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Seasonal trend analysis and influence of meteorological factors on the concentration of atmospheric pollutants in an urban area

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ABSTRACT

Introduction: Air pollution is a growing concern in Greater Noida, Uttar Pradesh, where meteorological factors play a major role. As urbanization accelerates, the region has not yet thoroughly examined the impact of factors like temperature, humidity, wind direction, and speed on pollutants like Particulate Matters ($PM_{2.5}$, PM_{10}), Nitrogen dioxide (NO_2), and Sulfur dioxide (SO_2)

Materials and methods: To explore this issue, a 12-month study (January to December 2023) was conducted to analyze the relationships between these meteorological factors and pollutant levels. In the present study, pollutant movement was tracked over time. Pearson correlation was used to correlate air pollution concentrations with weather conditions.

Results: The study revealed that the average concentrations of PM_{10}, $PM_{2.5}$, and NO_2 were 912.54 µg/m³, 257.42 µg/m³, and 65.98 µg/m³, respectively. In contrast, SO_2 had an average concentration of 26.85 µg/m³.

Conclusion: The study indicates that particulate matter and temperature are strongly negatively correlated, while wind speed shows a weak positive correlation with particulate matter. Pollution levels and relative humidity also display a negative correlation, as do particulate matter concentrations and humidity. However, gaseous pollutants exhibit little to no significant correlation with these weather conditions

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Introduction

The spatial variation, diffusion, and transport of pollutants are largely influenced by the geographical distribution of emission sources, with meteorological factors playing a crucial role. The National Air Quality Monitoring Program (NAMP) highlights that various climatic factors play a role in the dispersion and persistence of air pollutants. When atmospheric emissions surpass certain thresholds, they become pollutants, a process that can occur due to higher emissions and specific meteorological situations. Unlike emissions, which can be regulated, weather conditions remain beyond our control [1, 2]. For example, research in New Delhi, India, linked severe air pollution events to stagnant weather patterns [3].

It has been identified atmospheric impairment as one of the major ecological issues globally. It is also a rising issue in low-economic countries in South Asia, such as India, which are rapidly industrializing [3]. Fine Particulate Matter (FPM) has been recognized as the most serious environmental hazard due to its life-threatening toxicity to people's health. Municipal air contamination is a serious and growing ecological problem, particularly in emerging countries, and it significantly impacts public health worldwide, specifically respiratory and cardiac diseases.

The early mortality due to atmospheric impairment is the leading cause of death globally. In India, air contamination causes approximately 16.7 lakh untimely deaths, accounting for around eighteen percent of total mortalities. Eleven out of the twelve most polluted cities in the world with extreme PM concentrations are in India, raising serious concerns [4].

The quality of air in cities is affected by several factors such as micrometeorological conditions and urban growth trends. The combined impact of these factors can be more harmful to one's health than the impact of each factor on its own. The increasing occurrence of life-threatening weather events due to climate change caused by human activities is a cause for concern. To mitigate the negative effects of these factors, it is crucial to understand the relationships between different areas within a city, verify weather patterns, predict air quality, and control contamination [5]. Meteorological conditions also contribute to the increase of air impurities instead of just emissions into the atmosphere. Various studies have shown that factors such as temperature, humidity, air flow direction, and velocity have an effect on pollution concentrations within local areas.

Climatology and topography are the two major aspects that influence the occurrence of contamination [6], the extent of exposure, and the effects of pollution [7]. The dispersion, residence time, chemical transformations, and transport of contaminants in the air are all influenced by meteorology [8]. The levels of heavy metal-containing particulate matter are influenced by climatological factors such as speed and direction of the wind, temperature, and dampness [9]. The most severe exposure episodes occur predominantly during prolonged areas of low wind speeds and atmospheric stability, which favor secondary aerosol generation near the source locations [10]. According to numerous research, the largest amounts of particulate matter are seen in winter, followed by summer and the rainy season [11].

In some cases, daily levels of air pollutants are strongly influenced by weather factors such as wind speed and solar radiation [12], while in other cases, humidity and cloud cover can have an impact, particularly during the summer months for pollutants like Sulfur dioxide (SO_2) [13]. Nitrogen dioxide (NO_2) levels are strongly linked with temperature during the monsoon season and humidity and mist cover during winter.

Research has generally indicated a weak but significant relationship between PM_{10} levels and weather conditions. In one study conducted in Coimbatore, India, six different pollutants were examined in manufacturing, housing, rush-hour traffic, and commercial areas. Although tropospheric ozone and carbon monoxide showed weak correlations with temperature and wind speed, they did show a positive correlation with temperature and a negative correlation with humidity [14].

Meteorological elements like temperature, humidity, wind speed, and rainfall play a crucial role in influencing atmospheric pollutants. Understanding and monitoring these factors are essential for controlling pollution levels in urban settings. Various studies have shown the impact of weather conditions on air quality. However, while these studies have provided insights into the general air quality in Greater Noida, they have not specifically analyzed key pollutants across different seasons or explored the seasonal variations in detail [15-18].

This study aims to bridge the gap by offering a thorough analysis of air quality trends in Greater Noida from January to December 2023. It seeks to pinpoint significant changes and variations, providing insights into the success of pollution control measures and identifying any new pollution sources. Additionally, the study emphasizes the crucial role of meteorological factors in influencing air quality, highlighting the complex interactions between weather conditions, pollutant dispersion, and concentrations. The primary goal is to examine the relationship between pollutant levels and meteorological conditions and to evaluate the seasonal variations in air pollution in Greater Noida.

Materials and methods

Study area and sampling sites

Greater Noida, situated in the Gautam Buddha Nagar district of Uttar Pradesh, India, is positioned at 28.474400° N and 77.504000° E, spanning an area of around 40,000 hectares. As of March 2014, the city had a population of 107,676 across 124 localities and is part of the Delhi National Capital Region (NCR).

The climate in Greater Noida is similar to Delhi, featuring hot and dry summers, wet monsoons, and pleasant spring and autumn seasons. Classified as Seismic Zone III by the Bureau of Indian Standards, the city has a moderate earthquake risk. Additionally, a United Nations Development Programme (UNDP) assessment indicates its vulnerability to severe wind and cyclone damage.

Greater Noida experiences a tropical savanna climate with three main seasons: summer, monsoon, and winter. During summer (March to June), temperatures range from 23°C to 45°C. The monsoon season, from mid-June to mid-September, brings an average rainfall of 93.2 cm (36.7 in). In winter, temperatures can drop to 3–4°C, and dense fog often reduces visibility in January. The area was selected for the study due to its strategic importance as a growing hub for trade, tourism, population growth, and communication.

However, increasing traffic has led to a decline in air quality, contributing to rising pollution levels. The study was conducted at eight different locations in Greater Noida to measure concentrations of various air pollutants, as detailed in Table 1 and illustrated in Fig. 1.

Table 1. Sampling sites in Greater Noida

Site No.	Study Site	Category	Location	
S1	Pari Chowk	Major Road	$28^0$27’46.07” N	$77^0$31’00.31” E
S2	Banghel	Residential Road	$28^0$36’32.76” N	$77^0$26’44.93” E
S3	Sharda University	Arbitrary Road	$28^0$28’25.14” N	$77^0$29’03.89” E
S4	National Highway-91	Major Road	$26^0$33’41.47” N	$80^0$14’18.81” E
S5	Greater Noida West Link Road	Major Road	$28^0$29’51.61” N	$77^0$32’07.04” E
S6	Dadri Main Road	Major Road	$28^0$32’10.66” N	$77^0$25’19.12” E
S7	Alpha 1 Commercial Complex	Commercial Road	$28^0$28’16.29” N	$77^0$30’43.05” E
S 8	Amit Nagar, Sadarpur	Residential Road	$28^0$27’52.30” N	$77^0$32’28.21” E

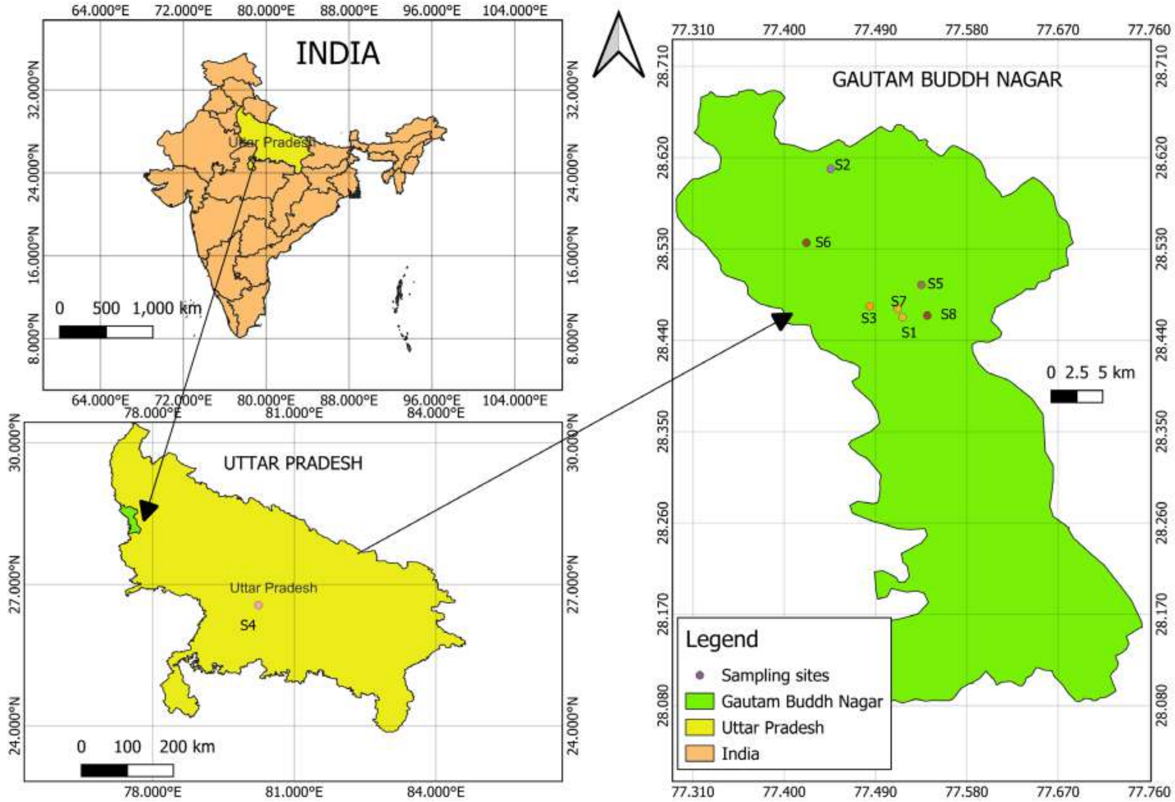

Fig. 1. Location map of study area

Table 2. Methods and instruments used for ambient air quality assessment

Parameter	Instrument used	Measurement method
PM_{10}	Respirable Dust Sampler (APM 460 NL)	Gravimetric Methodology IS 5182(Part 23): 2006
$PM_{2.5}$	Fine Particulate Sampler (APM 550 MFC)	Gravimetric Methodology IS 5182(Part 24): 2019
NO_2	Gaseous Pollutant Sampler (APM 433)	Modified Jacobs and Hochheiser method IS 5182(Part 6): 2017
SO_2	Gaseous Pollutant Sampler (APM 433)	Modified West & Gaeke Method IS 5182 (Part 2): 2001

Instrumentation and collection of data

The standard protocols were used for the ambient particulate and gaseous pollutants which are detailed in Table 2.

The primary objective was focused on the relationship between air pollution and weather in Greater Noida. Data on temperature, humidity, wind direction, and airspeed were gathered from Central Pollution Control Board (CPCB)'s online portal. CPCB ensures high data quality through rigorous sampling, review, and standardization processes.

Statistical analysis

The study analyzed the spatial distribution of air pollutants using statistical methods. Data processing was done with SPSS, while mapping and visualization were carried out using Origin Pro and SPSS. The Pearson correlation coefficient was employed to evaluate the relationship between weather factors and pollutant levels, indicating the strength and direction of their linear relationship, with values ranging from -1 to +1. A value of 0 signifies no correlation [19].

Results and discussion

The study examined particulate matter and gaseous pollutants at eight monitoring sites in Greater Noida. Results are shown in Table 3. The study period was divided into three seasons: winter (January-March), summer (April-June), and post-monsoon (October-December).

Fig. 2 shows seasonal variations in particulate matter at the eight sites. In winter, Dadri Main Road had the highest PM_{10} concentration at 912.54 µg/m³, while Pari Chowk had the lowest at 240.47 µg/m³. The highest $PM_{2.5}$ levels were also recorded in winter due to lower mixing layer heights, which cause pollutants to accumulate near the ground. This accumulation is driven by high emissions from vehicles, manufacturing, and fossil fuel combustion. The Mixing Layer Height (MLH) is a key factor that influences pollutant concentration near the surface.

The Dadri Main Road (912.54 µg/m³) had the greatest mean concentration of PM_{10}, followed by Bhangel (684.96 µg/m³) and Amit Nagar (478.57 µg/m³), while the Pari Chowk, Alpha 1 commercial complex, and Sharda University had the lowest.(340.45 µg/m³). Similar to $PM_{2.5}$, the greatest average concentration was found at Dadri Main Road (257.42 µg/m³), followed by Bhangel (141.13 µg/m³), and Sharda University (103.66 µg/m³), while the lowest concentration was found at Amit Nagar, Sadarpur. (35.63 µg/m³).

Table 3. Seasonal changes in air pollutants in the study area

Site	Pollutants (in ug/m³)	Seasons: Winter	Summer	Post- Monsoon
S1	PM_{10}	240.47	336.72	254.68
	$PM_{2.5}$	93.99	73.49	104.61
	NO_2	15.62	13.40	17.24
	SO_2	16.36	34.49	30.57
S2:	PM_{10}	684.96	585.71	650.78
	$PM_{2.5}$	141.13	78.74	135.94
	NO_2	40.54	15.69	26.46
	SO_2	24.55	35.64	28.93
S3:	PM_{10}	340.45	406.46	385.38
	$PM_{2.5}$	103.66	68.33	86.24
	NO_2	20.42	21.75	24.56
	SO_2	16.76	30.61	27.36

Table 3. Continued

Site	Pollutants (in ug/m^3)	Seasons Winter	Summer	Post- Monsoon
S4:	PM_{10}	372.45	472.16	514.23
	$PM_{2.5}$	88.30	75.56	105.36
	NO_2	22.59	20.72	28.56
	SO_2	26.58	32.65	26.86
S5:	PM_{10}	334.43	380.62	426.35
	$PM_{2.5}$	40.47	66.65	110.35
	NO_2	62.27	10.49	54.38
	SO_2	19.53	34.63	40.38
S6:	PM_{10}	912.54	536.51	754.23
	$PM_{2.5}$	257.42	73.37	153.85
	NO_2	12.55	10.69	15.68
	SO_2	10.89	32.65	34.59
S7:	PM_{10}	299.48	518.20	350.57
	$PM_{2.5}$	92.40	78.23	105.68
	NO_2	22.53	10.62	28.35
	SO_2	18.53	34.63	36.45
S8:	PM_{10}	478.57	250.68	385.13
	$PM_{2.5}$	35.63	36.54	75.68
	NO_2	24.71	10.50	31.86
	SO_2	13.97	43.66	34.58

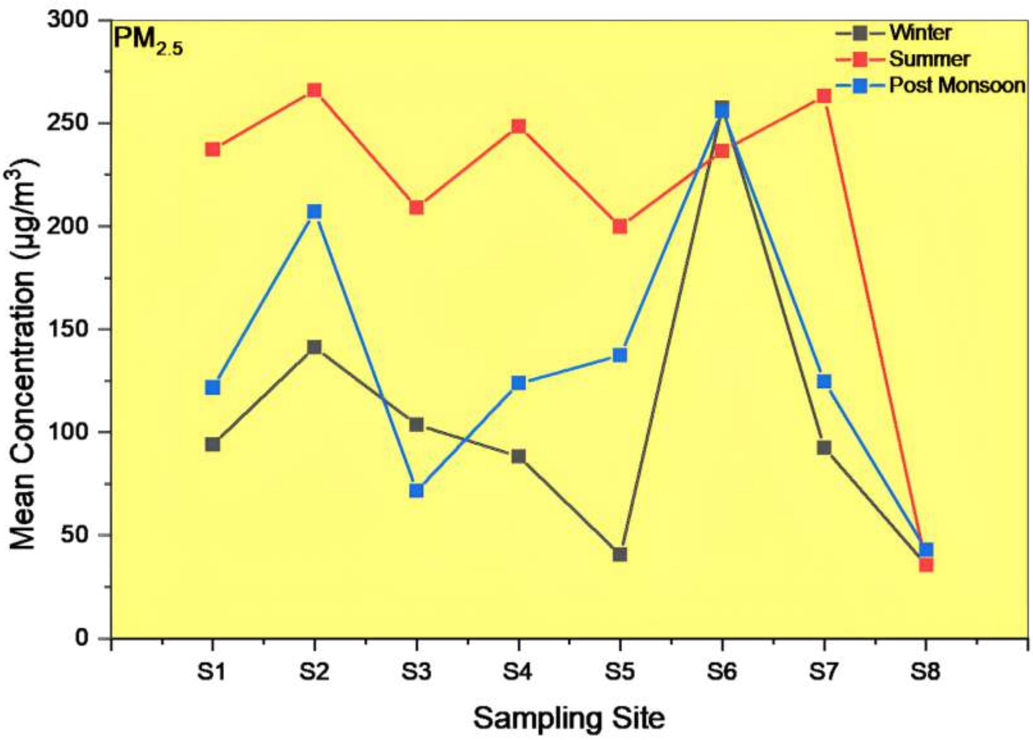

Fig. 2. Seasonal variation of ambient particulate matter in study area

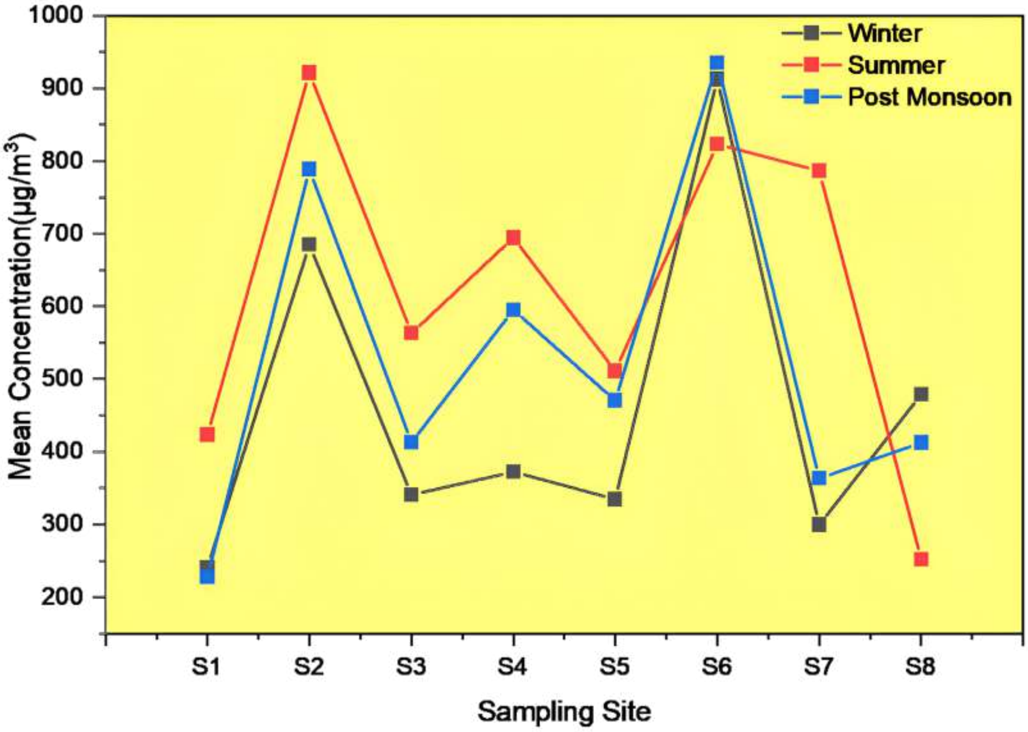

Fig. 2. Continued

Variability of ambient gaseous pollutants

The data in Fig. 3 highlights that the Noida-Greater Noida highway experienced the highest nitrogen dioxide levels in the winter, with Greater Noida following closely in the post-monsoon season. In comparison, the lowest nitrogen dioxide concentration was observed during the summer in Amit Nagar, Sadarpur. The primary reason for the higher concentration during the winter season is that the dispersion of gaseous pollutants is inversely proportional to temperature and wind speed, which means that cooler temperatures and lower wind speeds lead to poor dispersion of pollutants.

Variability of ambient gaseous pollutants

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According to the meteorological data collected from the CPCB portal, the wind speed in the study region varies from 0.00 to 5.43 m/s with an average speed of 1.46 m/s throughout the study tenure. During the study episode mainly North-Easterly, North-North Easterly, and East-North Easterly winds prevailed in the study area. To represent the wind flow in the study area a wind rose diagram was plotted by using WRPLOT View – Lakes Environmental Software which is shown in Fig. 5. The wind rose plot is imposed on satellite imagery of the study area by using Google Earth which is shown in Fig. 6 to show the flowing direction of the wind in the study area during different seasons.

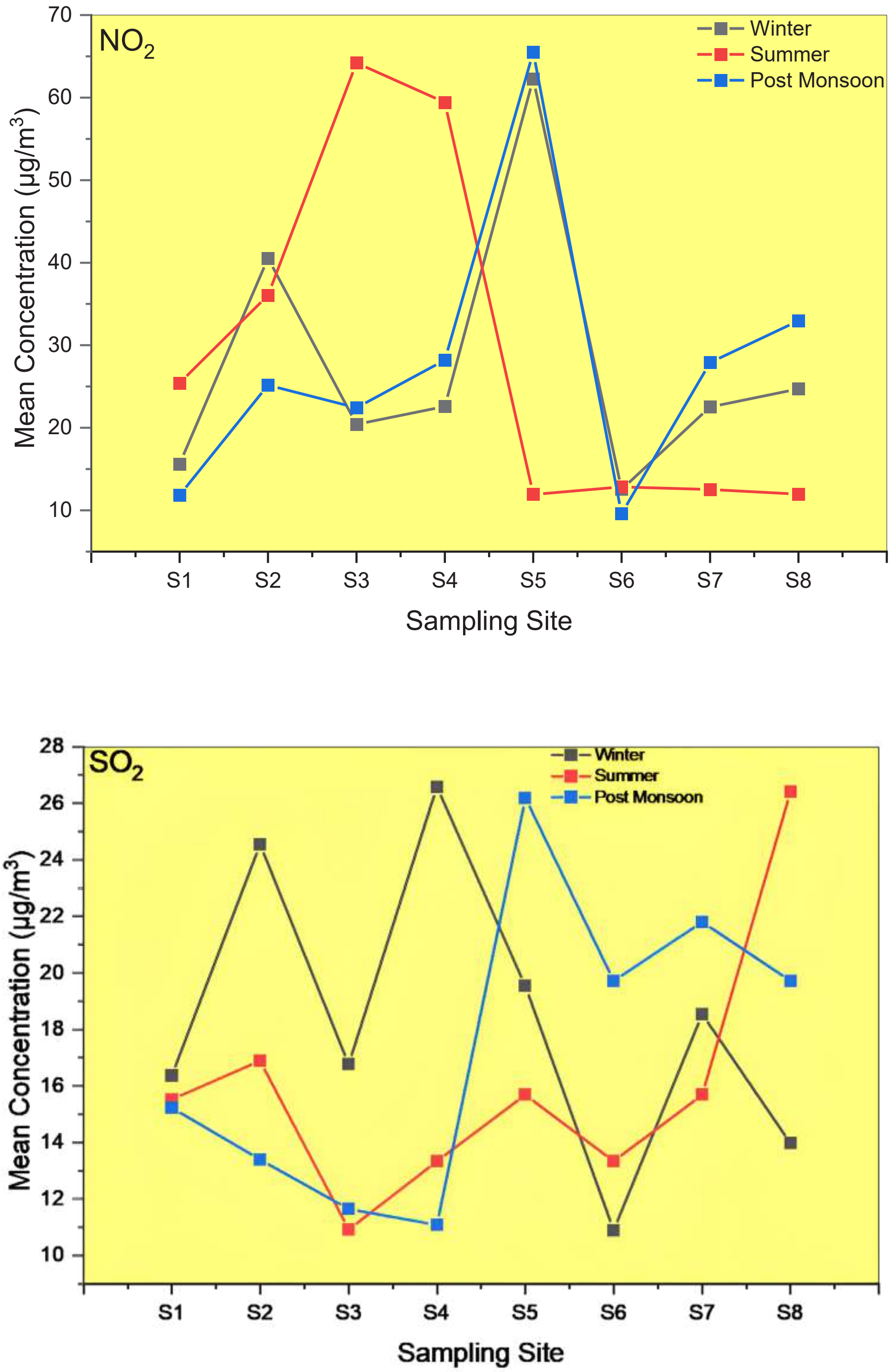

Fig. 3. Seasonal variation of gaseous pollutants in study area

Table 4. Variation of meteorological parameters in the study area

		Range	Minimum	Maximum	Mean	Standard Deviation	Variance	Skewness	Kurtosis
Winter	Temperature	8.51	26.92	35.43	31.60	1.57	2.46	-1.36	1.97
	Relative Humidity	36.40	43.48	79.88	63.46	8.40	70.54	0.039	-0.646
	Wind Speed	3.83	0.30	4.13	1.07	0.73	0.5	2.0	4.36
	Wind Direction	121.53	38.50	160.03	83.88	31.01	961.80	0.82	-0.356
Summer	Temperature	10.07	27.93	38.00	32.10	2.45	6.01	0.130	-1.045
	Relative Humidity	40.00	26.00	66.00	39.70	10.32	106.58	0.900	-0.098
	Wind Speed	5.43	0.00	5.43	2.41	1.05	1.11	0.44	0.04
	Wind Direction	103.83	47.17	151.00	95.16	29.15	849.91	0.25	-1.18
Post-Monsoon	Temperature	6.00	29.00	35.00	31.37	1.22	1.49	0.58	1.06
	Relative Humidity	33.00	49.00	82.00	62.23	8.12	65.91	0.65	0.24
	Wind Speed	2.00	0.00	2.00	0.90	0.51	0.26	-0.17	0.85
	Wind Direction	261.00	45.00	306.00	102.78	54.11	2927.87	2.24	5.27

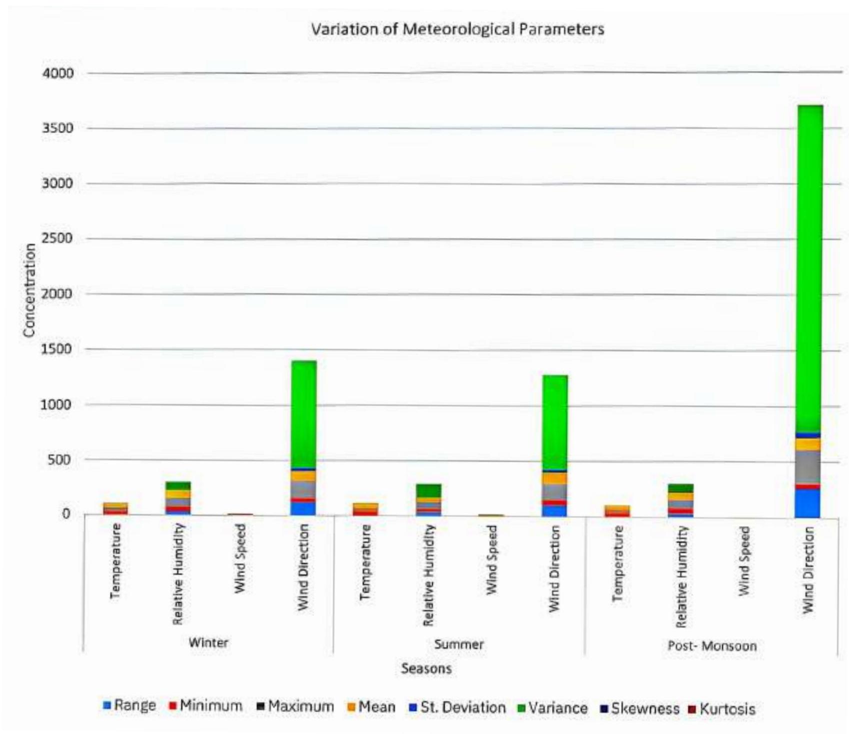

Fig. 4. Variation of meteorological parameters in the study area

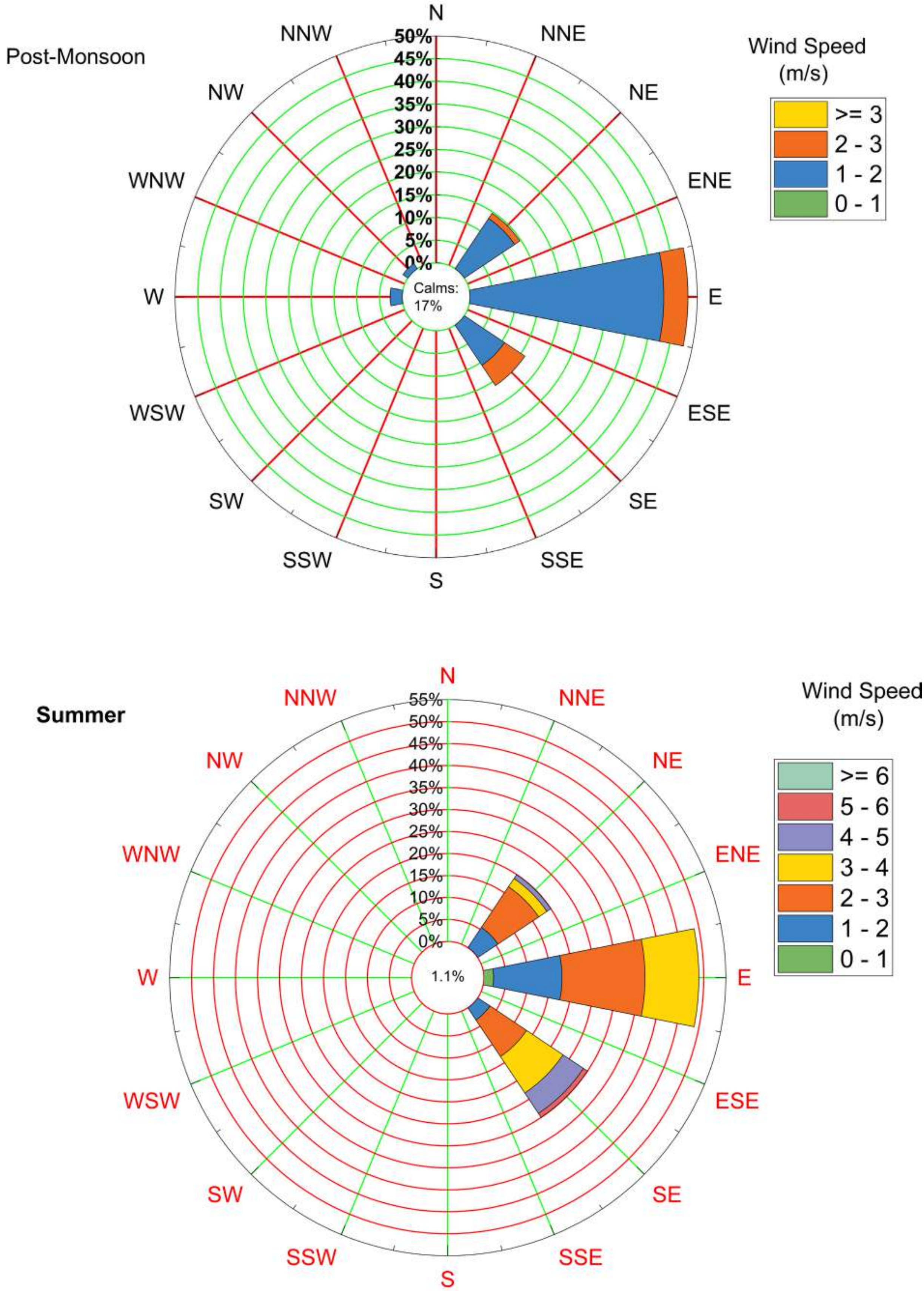

Fig. 5. Wind rose diagram for different seasons in the study area

Relationship between air pollutants and meteorological factors

The correlation analysis was carried out to explore the relationships between ambient air pollutant levels and meteorological factors such as temperature, humidity, wind speed, and wind direction, as illustrated in Table 5. The findings revealed that PM_{10} had the weakest negative correlation with all meteorological parameters, with correlation coefficients of -0.194 for temperature, -0.180 for humidity, -0.154 for wind speed, and -0.422 for wind direction. Higher temperatures contribute to increased mixing heights, resulting from greater heat flux and thermal turbulence, which helps disperse pollutants and reduce their concentrations in the air.

A consistent negative correlation between pollutant levels and relative humidity was observed throughout the study. Both $PM_{2.5}$ and PM_{10} concentrations were inversely correlated with humidity, with correlation values of r= -0.180 and r=-0.413, respectively, while gaseous pollutants showed strong positive correlations (r=0.881 and r=0.825). The negative relationship between PM_{10} and humidity can be attributed to particle clumping, as increased humidity causes particles to combine, grow larger, and settle out of the atmosphere through dry deposition. However, this pattern did not extend to gaseous pollutants. Similar studies support this negative correlation between particulate matter and humidity [25].

PM_{10} also demonstrated a negative correlation with wind speed (r=-0.154), while $PM_{2.5}$ had a slight positive correlation (r=0.228). Gaseous pollutants, however, exhibited weak or non-significant negative correlations with wind speed, with r=-0.080 and r=-0.350, respectively. Low wind speeds were linked to higher pollutant concentrations due to atmospheric stability, which hinders the dispersion of pollutants [26]. Wind speed had minimal positive correlations with particulate matter, but for $PM_{2.5}$, the relationship was moderate (r=0.270). Gaseous pollutants displayed weak negative correlations with airspeed (r=-0.219 and r=-0.145).

The inverse relationships between wind speed, humidity, and particulate matter suggest that both wind and humidity aid in dispersing pollutants. However, high wind speeds might also resuspend dust particles, leading to increased PM levels. Additionally, the positive correlation between wind direction and particulate matter indicates that ground-level dust resuspension likely contributed to elevated PM concentrations at the study site. Sunlight and temperature were also found to influence gaseous pollutants, with lower temperatures favoring particulate matter deposition in the atmosphere [27].

Table 5. Correlation between ambient air pollutants and meteorological parameters

		PM_{10}	**$PM_{2.5}$**	**NO_2**	**SO_2**	**Temperature**	**Relative Humidity**	**Wind Speed**	**Wind Direction**
PM_{10}	Pearson Correlation	1	.840**	-.183	-.176	-.194	-.180	-.154	-.422
	Sig. (2-tailed)		.009	.664	.678	.645	.669	.716	.297
	N	8	8	8	8	8	8	8	8
$PM_{2.5}$	Pearson Correlation	.840**	1	-.445	-.502	-.026	-.413	.228	.093
	Sig. (2-tailed)	.009		.270	.205	.951	.309	.587	.826
	N	8	8	8	8	8	8	8	8
NO_2	Pearson Correlation	-.183	-.445	1	.660	.153	.881**	-.080	-.540
	Sig. (2-tailed)	.664	.270		.075	.717	.004	.850	.167
	N	8	8	8	8	8	8	8	8
SO_2	Pearson Correlation	-.176	-.502	.660	1	-.259	.825*	-.350	-.447
	Sig. (2-tailed)	.678	.205	.075		.536	.012	.396	.267
	N	8	8	8	8	8	8	8	8

Table 5. Continued

		PM_{10}	$PM_{2.5}$	NO_2	SO_2	Temperature	Relative Humidity	Wind Speed	Wind Direction
Temperature	Pearson Correlation	-.194	-.026	.153	-.259	1	.042	.681	.333
	Sig. (2-tailed)	.645	.951	.717	.536		.922	.063	.420
	N	8	8	8	8	8	8	8	8
Relative Humidity	Pearson Correlation	-.180	-.413	.881**	.825*	.042	1	-.141	-.413
	Sig. (2-tailed)	.669	.309	.004	.012	.922		.739	.310
	N	8	8	8	8	8	8	8	8
Wind Speed	Pearson Correlation	-.154	.228	-.080	-.350	.681	-.141	1	.524
	Sig. (2-tailed)	.716	.587	.850	.396	.063	.739		.183
	N	8	8	8	8	8	8	8	8
Wind Direction	Pearson Correlation	-.422	.093	-.540	-.447	.333	-.413	.524	1
	Sig. (2-tailed)	.297	.826	.167	.267	.420	.310	.183	
	N	8	8	8	8	8	8	8	8

** Correlation is significant at the 0.01 level (2-tailed)
*Correlation is significant at the 0.05 level (2-tailed)

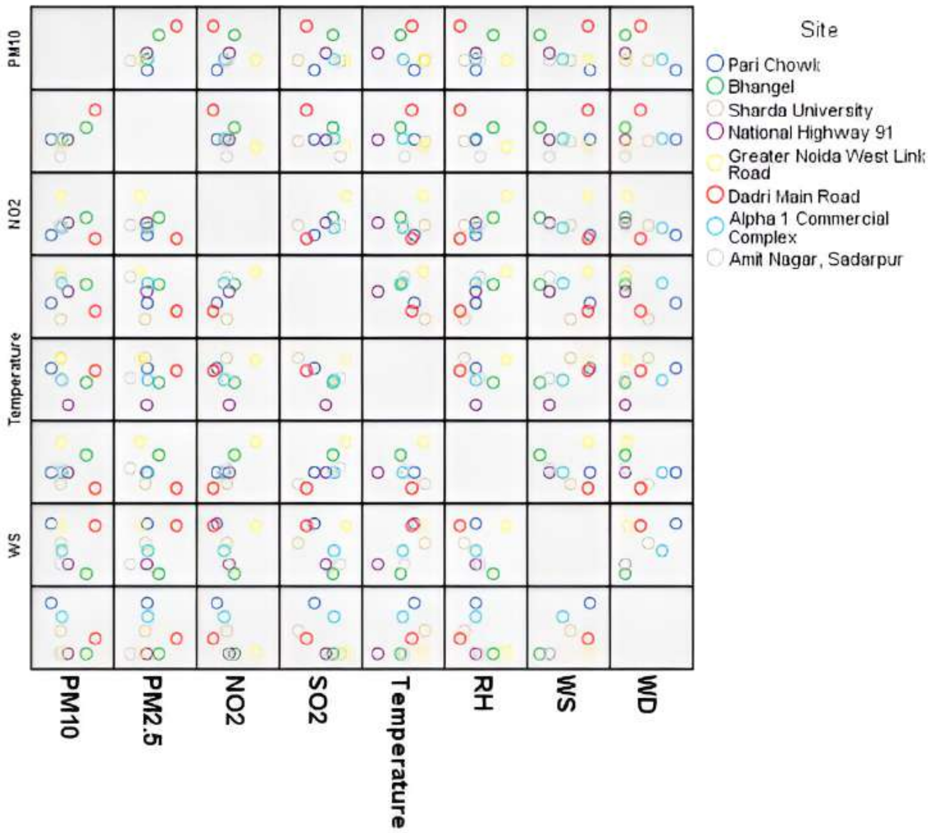

Fig. 6. Correlation matrix between ambient air pollutants and meteorological parameters

Conclusion

Throughout the study period, PM_{10}, $PM_{2.5}$, and NO_2 levels consistently surpassed the annual standards set by the Central Pollution Control Board (CPCB). Additionally, the 24-hour concentrations of these pollutants exceeded permissible limits, indicating deteriorating air quality in Greater Noida. Conversely, SO_2 levels remained within both the annual and 24-h limits set by the CPCB, likely due to effective government policies such as promoting LPG over coal for household fuel, reducing sulfur content in diesel, converting diesel vehicles to CNG, and enforcing Bharat Stage-VI emission standards.

Seasonal trends were observed for $PM_{2.5}$, PM_{10}, SO_2, and NO_2, with the highest concentrations during winter and the lowest in summer. This variation can be partially attributed to seasonal changes in the atmospheric boundary layer, which is lower in winter and higher in summer. These findings highlight the significant impact of meteorological factors on air pollutant concentrations.

Pearson correlation analysis revealed significant relationships between pollutants. PM_{10} and $PM_{2.5}$ showed a strong correlation, suggesting common sources. Notable correlations were also found between air pollutants and meteorological variables. Wind speed was inversely related to pollutant levels, emphasizing the role of wind in dispersing pollutants. Similarly, temperature was inversely correlated with pollutant concentrations, indicating that increased heat flux and thermal turbulence help reduce pollutant levels in the atmosphere.

This study provides valuable insights into how meteorological conditions influence air pollution, offering a foundation for policymakers to develop effective pollution control strategies. It also underscores the need to consider the impact of global climate change on air quality and public health. While the study focused on surface-level meteorological factors, it suggests that the vertical structure of the atmospheric boundary layer may also play a crucial role in influencing ground-level pollutant concentrations.

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Competing interests

The authors declare no conflict of interest.

Authors contributions

Suman (corresponding author): Oversight, conceptual development, methodology design, investigation, visualization, project management, validation, drafting the original manuscript, and reviewing and editing. Naresh Kumar (lead author): Conceptualization, methodology, investigation, and drafting of the original manuscript. Priya Ranjan: Involved in conceptualization, methodology, and investigation.

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Ethical considerations

The researchers have strictly followed all ethical guidelines, covering aspects such as plagiarism, informed consent, research misconduct, data fabrication or falsification, duplicate publication or submission, and redundancy.

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