



Influence of Temperature and Relative Humidity on PM_{2.5} Concentration over Delhi

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Abstract: The present study is an attempt to establish relationship between the concentrations of particulate matter especially (PM_{2.5}) and background meteorological parameters over Delhi, India with the help of statistical and correlative analysis. This work presents the evaluation of air quality in three different locations of Delhi. These locations were selected to fulfil the characteristics as residential, industrial and background locations and performed the analysis for pre and post covid-19, i.e. for 2019 and 2021. The outcome of the study shows that the meteorological parameters have significant influence on the PM_{2.5} concentration. It was also found that it has a seasonality with low concentration in the monsoon season, moderate in the pre-monsoon season and high during the winters and post-monsoon seasons. However, the statistical and correlative study shows a negative relation with the temperature during the winter, pre-monsoon and post-monsoon and has a positive correlation during the monsoon season. Similarly, it also has been observed that the concentration of PM_{2.5} shows strong negative correlation with temperature during the high humid conditions, i.e. when the relative humidity is above 50%. However, a weak correlation with ambient temperature has been established during the low humidity condition, i.e. below 50%. The overall study showed that the highest PM_{2.5} pollution has been observed at residential location followed by industrial and background. The study also concluded that the seasonal meteorology has a complex role in the PM_{2.5} concentration of the selected areas.

Keywords: Particulate matter (PM_{2.5}); Meteorological parameters; Air quality; Statistical analysis; Air pollution

1. Introduction

Delhi (capital city of India) is continuously rated as one of the most polluted city across the world (World Air Quality Report 2021). Due to its huge population, a number of factors could contribute to Delhi's air pollution, i.e. heavy traffic density (4.8 million registered vehicles), three coal-fired power plants, and over 1,25,000 small and medium scale industrial units [1, 2]. [1] reported that the Delhi has the largest number of on-road vehicles compared to any other city of India (including public, commercial and private) and road transport provides the majority of transportation to Delhi's urban population. [3] stated that assessment of air quality, especially for PM_{2.5}, over Indian

cities has become a core public concern due to serious health hazards. In the past years, PM_{2.5} exposure has caused approx.1 million premature deaths in India. As it is well known that the air quality index (AQI) of any specific place not only depends upon the source factors but also significantly depends upon the loss factors mainly governed by the background meteorological parameters.

Delhi is situated in the sub-tropical climatic zone; hence the prevailing meteorological conditions experience the maximum temperature of about 40–45 °C during the summer season while a minimum of about 1–2 °C during winter. The highest-ever rainfall recorded in one entire monsoon period over Delhi was around 611 mm. Delhi also experiences dry air conditions throughout the year except for monsoon season. The month of April and May are the driest months for this area. However, north-westerly winds prevail in Delhi except for June and July, when South-Westerly winds predominate [1].

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Meteorology is the science that deals with the atmosphere and its associated phenomenon, which have an influence on the fate of pollutants in the atmosphere. Background meteorological factors, i.e. wind speed, wind direction, temperature, atmospheric stability, mixing height, etc., have a significant impact on the concentration of pollutants in a certain area. Many scientists [1, 3–8] have investigated that the meteorological parameters play crucial role both directly or indirectly in the dispersion, transformation, and removal of particulate matter from the lower atmosphere. [9] stated that the air pollutants dispersion was influenced by the diurnal variation in boundary layer conditions and other meteorological parameters. The local and regional causes of particulate pollution can be understood by analysing the influence of meteorology.

Table 1 presents a comparative analysis of previous studies that deals with the impact of meteorology on concentration of pollutants in various locations. In several studies, precipitation, relative humidity, ambient temperature, wind speed, and wind direction were found to affect particulate matter concentration in ambient air [1, 10–12]. [13] stated that the stronger winds carry the pollutants away from the region which disperses and dilute them. Similar finding by [14] in Delhi concluded that particulate matter concentration shows seasonality, and it is attributed mainly to meteorology. The studies [1, 3] also stated that the concentration of $PM_{2.5}$ in any given location is negatively correlated with meteorological parameters like ambient temperature, wind, dew point, and wind gust, while it is positive with relative humidity.

In line with the previous studies, a systematic analysis has been performed over Delhi to investigate the impact of meteorological parameters (Ambient temperature and Relative Humidity) on the most concerned pollutant, i.e. $PM_{2.5}$ in three different locations which represent background, residential and industrial regions for the year of 2019 and 2021.

2. Data Selection and Analysis

The present study has been performed to investigate the role of meteorology on the concentration of $PM_{2.5}$ in the background, residential and industrial locations over Delhi, specifically for the years 2019 and 2021, which represents the pre-covid and post-covid year conditions. The site selection is based on the population density, traffic density and vicinity of Industries (details in Table 2).

The data of selected sites have been acquired from the Central Pollution Control Board (CPCB) website (<https://app.cpcbcr.com>). The CPCB has more than 53 Continuous Ambient Air Quality Monitoring (CAAQM) Stations over Delhi-NCR regions under air quality

management system (AQMS), which are operated in collaboration with State Pollution Control Board (SPCBs)/ pollution control committee (PCCs). CPCB provides data quality assurance or quality control (QA/QC) programs by defining rigorous protocols for the sampling, analysis and calibration [15, 16]. The acquired data are then segregated in accordance with the season, prevailing temperature and humidity. The available data have also been categorized in accordance with the different temperature bands, i.e. 0–10 °C, 10–20 °C, 20–30 °C, and 30–40 °C. To assess the air quality during each band of temperature, the $PM_{2.5}$ concentration values were grouped in various categories (details in Table 3).

The data have further been utilized for statistical and linear regression analysis to estimate the degree of dependency of $PM_{2.5}$ concentration on different meteorological parameters. Initially, the analysis was performed between $PM_{2.5}$ and ambient temperature (overall data) for both years and further the available data were categorized under two different bands of Relative Humidity (RH), i.e. RH below 50% and RH above 50%.

Further, the data has been segregated into four parts as per the seasons [15, 17], i.e. Winter (Dec–Feb), Pre-Monsoon (Mar–Jun), Monsoon (Jul–Sept) and Post-Monsoon (Oct–Nov) to investigate the seasonal impact on the variability of $PM_{2.5}$ concentration overall the three considered locations.

3. Result

The present work attempts to establish relation between temperature and humidity and the existence of $PM_{2.5}$ concentration at three locations represented as residential, industrial and background sites over Delhi. For better understanding, the study is divided into two parts. The first part deals with the impact assessment of ambient temperature on the concentration of $PM_{2.5}$. However, the second part of the study provided the variability of $PM_{2.5}$ concentration with the prevailing ambient temperature under different background relative humidity conditions.

3.1. Impact of Ambient Temperature on $PM_{2.5}$ Concentration

The regulatory body of India, i.e. CPCB issued a national air quality index for $PM_{2.5}$ based on its impact on human health as per the categories given in Table 2. In view of this, the analysed data plotted in Fig. 1a, b show the occurrence characteristics of different air quality indices under different temperature conditions for all three considered locations for the year 2019 and 2021.

Table 1 Details of previous studies carried out in various locations

Reference	Study area	Study period	Outcome
Present Study	Delhi (Rohini, Okhla and Pusa)	2019 and 2021	<ul style="list-style-type: none"> •The PM_{2.5} concentration has influenced by meteorological parameters, i.e. Temperature and Relative Humidity •PM_{2.5} shows significant correlation with temperature during high humid conditions •Pusa has better air quality followed by Okhla and Rohini
Singh et al. (2021)	Delhi (JNU, Mukherjee Nagar, Rohini, Anand Vihar and CP)	April 2012- March 2013	<ul style="list-style-type: none"> •The highest value of PM_{2.5} was observed in Winter and lowest in Monsoon season •The PM_{2.5} has strong negative correlation with temperature
Das et al. (2021)	Delhi	2018–2020	<ul style="list-style-type: none"> •There is a seasonal variation in concentration of PM in Delhi •Meteorological Parameters have close association with PM concentrations
Sharma et al. (2022)	Delhi (North, East, South and West)	2013–2016	<ul style="list-style-type: none"> •The study depicts that North and East regions are the most polluted areas of Delhi •Seasonal Meteorology has a complex role in the PM concentration
Kayes et al. (2019)	Dhaka (Bangladesh)	2013–2017	<ul style="list-style-type: none"> •Most of the pollutants resulted negative correlation with atmospheric temperature and relative humidity
Zhang et al. (2015)	China	March 2013-Feb 2014	<ul style="list-style-type: none"> •Clear Seasonal trends were observed with maximum concentration in the winter and the minimum in the summer
Kermani et al. (2020)	Karaj, Iran	2018- 2019	<ul style="list-style-type: none"> •Seasonal variation trends of PM_{2.5} was observed with maximum concentration in autumn and minimum in spring season •There is a positive correlation of PM_{2.5} concentration observed with temperature, relative humidity and pressure
Jayamurugan et al. (2013)	Chennai, India	2010- 2011	<ul style="list-style-type: none"> •The particulate pollutant has positive correlation with temperature in all season except post-monsoon season and significant negative correlation with humidity in all the four seasons
Wang and Ogawa (2015)	Nagasaki, Japan	2013	<ul style="list-style-type: none"> •PM_{2.5} concentration has strong positive correlation with temperature and negative correlation with humidity and precipitation
Trivedi et al. (2014)	IITM, New Delhi	Dec 2010- Nov 2011	<ul style="list-style-type: none"> •Meteorological parameters influencing PM concentration in the Delhi region are PBL and wind during post-monsoon and winter, dust-storm during summer and temperature and rain during monsoon •Diurnal variations of PM₁₀ and PM_{2.5} concentration shows two maxima in all the seasons: one during day and other during night
Singh et al. (2022)	Delhi, India and Riyadh, Saudi Arabia	Jan 2020- May 2020	<ul style="list-style-type: none"> •Strong negative correlation was observed between PM_{2.5} and PM₁₀ with ambient temperature and wind speed
Li, J. et al. (2021)	Delhi, India	2013–2020	<ul style="list-style-type: none"> •Annual mean PM_{2.5} concentration in Delhi all exceeded 100 mg/m³ •The resultant lower passage of Wind direction, lower PBL, weak winds and less precipitation contributed to severe particulate pollution in Delhi
Tiwari et al. (2013)	Delhi, India	2011	<ul style="list-style-type: none"> •Meteorological parameters have strong correlation with the PM_{2.5} concentration in an area. It has a significant correlation with temperature and relative humidity

Table 2 Details of selected study sites of Delhi

S. no	Name of location	Type of location	Latitude	Longitude	Traffic density	Emission sources
1	Rohini	Residential	28.73	77.11	High	Dense population, high-rise buildings, vehicles and road dust
2	Okhla Phase-2 (Okhla)	Industrial	28.53	77.27	Moderate-High	Industries, DG sets, vehicles
3	Pusa	Background	28.63	77.14	Low	Vehicles and road dust

Table 3 Categories of PM_{2.5} on the basis of air quality index

S. No	AQI categories	Range ($\mu\text{g}/\text{m}^3$)
1	Good	0–30
2	Satisfactory	31–60
3	Moderate	61–90
4	Poor	91–120
5	Very Poor	121–250
6	Severe	> 250

It is seen from Fig. 1a, b that the occurrence frequency of Good to Moderate conditions was higher under the higher temperature band, i.e. 30–40 °C. However, Poor to Severe conditions were more predominant under lower temperatures, i.e. 10–20 °C during the year 2019. It has also been observed that the background observation site, i.e. Pusa experienced the maximum number of days (~ 92 days) under the good to satisfactory category. On the other hand, Rohini (residential) and Okhla (industrial) experienced good to satisfactory air quality conditions for, i.e. 57 and 84 days, respectively, under high ambient

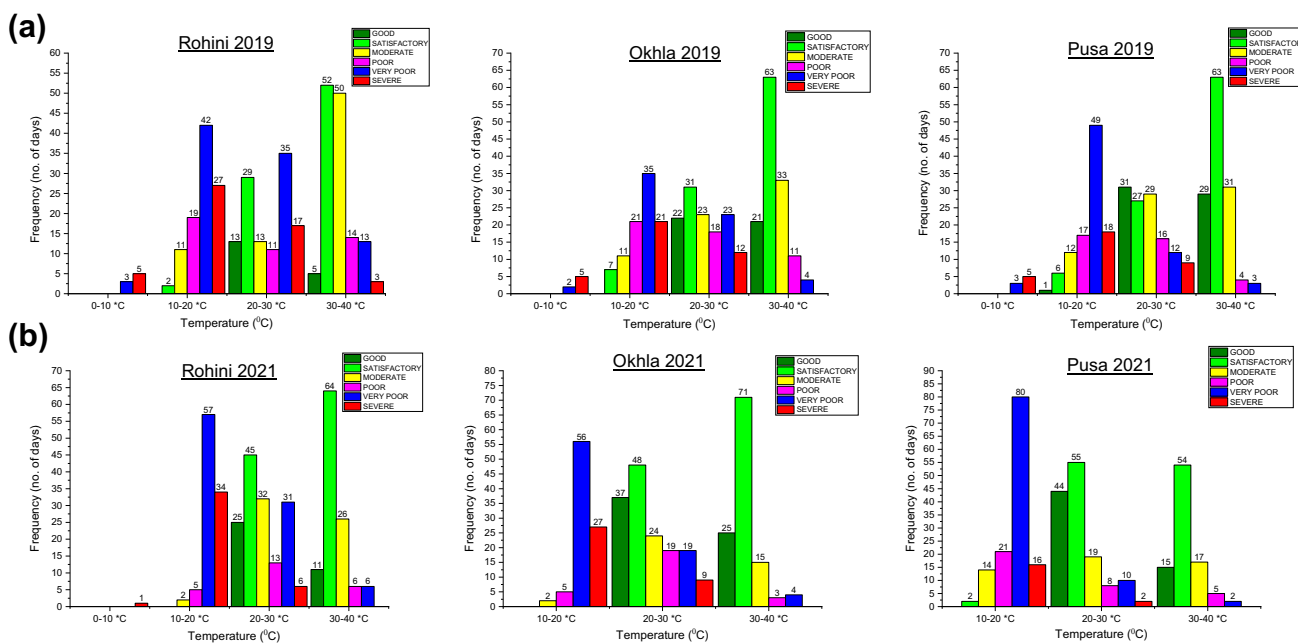
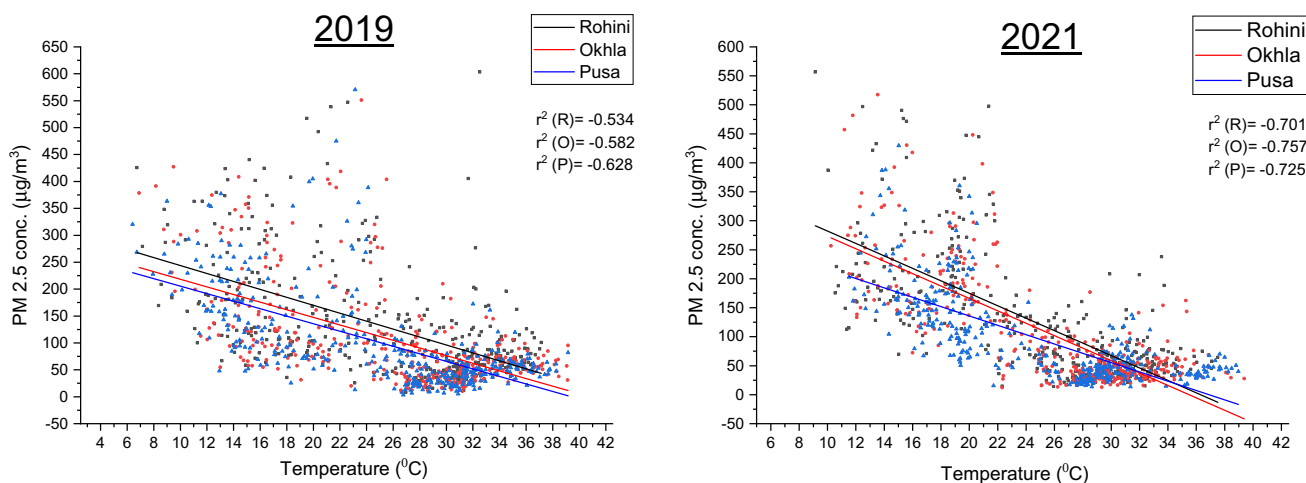
**Fig. 1** a Frequency of PM_{2.5} concentration in different temperature band for 2019. b frequency of PM_{2.5} concentration in different temperature band for 2021**Fig. 2** Correlation between ambient temperature and concentration of PM_{2.5}

Table 4 Correlation coefficient between temperature and PM_{2.5} in different seasons

S. no	Station name	Type of location	Winter		Pre-monsoon		Monsoon		Post-monsoon	
			2019	2021	2019	2021	2019	2021	2019	2021
1	Rohini	Residential	- 0.247	- 0.097	- 0.046	- 0.127	0.557	0.501	- 0.521	- 0.794
2	Okhla Phase-2 (Okhla)	Industrial	- 0.244	- 0.157	- 0.075	- 0.078	0.577	0.235	- 0.440	- 0.777
3	Pusa	Background	- 0.654	- 0.586	- 0.078	- 0.269	0.566	0.275	- 0.495	- 0.812

temperature conditions (i.e. fall under the band of 30–40 °C). Similarly, under low ambient temperature conditions, i.e. when the temperature falls under 10–20 °C band, the severe category of PM_{2.5} has been observed at Rohini for 27 days, Okhla for 21 days, and Pusa for 18 days.

In 2021, the frequency of Good to Moderate category days was higher than that of 2019 under temperature bands of 20–30 °C and 30–40 °C in all the considered locations. Similar to the year 2019, the background site, i.e. Pusa, again dominated the other sites and experienced 44 good days, 55 satisfactory days and, 15 good days, 54 satisfactory days under the ambient temperature band 20–30 °C and 30–40 °C, respectively. Similarly, the industrial site, Okhla, observed 37 good days, 48 satisfactory days, and 25 good days, 71 satisfactory days under temperature bands 20–30 °C and 30–40 °C, respectively. However, the air quality of the residential site, Rohini, is inferior compared to the other two sites. The results show that 25 good days, 45 satisfactory days in 20–30 °C, and 11 good days, 64 satisfactory days under 30–40 °C.

The results showed that the frequency occurrence of very poor to severe category days was highest under the temperature band 10–20 °C during the year 2019 over all the considered locations.

While improved air quality has been observed during the year 2021 compared to the year 2019 and the considered background station, Pusa dominated the other two locations and experienced less pollution. The study was further extended to establish a possible correlation between the concentration of PM_{2.5} and ambient air temperature for all three considered sites for the years 2019 and 2021. Accordingly, the acquired data have been analysed and shown in Fig. 2. The result reveals a negative correlation between the concentration of PM_{2.5} and temperature. The estimated correlation coefficients evident better dispersion of PM_{2.5} with the increase in temperature during the year 2021 as compared to the year 2019.

The season-wise response of PM_{2.5} concentration to the ambient temperature has also been investigated. The season-wise estimated correlation coefficients are listed in Table 4.

Figure 3a,b,c,d shows the variation of PM_{2.5} concentration with variation in ambient air temperature during the

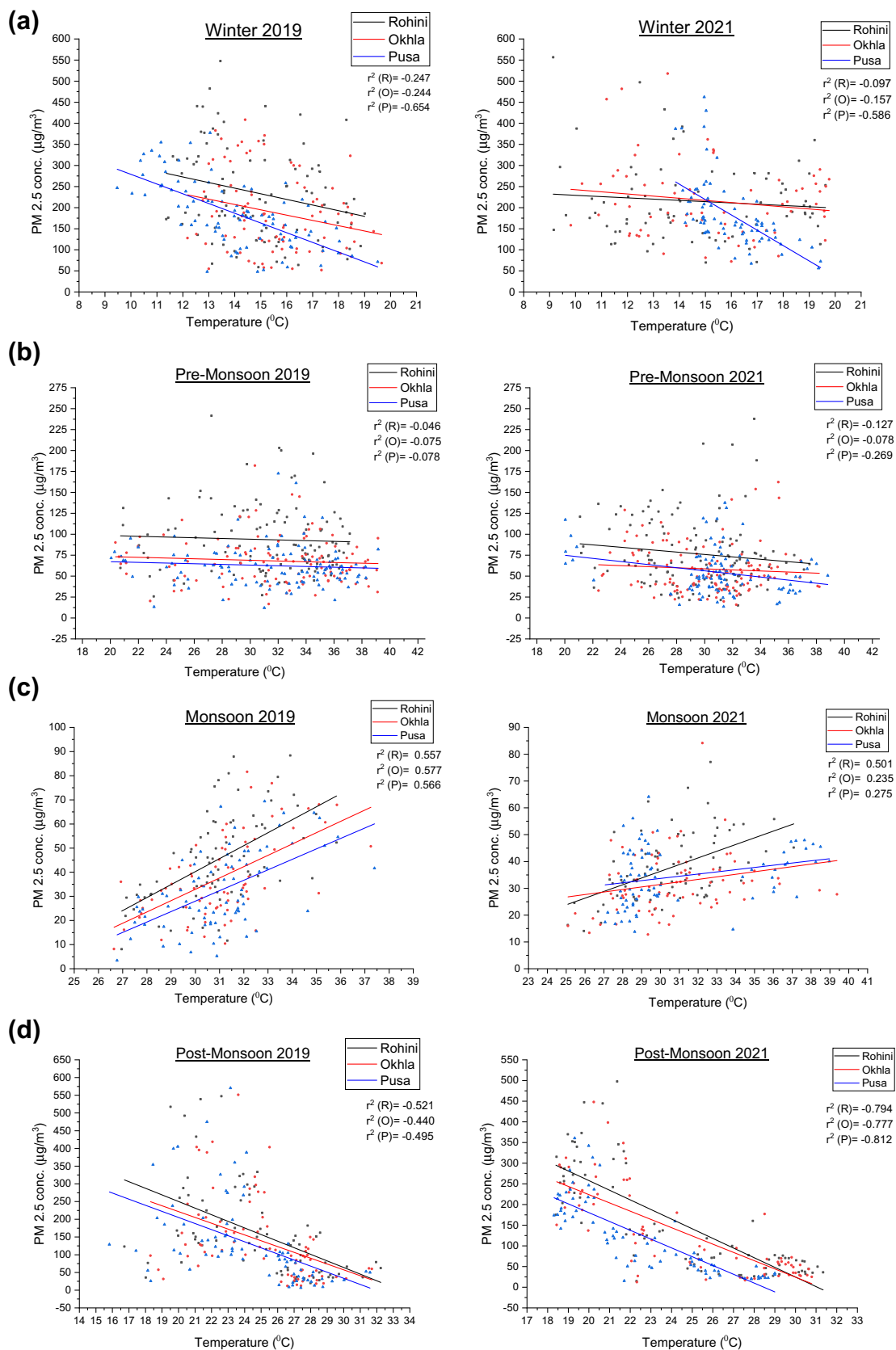
different seasons over the considered locations for the years 2019 and 2021. The result shows a strong negative correlation between PM_{2.5} concentration and ambient air temperature during the winter season for both years over the background station, i.e. Pusa, compared to the other two locations. Similarly, a strong negative correlation has been observed during the year 2021 during the post-Monsoon season. Unlike the above seasons, the variation of PM_{2.5} concentration shows a significant positive correlation with ambient air temperature during 2019. But, during the year 2021, only the residential location, i.e. Rohini, shows a considerable and positive correlation between the PM_{2.5} concentration and ambient temperature during the Monsoon season. However, a highly nonlinear relationship has been observed during the Pre-Monsoon season over all the locations for both years.

3.2. Combined Impact of Ambient Temperature and Relative Humidity (RH) on PM_{2.5} Concentration

To examine the combined impact of ambient temperature and relative humidity on the PM_{2.5} pollution, the data of ambient air temperature and associated PM_{2.5} concentration for all three locations has been segregated under two relative humidity bands, i.e. above and below 50%.

The results shown in Fig. 4a evident that the occurrence frequency of satisfactory and moderate conditions was higher at Pusa and Okhla during the year 2019; however, at residential sites, i.e. Rohini, the occurrence frequency of moderate and very poor conditions was higher, when RH was below 50%. It has also been observed that the frequency of moderate conditions decreased during the year 2021, which eventually increased the count of good to satisfactory conditions at both locations. On the other hand, the residential site, i.e. Rohini, remains mostly under moderate conditions.

However, the results in Fig. 4b show that the concentration of PM_{2.5} varies from good to severe conditions for both years under high humidity, i.e. when RH was above 50%. The results evident a high occurrence percentage of severe conditions (~ 25% in 2019 and ~ 13% in 2021) at the residential site “Rohini”, while the maximum frequency of good conditions (~ 20%) in the year 2019 has



◀ **Fig. 3** **a** Correlation between ambient temperature and concentration of PM_{2.5} in winter. **b** Correlation between ambient temperature and concentration of PM_{2.5} in pre-monsoon. **c**: correlation between ambient temperature and concentration of PM_{2.5} in monsoon. **d** Correlation between ambient temperature and concentration of PM_{2.5} in post-Monsoon

been observed at background station “Pusa”. On the contrary, the maximum frequency of good conditions has been observed at the industrial site, i.e. Okhla (~ 23%) during the year 2021. It is also observed from Fig. 4a, b that the air quality improved during the year 2021 compared to the year 2019. Apart from this, a correlation study has also been carried out to establish the dependency of PM_{2.5} concentration on ambient air temperature under low and high humidity conditions, i.e. RH below 50% and RH above 50%. The results are presented in Fig. 5, and the correlation coefficients are listed in Table 5.

Figure 5a shows the correlation between the concentration of PM_{2.5} and ambient air temperature under low humidity conditions, i.e. Relative Humidity is below 50% for all the three considered locations during the years 2019

and 2021. The result reveals a significant negative correlation between the PM_{2.5} concentration and ambient temperature over the residential location, i.e. Rohini, during the year 2019. However, a nonlinear behaviour has been observed over the other two sites, i.e. the Industrial station “Okhla” and background station “Pusa”. The similar nonlinear behaviour has also been observed during 2021 but for all three considered locations.

On the other hand, Fig. 5b shows a strong negative correlation between the concentration of PM_{2.5} and ambient temperature under high humidity conditions, i.e. when the relative humidity is above 50%, especially during the year 2021 for all three locations. A similar but comparatively weak negative relationship was established during the year 2019.

4. Discussion

The above-explained results evident that ambient air temperature and humidity play an essential role in the

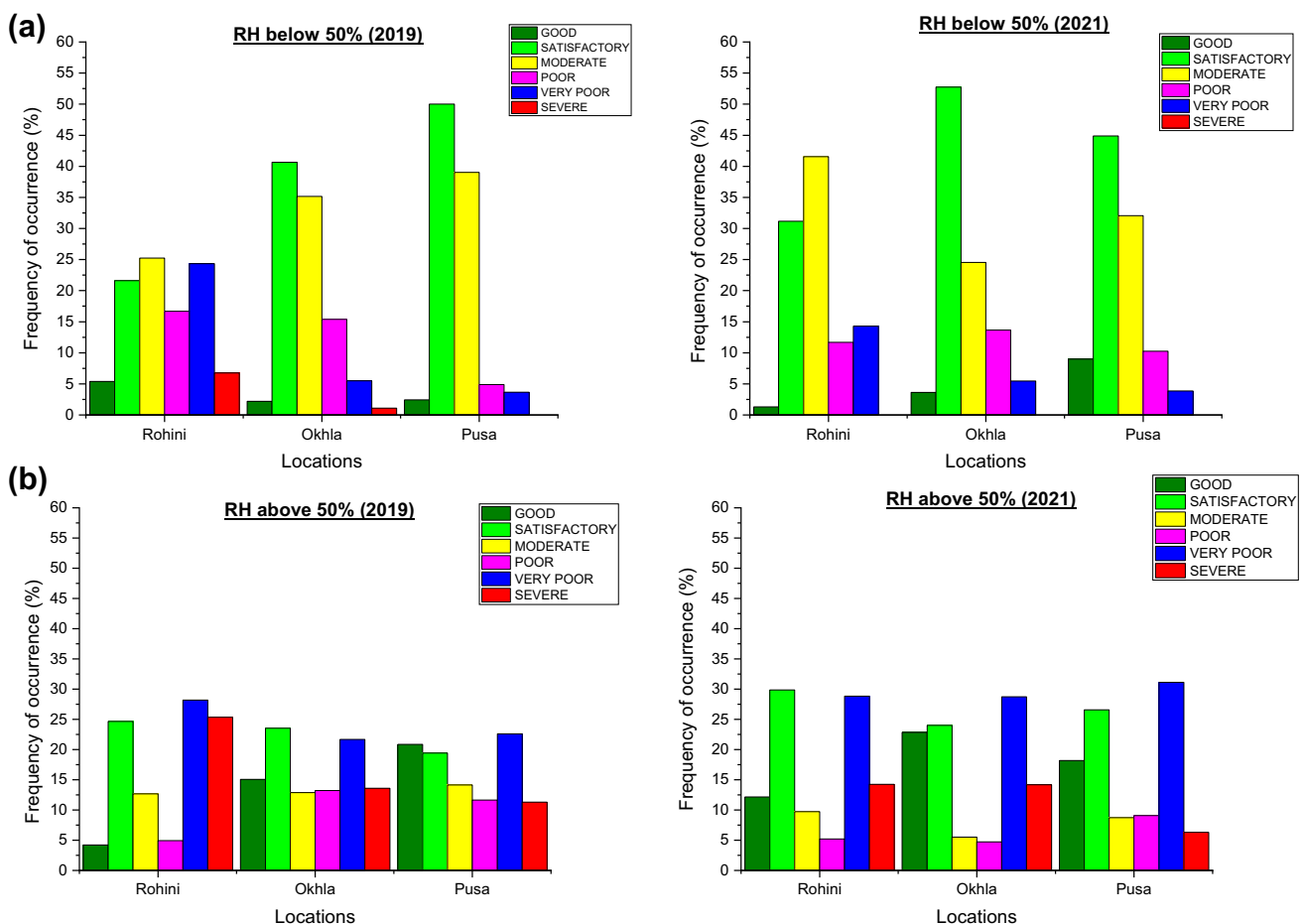


Fig. 4 **a** Frequency of PM_{2.5} concentration when relative humidity is below 50%. **b** Frequency of PM_{2.5} concentration when relative humidity is above 50%

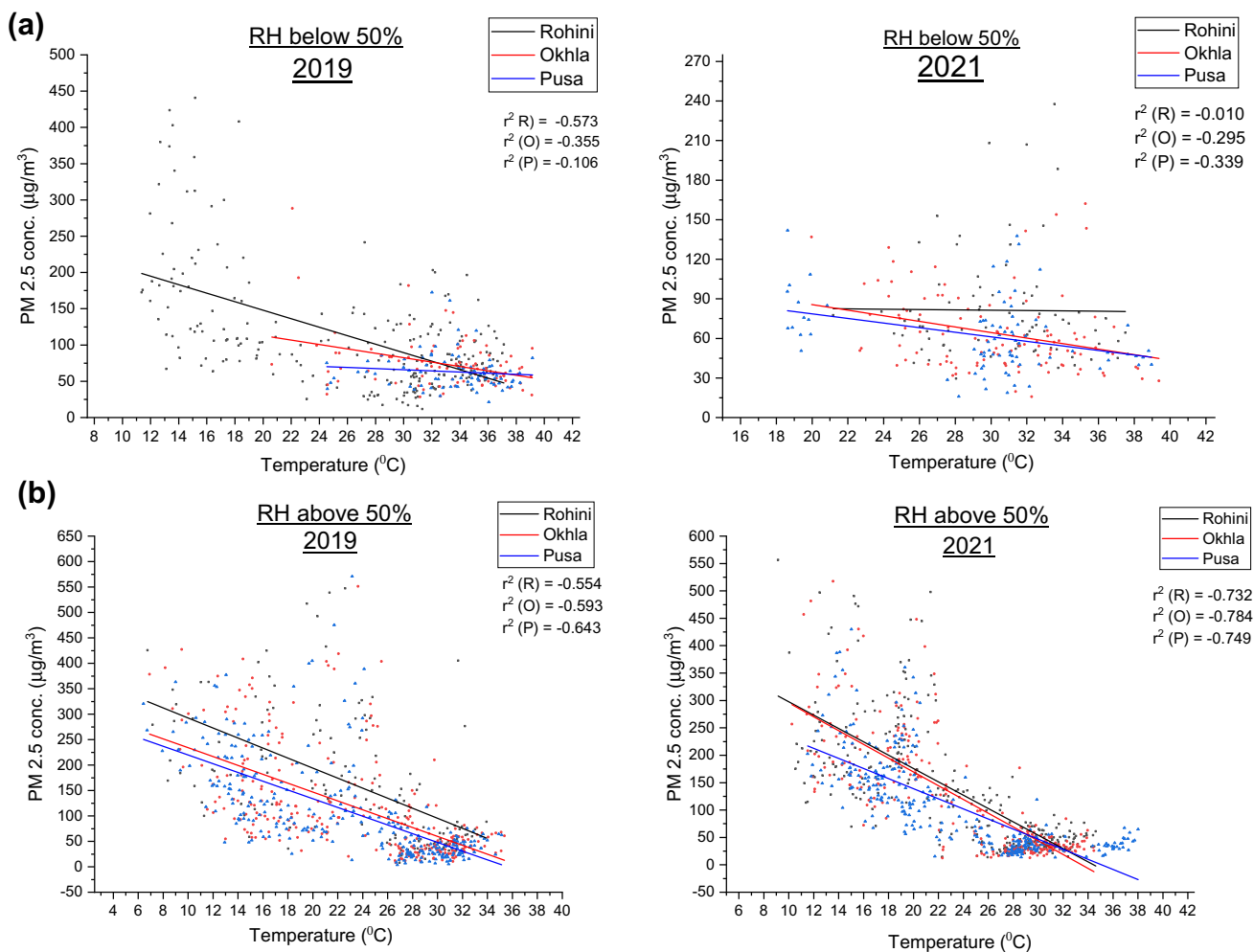


Fig. 5 a: Correlation between ambient temperature and concentration of $PM_{2.5}$ when relative humidity is below 50%. **b:** correlation between ambient temperature and concentration of $PM_{2.5}$ when relative humidity is above 50%

Table 5 Correlation coefficient between temperature and $PM_{2.5}$ based on relative humidity

S. no	Station Name	Type of Location	Relative humidity below 50%		Relative humidity above 50%	
			2019	2021	2019	2021
1	Rohini	Residential	-0.573	-0.010	-0.554	-0.732
2	Okhla Phase-2 (Okhla)	Industrial	-0.355	-0.295	-0.593	-0.784
3	Pusa	Background	-0.106	-0.339	-0.643	-0.749

dispersion of polluted air. An overall strong inverse relationship between concentration of $PM_{2.5}$ and temperature are evident of the significant impact of ambient temperature on $PM_{2.5}$ concentration. The results show that $PM_{2.5}$ concentration increases exponentially with a temperature decrease. This might be because the compressed boundary layer, as manifestation of low temperature, restricts the efficient vertical dispersion of pollutants in the atmosphere. [18] also stated that due to low wind speed and temperature, the pollutants are not dispersed and they get trapped

below the boundary layer, which leads to higher ground level concentration of pollutants. [8] found that high PM concentration are sensitive to boundary layer variations and meteorology during their study over Delhi. Similar findings were reported by [3, 6, 19, 20].

In a similar line, the seasonal variation in $PM_{2.5}$ concentration over Delhi has also been studied, which evident a clear seasonality having low concentration in monsoon, moderate in pre-monsoon and high in winter and post-monsoon seasons [14, 21]. Further, the concentration of

PM_{2.5} shows a negative correlation with temperature during the winter, pre-monsoon, and post-monsoon, while a positive correlation has been observed during the Monsoon season. As it is well known that during winters, the ambient air near earth's surface experiences lower temperatures and gradually increases with an increase in altitude, which lowers the atmospheric mixing height and restricts the vertical mixing and dispersion of PM_{2.5} [10, 14]. This results in negative correlations between concentrations of PM_{2.5} and ambient air temperature. In pre-monsoon season, the atmospheric temperature experienced maximum (up to 40 °C) and increased the mixing height, due to which the highest dispersion has been observed and resulting in a weak negative correlation with temperature [5]. The results of this study are consistent with the study conducted by [1, 19, 22, 23].

Saraswati et al. [9] also reported that during winter season, low wind speed and formation of lower stable boundary layer played an important role in slower dispersion of pollutants and localized emission also increased due to enhanced biomass burning. Similar finding was reported by [24] that combined effect of increased local emission due to open burning and non-favourable meteorological conditions can be the major reason for sudden increment in the concentration of pollutant.

Similarly, in Monsoon Season, exponential decay of PM_{2.5} concentration has been observed with an increase in temperature. It might be due to the settlement of particulate matters (PM) by frequent precipitation, therefore there has been a greater chance of reducing the amount of PM in the atmosphere. The impact of precipitation has also been confirmed through the results of non-rainy days. It has been observed during the non-rainy days, that the concentration of PM_{2.5} is on the higher side during the high ambient air temperature conditions as a result of natural cleaning process failing as described by [5]. In post-monsoon, the ambient temperature decreases to set up the winter season over the North Indian sector. The lowering of temperature with various biomass-burning activities in neighbouring states was responsible for high concentrations of PM_{2.5} [10, 14]. The negative correlation with the temperature is evident for the reduction in mixing height and PBL, which restricts the air mass dispersion far away. According to [14] study, particulate matter and PBL are significantly correlated during the winter and post-monsoon seasons. It signifies that the greater the PBL height, the lower the concentration of particulate matter and vice-versa. [25] found low mixing heights at Delhi during winters, while during the hot season, mixing heights are high due to large sensible heat fluxes from the surface. Heating the earth's surface causes convection, raises the mixing height, and identifies the exact cause of the greatest dispersion of pollutants. [26, 27] also reported the similar findings that

the high concentration of particulate pollution during colder months are mainly be attributed to stable meteorological conditions.

The results of the study are in close relation with the findings reported by [1, 3, 5–8, 14, 28–30] in which the authors show that the seasonal variations in PM_{2.5} concentration are strongly correlated with meteorological variables.

The results also show a significant and strong negative correlation with temperature under high humidity conditions, i.e. when the relative humidity has been above 50% otherwise, a weak negative correlation has been observed. This might be because the increase in atmospheric humidity absorbs significant amount of solar radiation, resulting in reduced radiation closer to the earth surface. As a result, the earth's surface temperature drops below that of the upper layers, which weakens incoming air currents and raises pollutant concentrations [5].

The observations also reveal that the background site "Pusa" is less polluted, followed by the Industrial Site "Okhla" and the residential site "Rohini". Such observation could be attributable to an area's land use pattern, demography and local meteorology [7]. The most striking observation of this work is that the residential site located at the North-West of Delhi experiences high pollution due to less air mass from the location. Similar results have also been reported by [10] but for North and East Delhi. This might be due to the fact that the residential area of North West Delhi has high population density with unplanned residential and commercial setup.

The overall result also observed that the air quality in respect to the PM_{2.5} concentration improved during the year 2021. This may be accounted to the fact that there was a lockdown imposed due to prevailing COVID-19 pandemic conditions during the year 2020 and the initial part of 2021, and subsequently slower rate of restart of public activity in the country as well as in Delhi. This results in fewer vehicles on the road, fewer operational factories/industries, and somewhat less public activity.

5. Conclusion

The present work is concluded with the following findings:

- The concentration of particulate matter (PM_{2.5}) has been significantly influenced by meteorological parameters especially by ambient temperature and relative humidity. The results show that the concentration of PM_{2.5} has inverse relationship with the temperature.
- It has also been observed that the concentration of PM_{2.5} has strong negative correlation with temperature during high humid conditions.

- The result also reveals that the background site Pusa has better air quality followed by industrial site Okhla and residential site Rohini.
- In the overall result, it is observed that the PM_{2.5} concentration in the year 2021 is lower than the year 2019 due to prevailing lockdown conditions.

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