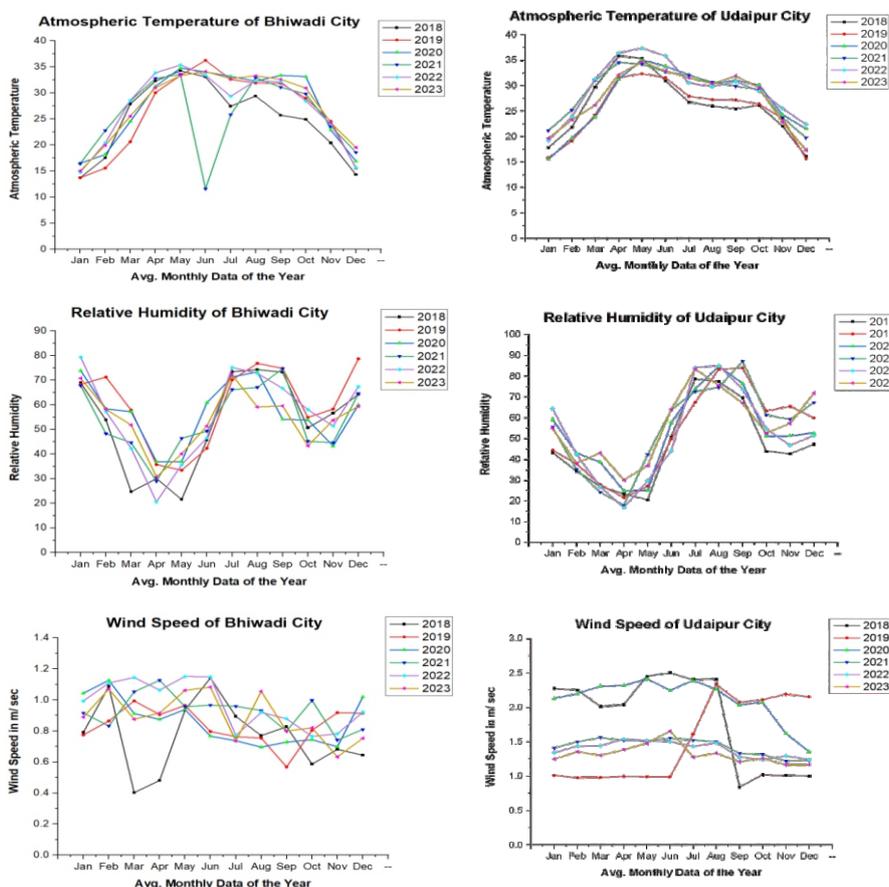


Fig. 7: Quantifying Meteorological Parameters at Bhiwadi and Udaipur in various seasons of the years 2018 to 2023.

Quantifying Wind Speed and Direction in Bhiwadi city

In Bhiwadi, wind directions during the winter predominantly show a south-westerly to westerly trend. The highest recorded wind direction in this period was in December 2020 at 252.38° , suggesting a significant deviation possibly due to specific meteorological conditions like cyclonic circulations. The lowest direction noted was in February 2019 at 191.45° , indicating a more westerly direction, which could be attributed to the prevailing winds from the land during this cooler season. Generally, the winter season features consistent but mild directional changes, with average directions slightly increasing through the period as shown in Fig. 8. The pre-monsoon season in Bhiwadi sees varied wind directions, often fluctuating due to heating of the land and beginning of transition towards monsoon patterns. April 2022 displayed highest direction at 221.43° , aligning with the strengthening of the pre-monsoonal winds influenced by increasing land temperatures.

The lowest during this season was in May 2021 at 174.20° , reflecting a transient cooling or other local meteorological effects. Wind directions in this season generally trend from westerly to south-westerly as temperatures increase, as shown in Fig. 8. During monsoon months, wind directions are heavily influenced by the monsoonal flow, primarily showing westerly to south-westerly directions. A remarkable deviation was observed in August 2023 with a direction of 222.72° , possibly enhanced by strong monsoon currents or temporary meteorological disturbances. July 2022 saw the lowest direction at 138.13° , which could suggest the impact of a weaker monsoon or the intrusion of divergent air flows. The monsoon typically stabilizes wind directions, aligning them more consistently with the southwestern flow as shown in Fig. 8. Post-monsoon, wind directions in Bhiwadi tend to vary more widely as the region transitions away from the monsoonal influence. The highest in this period was seen in November 2019 at 210.31° , a residual effect of the monsoonal patterns. Conversely, September 2021 showed a much lower direction at 108.64° , indicative of significant meteorological shifts, possibly early retreat of the monsoon or other atmospheric changes. This season is characterized by fluctuating wind directions as the influence of the monsoon wanes and northerly winds begin to set in, as shown in Fig. 8. Bhiwadi's wind direction patterns reflect the dynamic interplay of local and regional meteorological influences across different seasons. Seasonal variations are marked by transitions from westerly winds in winter to more varied directions in the pre-monsoon, stabilizing during monsoon with strong south-westerly flows,

and again becoming erratic post-monsoon as different weather systems influence the region. Anomalies in wind directions can often be linked to specific weather events, changes in regional climate patterns, or even broader atmospheric conditions.

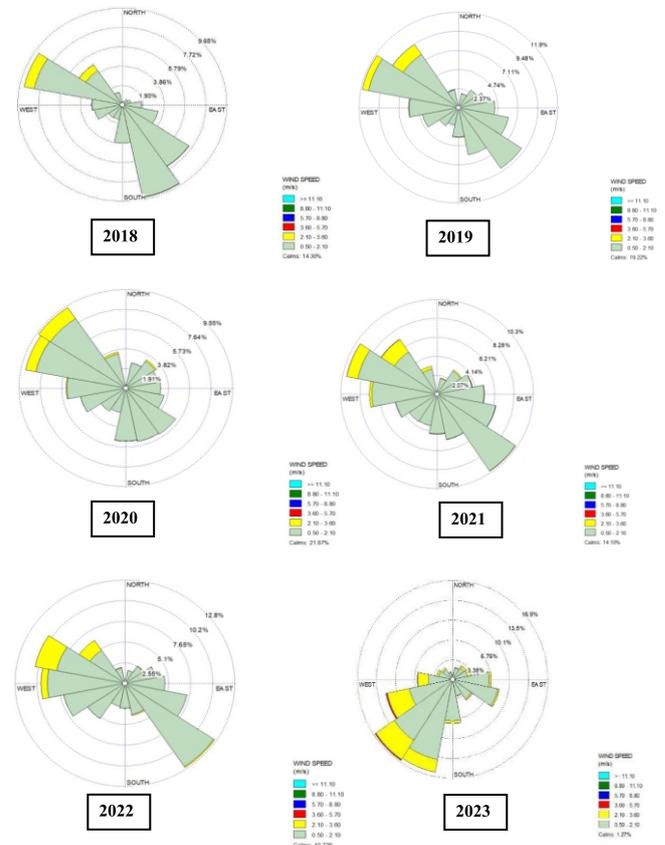


Fig. 8: Quantifying Wind Speed and Direction in Bhiwadi city during various seasons of the years 2018 to 2023.

Quantifying Wind Speed and Direction in Udaipur city

In Udaipur, winter months feature relatively high and consistent wind directions. January consistently shows wind directions above 229° , with highest in 2019 at 247.04° , suggesting strong northerly to north-easterly winds. February's direction peaks in 2023 at 247.12° , displaying a trend of increasing directional values which could be related to persistent atmospheric conditions influenced by broader climatic patterns. December's wind direction stabilizes around 240° , with slight variations indicating stable winter wind patterns influenced by regional meteorological conditions, as shown in Fig. 9. The pre-monsoon season sees a progressive increase in wind directions, reaching a peak in April 2018 at 286.79° , possibly due to heating of the land and the shifting of pressure systems, which can intensify wind flows. March and May show somewhat lower values, averaging around 250° , which reflects the transition

period with varying wind speeds and directions as the region prepares for the monsoon as shown in Fig. 9. During monsoon, June starts with slightly lower wind directions, the lowest in 2023 at 233.48°, possibly due to the initial onset of the monsoon, which can disrupt regular wind patterns. July and August show more variability; July's highest was in 2018 at 240.11° and August peaked in 2021 at 255.99°, indicative of the fluctuating influence of the monsoon as it progresses, as shown in Fig. 9. Post-monsoon months in Udaipur present high wind directions, with September and October often exceeding 260°. September 2023 saw the highest wind direction at 270.26°, and October 2023 also showed a high value of 271.80°, suggesting strong

residual monsoon influences or the establishment of post-monsoon circulatory wind patterns. November generally shows slightly lower wind directions, around 250°, as the effects of the monsoon begin to diminish, as shown in Fig. 9. As a result, Udaipur experiences a broad range of wind directions influenced heavily by the seasonal transitions from monsoon and post-monsoon periods. The data reflects the complex interaction of local topographical influences and broader atmospheric conditions, which dictate wind direction throughout the year. The analysis suggests a strong influence of both local and regional meteorological dynamics on the observed wind directions.

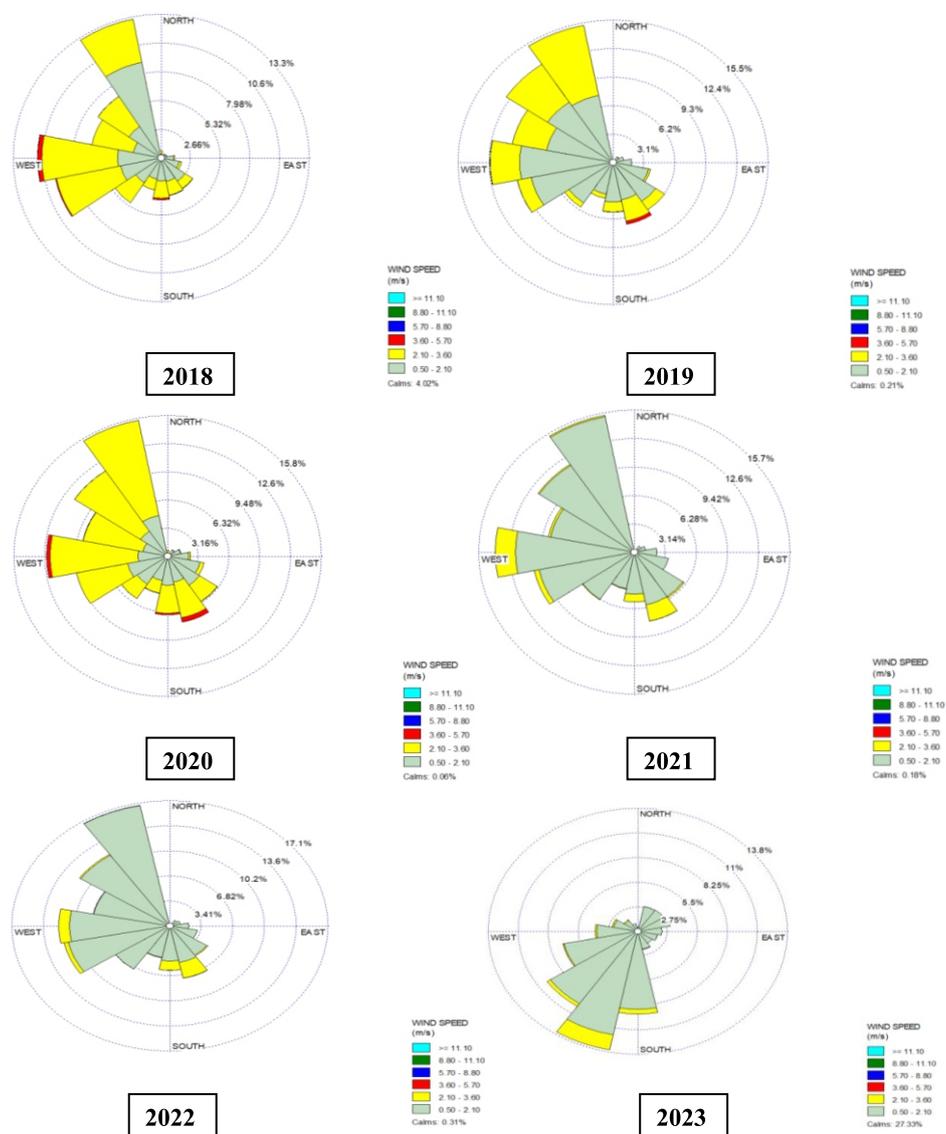


Fig. 9: Quantifying Wind Direction and Wind Speed in Udaipur city during various seasons of the years 2018 to 2023.

3. Statistical Analyses (Regression and correlation) of air Concentration of pollutants as a function of meteorological parameters in Bhiwadi

The regression analysis of air pollutants and temperature (T) for Bhiwadi from 2018-2023 revealed a strong and moderate correlation. The results presented in Table 1 are statistically significant (p-

values). The coefficient for T suggested that for each unit increased in T, air pollutant levels decreased by units (Table 1), except in NO₂ during 2022, and O₃ during 2018, 2019, 2020, and 2023 showed a positive relation with T.

Overall, T played variation in influencing air pollutant levels in Bhiwadi. The regression analysis of air pollutants and RH for Bhiwadi from 2018-2023 showed a strong as well as weak correlation. The coefficient for RH suggested that increased in RH had decreased units on air pollutants except PM_{2.5} levels slightly increased with increased RH during 2023. Overall, RH appears to have no meaningful impact on air pollutant levels in Bhiwadi. The regression analysis of air pollutant levels and WS for Bhiwadi from 2018-2023 showed a strong correlation. The Table approaches statistical significance (p-values). The coefficient for WS indicated that as WS increased,

the PM_{2.5} and PM₁₀ values decreased during 2018, 2021, and 2023, similarly for NO₂ during 2020, 2021, 2022, and O₃ during 2018, 2020, and 2023, and rest of the cases where air pollutant values increased with increased the WS. Though WS has an impact on concentration of air pollutants, the significance is marginal. The regression analysis between air pollutants and WD for Bhiwadi during 2018-2023 indicated no significant relationship. The coefficient for WD, which implied no meaningful change in air pollutants with changes in WD, except for the strong correlation between PM pollutants and WD in few years, like 2020, 2021, 2022. Thus, WD had no notable effects on air pollutant concentration levels, as shown in Table 1.

Concentration of pollutants as a function of meteorological parameters in Udaipur

In Udaipur, the regression coefficients indicated an

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

(Dependent variables (µg/m ³))	Independent variables				
	Year	Temp (T)	RH	WS	WD
PM _{2.5}	2018	-3.691 p=0.026	-1.116 p=0.142	-24.096 p=0.773	0.292 p=0.148
	2019	-3.029 p=0.008	-0.142 p=0.840	126.677p=0.027	0.219 p=0.326
	2020	-1.599 p=0.159	-0.965 p=0.403	74.700 p=0.586	0.686 p=0.183
	2021	-	-1.823 p=0.071	-49.690 p=0.708	1.118 p=0.006
	2022	-1.346 p=0.066	-1.557 p=0.003	136.840p=0.043	0.802 p=0.013
	2023	-4.573 p=0.023	0.035 p=0.978	-175.974p=0.053	0.012 p=0.984
PM ₁₀	2018	-5.791 p=0.113	-2.954 p=0.051	-85.57 p=0.620	0.191 p=0.664
	2019	-3.853 p=0.080	-1.390 p=0.242	239.347 p=0.014	0.612 p=0.099
	2020	-2.932 p=0.155	-1.759 p=0.401	124.614 p=0.617	1.262 p=0.177
	2021	-	-3.972 p=0.037	-41.362 p=0.872	2.278 p=0.003
	2022	-1.623 p=0.306	-2.833 p=0.012	171.133 p=0.247	1.959 p=0.001
	2023	-7.511 p=0.022	-0.711 p=0.730	-234.544 p=0.129	0.289 p=0.765
NO ₂	2018	-0.448 p=0.679	-1.104 p=0.003	44.792 p=0.345	0.095 p=0.436
	2019	-1.321 p=0.060	-0.191 p=0.628	59.766 p=0.077	0.228 p=0.051
	2020	-0.386 p=0.358	-0.431 p=0.293	-40.057 p=0.410	-0.001 p=0.996
	2021	-	-0.181 p=0.688	-48.856 p=0.363	0.349 p=0.060
	2022	0.790 p=0.134	-0.247 p=0.583	-9.798 p=0.852	0.062 p=0.815
	2023	-1.107 p=0.122	-0.165 p=0.693	12.611 p=0.704	0.163 p=0.398
SO ₂	2018	-0.742 p=0.417	-0.818 p=0.018	63.880 p=0.098	0.083 p=0.423
	2019	-0.827 p=0.183	-0.590 p=0.053	44.953 p=0.122	0.188 p=0.058
	2020	-0.525 p=0.142	-0.301 p=0.408	5.289 p=0.903	0.125 p=0.455
	2021	-	-1.056 p=0.009	96.480 p=0.070	0.405 p=0.035
	2022	-0.436 p=0.027	-0.434 p=0.003	48.413 p=0.005	0.159 p=0.107
	2023	-0.361 p=0.217	-0.109 p=0.511	4.133 p=0.756	0.026 p=0.738
O ₃	2018	1.084 p=0.006	-0.261 p=0.177	-6.992 p=0.740	-0.015 p=0.785
	2019	0.838 p=0.003	-0.366 p=0.022	14.285 p=0.385	-0.032 p=0.584
	2020	0.352 p=0.002	-0.249 p=0.051	-0.092 p=0.995	-0.008 p=0.899
	2021	-	-0.208 p=0.237	34.341 p=0.096	-0.075 p=0.350
	2022	-0.156 p=0.289	-0.359p=3.26E-06	21.504 p=0.106	0.051 p=0.472
	2023	0.178 p=0.445	-0.163 p=0.193	-1.024 p=0.921	-0.034 p=0.580

inverse relationship between T and particulate concentrations ($PM_{2.5}$ and PM_{10}). The coefficient (r) for T units, suggested that for each unit increase in T, air pollutants ($PM_{2.5}$, PM_{10} , NO_2 , SO_2 , and O_3) levels decreased by the given units, except for there was a positive relation between NO_2 and T during 2022, SO_2 and T during 2018, O_3 and T during 2018, 2019, 2022, 2023 as shown in Table 2. The regression analysis examining the relationship between air pollutant concentration levels and T at the Udaipur site reveals a strong correlation, indicated by the regression results showed a significance level (p-values), indicating that the relationship between air pollutants and T is statistically significant at the given values (Table 2). This statistically significant negative/ positive relationship underscores the impact of temperature fluctuations on air quality at the Udaipur site, highlighting the ample importance of considering meteorological factors in air pollution management strategies. There was a negative/inverse relationship between air pollutants ($PM_{2.5}$, PM_{10} , NO_2 , SO_2 , and O_3) and RH except in 2020 for NO_2 , 2020, and 2023 for SO_2 showed a positive relationship.

Conversely, O_3 and RH had an inverse relationship. The regression analysis assessing the relationship between air pollutant levels and RH at the Udaipur site revealed a very weak correlation. The regression results yield a significance level (p-values), demonstrating that the relationship was not statistically significant. The coefficient for RH units indicated that for each unit increase/decrease in RH, air pollutant levels decreased units; however, this relationship was not statistically significant, as reflected by the high p-value. Overall, the results suggested that RH has little to no impact on air pollutant levels in Udaipur, emphasizing the need to explore other factors affecting air quality in this region. Majorly, there was a negative relationship between air pollutants ($PM_{2.5}$, PM_{10} , NO_2 , and SO_2) and WS except in 2018 for $PM_{2.5}$ and SO_2 , 2022 for NO_2 , 2018, 2021, 2022, 2023 for O_3 , which showed a direct relationship with WS, that indicated that WS promoted better dispersion of air pollutants across the study sites and consequently higher air pollutant concentrations. The regression analysis of air pollutant levels in relation to WS at the Udaipur site shows a moderate correlation, indicated by the regression results yielding a significance level (p-values), which means the relationship between air pollutants and WS was not statistically significant.

The coefficient for WS values, suggests that for each

unit increased in WS, air pollutants levels decreased by the given units; however, this effect was not statistically significant, as indicated by the high p-values. Overall, these findings imply that while there may be some relationship between WS and air pollutant levels in Udaipur, it was not strong enough to be deemed significant, highlighting the necessity to investigate other environmental factors that could influence air quality. There was a positive relationship between air pollutants ($PM_{2.5}$, PM_{10} , NO_2 , SO_2 , and O_3) and WD and there were also negative relationships between air pollutants and WD i.e., during 2018, 2020, and 2023 between PM pollutants ($PM_{2.5}$, PM_{10}) and WD, between NO_2 and O_3 during 2020, between SO_2 and WD during 2018, 2020, 2023, and between O_3 and WD in 2023. This implied that the local sources of vehicular emissions were more existing in the study sites. The regression analysis examining the relationship between air pollutant levels and WD at the Udaipur site revealed a moderate correlation, evidenced by regression results showing a significant F-level (p-values), indicating that the relationship between air pollutant and WD was not statistically significant. The coefficients for WD, suggest that for each unit increase in WD, air pollutant levels decreased, as shown by different units (Table 2). However, this effect was not statistically significant due to the high p-values. Overall, these findings suggested that while there may be a slight association between WD and air pollutant levels, it lacks statistical significance, highlighting the need for further research to explore additional environmental variables that might affect air quality in Udaipur.

4. Correlation analysis of air pollutants and meteorological parameters

a). In Bhiwadi

The correlation plots of air pollutants and meteorological parameters for Bhiwadi during 2018-2023 (Fig. 10) highlighted the strong inter-relationships among pollutants and the influence of meteorological factors in this highly industrialized region. Across all years, $PM_{2.5}$ and PM_{10} showed a consistently strong positive correlation ($r = 0.84-0.99$), confirming their common sources, including vehicular exhaust, industrial emissions, and resuspended road or construction dust. Both particulate pollutants exhibited moderate to high correlations with NO_2 and SO_2 , indicating combined impact of combustion processes and industrial fuel burning, which were dominant in the Bhiwadi industrial belt. The negative correlation between O_3 and primary pollutants ($PM_{2.5}$, PM_{10} , NO_2 , and SO_2) was

Table 2: The regression analysis of the data showing the relationship between air pollutants and meteorological parameters with correlation coefficient (r) and significance value (p-value) at Udaipur.

(Dependent variables ($\mu\text{g}/\text{m}^3$))	Independent variables				
	Year	Temp (T)	RH	WS	WD
PM _{2.5}	2018	-1.010 p=0.222	-0.463 p=0.023	0.978 p=0.886	-0.544 p=0.262
	2019	-2.153 p=0.002	-0.093 p=0.679	-2.505 p=0.783	0.015 p=0.973
	2020	-2.202 p=0.002	-0.164 p=0.535	-44.995 p=0.000	-0.084 p=0.827
	2021	-3.437 p=0.000	-0.233 p=0.445	-79.021 p=0.102	0.148 p=0.718
	2022	-1.353 p=0.185	-0.507 p=0.044	-43.681 p=0.424	0.741 p=0.157
	2023	-2.265 p=0.003	-0.065 p=0.839	-44.644 p=0.233	-0.573 p=0.151
PM ₁₀	2018	-1.736 p=0.445	-1.181 p=0.034	-2.834 p=0.877	-0.865 p=0.515
	2019	-6.565 p=0.001	-0.506 p=0.437	-26.242 p=0.313	0.035 p=0.978
	2020	-4.331 p=0.003	-0.385 p=0.465	-87.357 p=0.000	-0.016 p=0.984
	2021	-4.559 p=0.010	-0.681 p=0.145	-85.087 p=0.289	0.421 p=0.518
	2022	-1.902 p=0.383	-1.233 p=0.013	-36.001 p=0.755	1.661 p=0.124
	2023	-4.244 p=0.004	-0.431 p=0.473	-64.308 p=0.373	-0.935 p=0.224
NO ₂	2018	-0.504 p=0.210	-0.120 p=0.273	-0.610 p=0.854	0.041 p=0.868
	2019	-1.813 p=0.002	-0.193 p=0.295	-8.189 p=0.270	0.120 p=0.745
	2020	-1.140 p=0.005	0.088 p=0.536	-16.992 p=0.032	-0.127 p=0.534
	2021	-1.914 p=0.005	-0.067 p=0.731	-51.427 p=0.090	0.155 p=0.548
	2022	0.565 p=0.347	-0.458 p=1.68E-05	9.326 p=0.770	0.805 p=0.001
	2023	-0.462 p=0.501	-0.043 p=0.855	-32.737 p=0.233	0.253 p=0.404
SO ₂	2018	0.042 p=0.795	-0.060 p=0.142	1.977 p=0.097	-0.194 p=0.017
	2019	-0.240 p=0.187	-0.104 p=0.013	-4.056 p=0.018	0.013 p=0.888
	2020	-0.291 p=0.016	0.010 p=0.806	-5.894 p=0.004	-0.061 p=0.282
	2021	-0.779 p=0.045	-0.126 p=0.196	-3.198 p=0.851	0.010 p=0.942
	2022	-0.209 p=0.023	-0.015 p=0.589	-4.690 p=0.380	0.008 p=0.886
	2023	-0.270 p=0.014	0.060 p=0.145	-8.924 p=0.063	-0.035 p=0.535
O ₃	2018	0.565 p=0.086	-0.228 p=0.003	1.250 p=0.655	0.057 p=0.781
	2019	0.188 p=0.691	-0.323 p=0.000	-11.018 p=0.008	0.484 p=0.021
	2020	-0.022 p=0.969	-0.453 p=0.000	-6.136 p=0.561	0.371 p=0.110
	2021	-0.406 p=0.583	-0.476 p=0.000	13.113 p=0.656	0.128 p=0.584
	2022	0.377 p=0.610	-0.563 p=6.33E-06	43.686 p=0.243	0.568 p=0.116
	2023	0.404 p=0.466	-0.461 p=0.002	20.053 p=0.373	-0.011 p=0.963

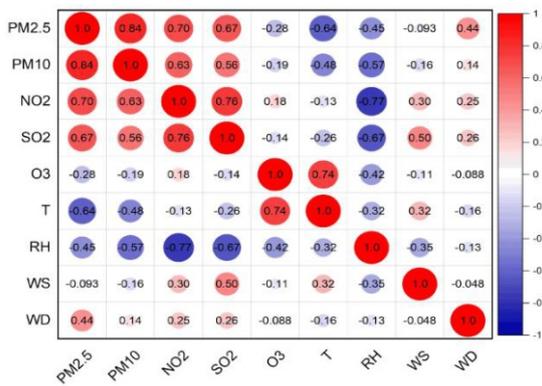
evident throughout the study period, particularly during 2020-2023, suggesting that ozone levels were suppressed by high NO_x concentrations typical of polluted, emission-heavy environments. However, O₃ consistently correlated positively with temperature ($r = 0.74-0.80$), reflecting enhanced photochemical formation of ozone under warm and sunny conditions. Meteorological parameters showed significant seasonal influences on pollutant dispersion. T displayed a negative correlation with PM and gaseous pollutants, indicating the reduced pollutant concentrations during warmer months due to increased vertical mixing. RH generally exhibited negative relationships with O₃ and temperature but moderate positive associations with PM and SO₂, suggesting moisture-facilitated accumulation of particulates. WS and WD correlations varied annually.

In most years, WS showed weak or negative relationships with PM and NO₂, implying limited dispersion under stagnant air conditions that favored pollutant build-up. Conversely, positive correlations between WS and WD ($r = 0.70-0.83$) indicated the coordinated role of prevailing wind patterns in transporting pollutants from nearby industrial sources. Overall, the correlation analysis revealed that Bhiwadi's air quality was influenced by strong local emission sources and meteorological stagnation, with temperature and wind playing key roles in pollutant dispersion. While the relationships remained strong across all years, slight weakening in inter-pollutant correlations by 2023 may have reflected gradual improvements in emission management and regulatory interventions.

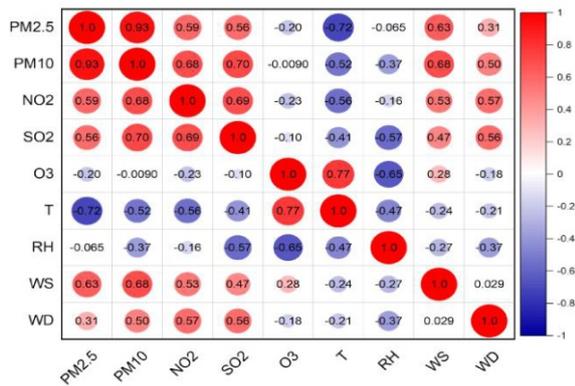
b). In Udaipur

The correlation analysis of air pollutants and meteorological parameters in Udaipur from 2018 to 2023 (Fig.11a-f) provided insights into the interactions between primary emissions, secondary pollutant formation, and atmospheric dynamics. Throughout the study period, PM_{2.5} and PM₁₀ consistently exhibited a strong positive correlation (r = 0.83-0.99), confirming their common origin from vehicular exhaust, road dust, and construction-related

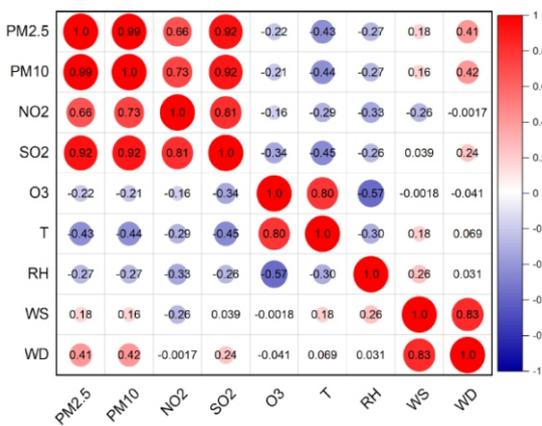
emissions. Moderate correlations of PM_{2.5} and PM₁₀ with NO₂ and SO₂ during 2018-2020 indicated the influence of combustion processes and fossil fuel burning in urban activities. In contrast, these associations weakened in later years (2022-2023), suggesting gradual improvement in emission control and dispersion efficiency. O₃ displayed an inverse relationship with particulate and gaseous pollutants (PM_{2.5}, PM₁₀, NO₂), particularly evident during 2020-2023, reflecting the photochemical nature of ozone



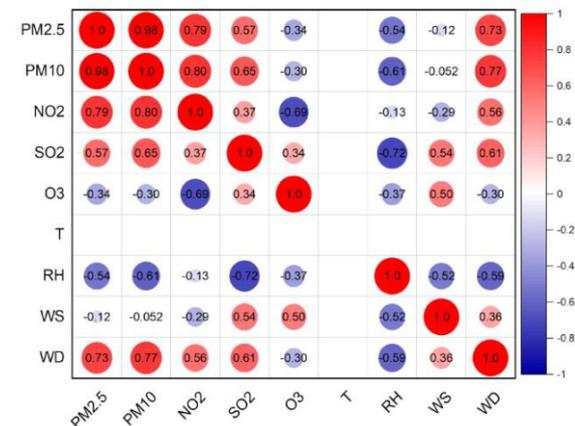
a. Corrplot of Bhiwadi 2018



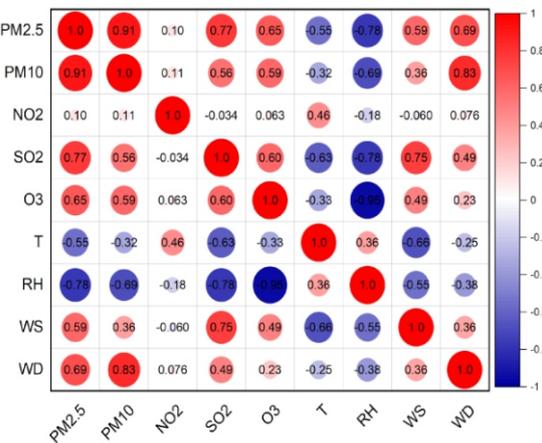
b. Corrplot of Bhiwadi 2019



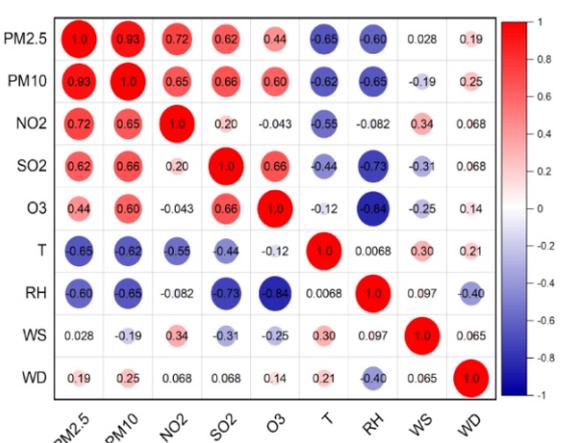
c. Corrplot of Bhiwadi 2020



d. Corrplot of Bhiwadi 2021



e. Corrplot of Bhiwadi 2022



f. Corrplot of Bhiwadi 2023

Fig. 10: Correlation plots (a to f) of Air Pollutants and meteorological parameters at Bhiwadi from 2018 to 2023.

and its reduction under high NO_x conditions. Conversely, a strong positive correlation between O₂ and T ($r = 0.77-0.93$) highlighted enhanced ozone formation during warmer periods, while RH showed negative associations with O₂, indicating suppression of photochemical activity under moist conditions. Meteorological factors played a crucial regulatory role in pollutant dispersion. T generally exhibited negative correlations with particulate pollutants and positive correlations with O₂, reflecting the seasonal temperature dependence of photochemical reactions. WS and WD correlations with PM and gaseous pollutants varied annually; moderate to strong positive relationships during 2020-2023 suggested the influence of transported dust or emission plumes under specific wind regimes. Meanwhile, RH showed variable but often negative correlations with PM and NO₂, signifying enhanced pollutant washout during humid or monsoonal periods. Overall, results indicated that Udaipur's air quality gradually improved from 2018 to 2023, with a noticeable shift from strong pollutant interdependencies to meteorologically moderated interactions. This transition reflected the combined impact of emission management, seasonal climatic variability, and improved atmospheric mixing in a tourism- and traffic-driven urban environment.

A comparative evaluation of correlation patterns between air pollutants and meteorological parameters in Bhiwadi and Udaipur from 2018 to 2023 revealed distinct emission characteristics and climatic influences shaped by their contrasting land-use and industrial profiles. Bhiwadi, a rapidly industrializing region, exhibited stronger inter-pollutant correlations, particularly among PM_{2.5}, PM₁₀, NO₂, and SO₂, throughout the study period. These strong associations reflected dominant contributions from anthropogenic sources such as industrial combustion, vehicular emissions, and dust resuspension. In contrast, Udaipur, a tourism- and traffic-driven city, showed moderate pollutant interrelationships and relatively greater influence of meteorological parameters, highlighting the role of climatic variability and lower industrial intensity. In both cities, O₃ consistently showed inverse correlations with primary pollutants (PM_{2.5}, PM₁₀, NO₂), confirming its secondary photochemical formation. However, T-O₃ correlation was stronger in Udaipur, suggesting higher photochemical reactivity under warmer and cleaner atmospheric conditions, whereas in Bhiwadi, ozone formation was often inhibited by excessive NO_x concentrations. Wind speed and direction played a comparatively greater role in Udaipur, aiding pollutant dispersion, while in Bhiwadi their effects

were weaker due to frequent atmospheric stagnation and dense industrial clustering. Overall, these findings emphasized that air quality degradation in Bhiwadi was primarily emission-driven, while Udaipur's pollution levels were more meteorologically modulated. The comparative analysis underscored the necessity for region-specific mitigation strategies, focusing on industrial emission control in Bhiwadi and traffic and seasonal management in Udaipur, to improve ambient air quality across contrasting urban environments.

Meteorological parameters played a significant role in deciding the ambient air quality of the urban sites of Bhiwadi and Udaipur during 2018 and 2023. Seasonal analyses revealed that temperature, relative humidity, wind speed, and direction strongly influenced pollutant dispersion and accumulation. Numerous studies observed correlation and regression analyses between gaseous and air pollutant concentrations and meteorological parameters (Tables 1, 2, and Figs. 7-11) (İçağa and Sabah, 2009; Tiwari *et al.*, 2013; Jassim *et al.*, 2018; Manju *et al.*, 2018; Bodor *et al.*, 2020; Mukta *et al.*, 2020; Pérez *et al.*, 2020; Haddad and Vizakos, 2021; Shelton *et al.*, 2022). During winter, low temperatures and atmospheric stability contributed to pollutant build-up, especially in Bhiwadi, consistent with findings by İçağa and Sabah (2009) and Bodor *et al.* (2020). Conversely, pre-monsoon and monsoon periods exhibited enhanced dispersion due to higher temperatures, convective activity, and rainfall, leading to reduced particulate and gaseous concentrations, aligning with observations by Jassim *et al.* (2018) and Mukta *et al.* (2020). Wind patterns were particularly influential in Udaipur, where higher speeds and favorable topography promoted pollutant transport and dilution, while Bhiwadi's industrial and urban layout limited effective dispersion, echoing results of Haddad and Vizakos (2021) and Shelton *et al.* (2022). Relative humidity modulated particulate accumulation, with higher RH during monsoon facilitating wet deposition of PM_{2.5} and PM₁₀. 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.

CONCLUSION

Spatial, seasonal, and annual pattern analyses of air quality parameters are important for source identification. Moreover, this pattern of analysis focuses management strategies on the effects of concerning pollutants. This study monitored the ambient air quality

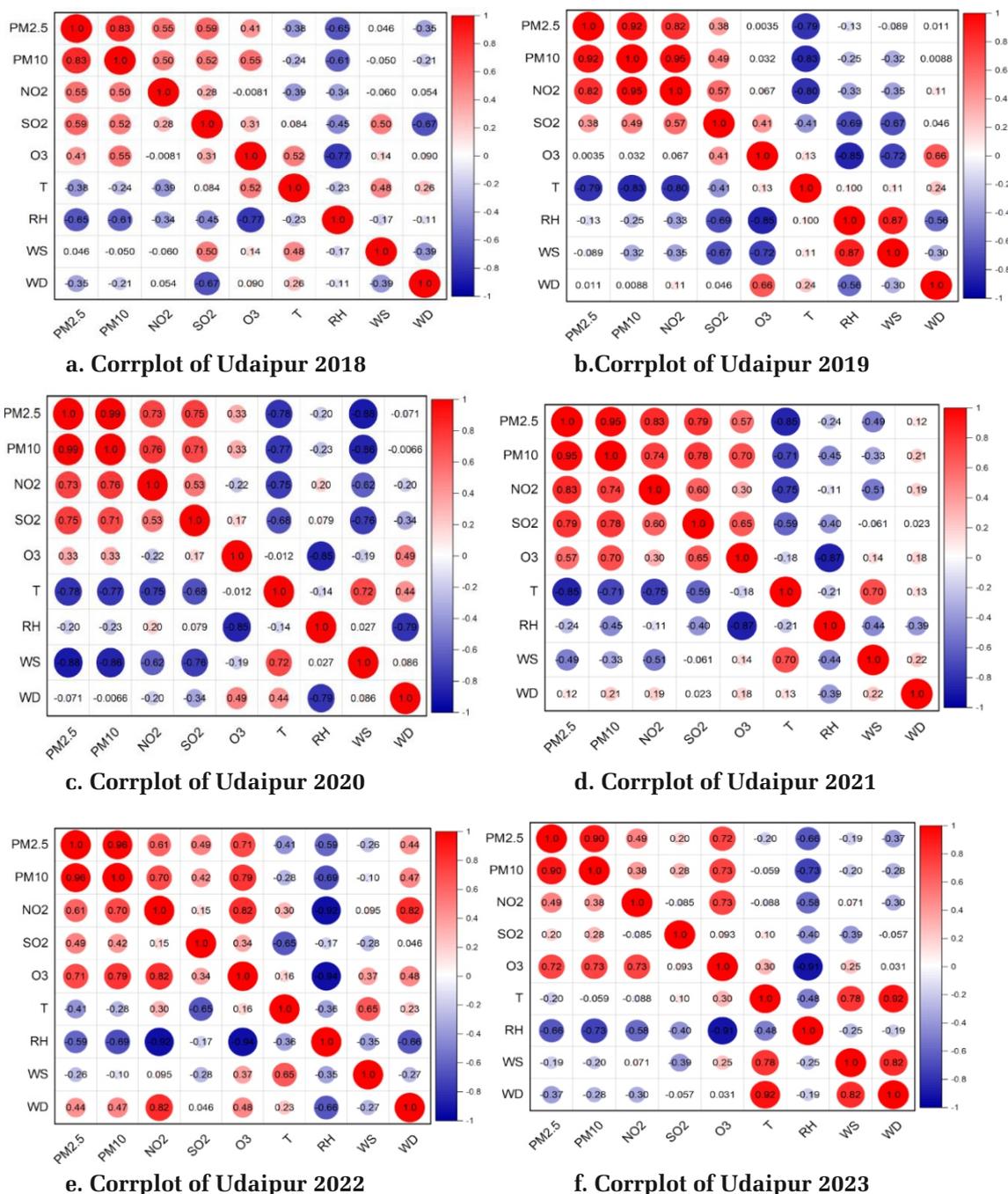


Fig. 11: Correlation plots (a to f) of air pollutants and meteorological parameters at Udaipur from 2018 to 2023.

status at two different locations (industrial, traffic, and commercial/residential) in urban areas of Rajasthan, India, during 2018-2023. The results showed that pollutants varied among locations and seasons. While air pollutant levels exceeded NAAQS guideline values in both selected areas, especially the industrial area. The increased air pollutants in ambient air have a significant health impact.

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CONFLICT OF INTEREST

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

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