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Seasonal Trends in Air Pollution at an industrial site in Haryana and its relation with meteorological variables

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Abstract
This paper examines the seasonal changes in air pollution levels and their relationship with meteorological parameters in two locations in Panipat (Industrial site and Vehicular site) over two years (2021-2022). The concentrations of SO_2, NO_2, $PM_{2.5}$, PM_{10}, CO, and Pb were analysed. The findings indicate that the maximum concentration of pollutant was recorded during the post-monsoon season, especially $PM_{2.5}$ and PM_{10} because the wind velocity remained low, the temperature was high, and the relative humidity was high. Industrial emissions were also at the forefront at both the Industrial Site and the Vehicular Site in raising SO_2 as well as particulate matter, whereas at the Vehicular Site, the traffic-related emissions had the largest influence in raising the level of NO_2 and CO. Wind speed, temperature, and relative humidity (meteorological factors) had a high correlation with pollutant concentration, with low wind speed and high temperatures during the Post-monsoon season aggravated the quality of air through limitation of dispersion of the pollutants. The research emphasizes the relevance of meteorological conditions in air quality management plans.
Keywords: *Air quality, Meteorological factors. Urban air pollution*

1. INTRODUCTION

Air pollution is an environmental and health issue in both developed and developing nations but in South Asian countries air pollution is a major problem especially in India. With the rise in populations in our cities and the increase in the rate of industrialization, cities such as Panipat in Haryana are being exposed to excessive pollution by various anthropogenic sources. They entail the industrial emissions, the traffic on roads, and the local practise in areas neighbouring the region; it includes the crop residue burning and the utilisation of solid bio-mass fuels in the vicinity of the area (Ravindra et al., 2022; Ravish et al., 2025; Ravish & Chaudhry, 2024). Such pollutants as sulphur dioxide (SO_2), nitrogen dioxide (NO_2), particulate matter ($PM_{2.5}$, PM_{10}), carbon monoxide (CO), and lead (Pb) affect the quality of air not only negatively but also significantly harm human health, causing respiratory and cardiovascular diseases, and acting as one of the causes of premature death (Adler, 2010; Alamgir & Shan, 2024; Balakrishnan et al., 2019)

Medium-sized cities that are also fast growing and urbanizing, such as Panipat, have gained little or no consideration in previous air pollution studies, despite many studies on this topic being carried out in bigger metropolitan capitals like Delhi, Mumbai, and Kolkata (Akhtar et al., 2018; Bhuyan et al., 2025; Chaudhuri & Roy, 2025). The absence of this research is also significant because these cities have distinctive problems because of the emissions of the industry and vehicles. Also, it is not always well known how the level of pollutants in such cities changes with the seasons. The area of industrial and vehicular pollution is mostly studied in big cities but not in small cities and the cumulative impact of the combination of these two kinds of pollutants in small cities (particularly in different seasons) has not yet been thoroughly investigated (Guttikunda et al., 2022; Guttikunda & Jawahar, 2020). This research will close this gap by undertaking inclusive evaluation of air pollution in Panipat covering two years (2021-2022). Using the air quality sampling in various seasons, winter, pre-monsoon and post-monsoon, this study will be able to capture maximum variations in the pollutants occurring throughout the year. Another major distributive aspect of this study is the aspect of comparing the pollution levels between the industrial and vehicular sites. Although both the sources are contributing to the total pollution pressure, their definite effects to the atmosphere and the health of the people can differ, and more specifically, it can rely on seasonal dynamics and weather. By following this way of analysis, one can understand the seasonal nature of air pollution better and separate the input that is made by industrial production and that made by motor vehicles which is really rarely appropriately done in most studies as well. The extent of the air sampling carried out as part of the research will include several important industrial and vehicular spots, which will become valuable sources of information about how the concentration of pollutants changes with the seasons as well as giving a reference opinion on what role does the meteorological factor play in the distribution and level of pollutants as temperatures and wind speed as well as humidity. This is essential analysis that will be used to develop specific and effective air quality management policies since it will enable identification of the particular sources and conditions that contribute to the maximum pollution during various seasons of the year (Ravindra et al., 2015a; Ravindra et al., 2019b).

Since air pollution continues to be a key source of health challenges and climate change, especially in metropolitan areas such as Panipat, a seasonal fluctuation and source specific impact is indispensable in achieving empowered policies on the subject. The proposed study will be of assistance to other local and regional initiatives in their efforts to tackle the impact of pollution and air quality improvement and hence the insights obtained may be useful to other medium size cities having problems similar to those outlined above. The study addresses only a medium-sized city where research has not been conducted much, which is a major gap in the research and makes it possible to have an in-depth comprehensive evaluation of air pollution within an under-studied type of setting.

2. MATERIAL AND METHOD

This study assesses the seasonal variations in air pollution at industrial and vehicular sites in Panipat over a two-year period (2021–2022). The methodology follows a comprehensive sampling approach, where air quality is measured at both types of sites during different seasons, followed by statistical analysis to evaluate trends and compare pollutant levels. The following sections outline the materials, sampling procedure, data analysis techniques, and statistical methods used in this study.

2.1 Study Area

Panipat district is situated in the northern part of Haryana, India, located about 95 km north of Delhi and is known for its historical and industrial significance. Covering an area of about 1,268 km^2. It had a population of approximately 12 lakhs (1.2 million) according to the 2011 census. Geographically, the district lies between the coordinates 29° 11′ 30″ N to 29° 58′ 30″ N latitude and 76° 31′ 15″ E to 77° 13′ 45″ E longitude while city centre is located at approximately 29° 23′ 20″ N latitude and 76° 58′ 05″ E longitude as shown in figure 1. Panipat is home to a wide variety of manufacturing industries, including wool and cotton milling, textile production, saltpetre refining, glass production, electrical appliances, and other goods.

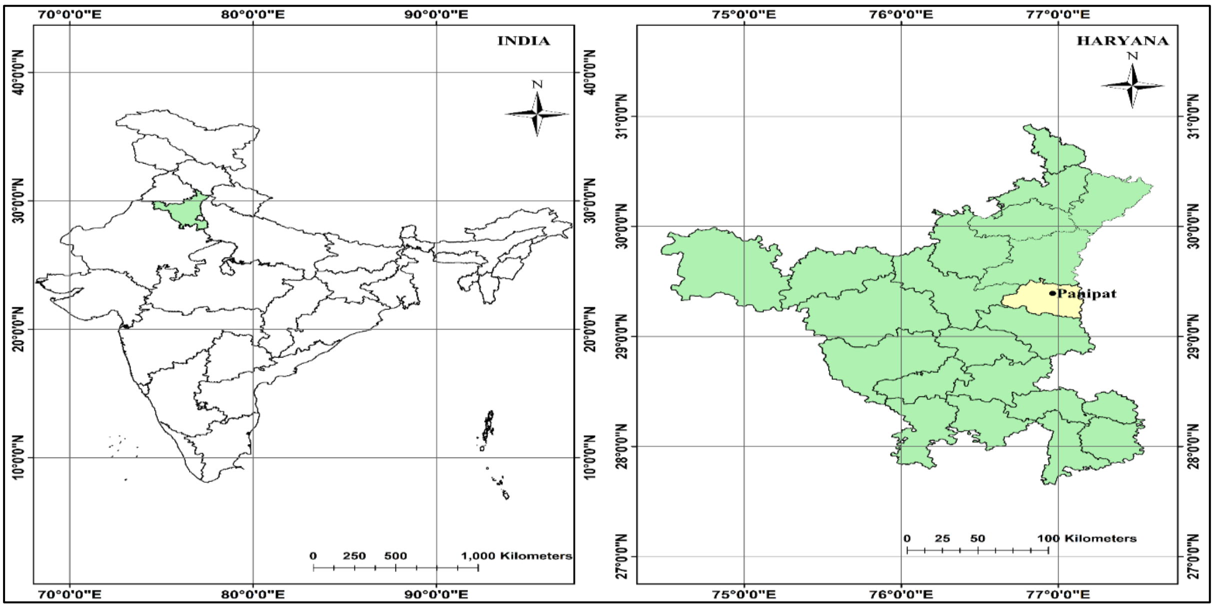

Figure 1: Location of Panipat in Haryana, India

As a result of these extensive industrial activities, Panipat has earned the designation of a Critically Polluted Industrial Area in India, with the city's Comprehensive Environment Pollution Index (CEPI) recorded at 71.91, indicating severe pollution levels. Panipat experiences a semi-arid climate, with hot summers, cold winters, and a monsoon season. The city's annual rainfall is around 560 mm, most of which occurs during the monsoon months from July to September. The average annual temperature is 24°C, with summer temperatures reaching as high as 45°C in May and June, and winter temperatures dipping as low as 2°C in December and January. Given its industrial significance, Panipat experiences high pollution levels, especially from its industrial and vehicular sources, making it an ideal location for studying air quality dynamics.

2.2 Sampling Locations and Period

The study focuses on two designated locations for air quality monitoring in Panipat:

- Industrial Site (IS): Located near Panipat Thermal Power Station in village Asan khurd situated on SH-14, this site is characterized by high industrial emissions, including emissions from factories, power plants, and other manufacturing units.
- Vehicular Site: Located near the L&T Toll Plaza area on NH-44, this site is subject to significant vehicular emissions, contributing to high levels of traffic-related air pollution.

These two sites were selected to assess the pollution levels from industrial emissions and vehicular traffic, two major contributors to the region's air quality degradation. Air samples were collected from both the industrial and vehicular sites in Panipat over a two-year period, spanning different seasons to capture the seasonal variability in pollutant levels. The study was conducted in 2021 and 2022, and the sampling was carried out during three key seasons:

- Winter: December– February
- Pre-monsoon: April – June
- Post-monsoon: October – December

Sampling stations were strategically located at each of the two sites to ensure the data adequately reflects pollution levels from both primary sources. The sampling period across the two years (2021 and 2022) ensured the collection of consistent data over varying meteorological conditions.

2.3 Sampling Methodology

Air samples were collected using High-Volume Air Samplers (HVAS) for particulate matter (PM), HVAS gaseous pollutant sampling attachment and NDIR gas analyser for gaseous pollutants. The following pollutants were targeted for sampling:

- Sulphur dioxide (SO_2)
- Nitrogen dioxide (NO_2)
- Particulate Matter ($PM_{2.5}$ and PM_{10})
- Carbon monoxide (CO)
- Lead (Pb)

Instrumentation and Analytical Methods:

- Measurement of Particulate Matter: High-Volume Air Sampler was to collect particulate matter ($PM_{2.5}$ and PM_{10}) samples on filters for subsequent gravimetric analysis. Filters (Glass fibre filter for PM_{10} and PTFE for $PM_{2.5}$) were weighed before and after sampling to determine the mass of particulate matter collected.
- Gaseous pollutant sampling attachment: Employed to capture gaseous pollutants such as SO_2 and NO_2, these samplers use absorbent materials to trap the gases.
- Measurement of SO_2: The concentration of SO_2 was determined using the West and Geake (1956) method, which involves the use of sodium tetrachloromercurate as the absorbent medium. This method effectively captures SO_2 from the air sample, and the absorbance is measured to calculate the concentration.
- Measurement of NO_2: The concentration of NO_2 was determined using the Jacob and Hoccheiser (1958) methodology. In this method, sodium hydroxide was used as the absorbent medium to trap NO_2 from the air. The resulting chemical reaction allows for the quantitative determination of NO_2 levels.
- NDIR gas analyser was used to monitor CO gas pollutant.

- Lead Sampling was conducted using acid digestion of exposed glass fibre filters obtained from air sampler and then analysed in the laboratory using Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

Samples were collected over 24-hour periods, with six replicate sampling events conducted during each season (winter, pre-monsoon, and post-monsoon) in both study years. At each event, duplicate samples were collected to ensure quality assurance.

2.4 Meteorological Data

Meteorological data such as temperature, wind speed, wind direction, and relative humidity data were also collected from the Indian Meteorological Department (IMD) and ECMWS. This data was essential for understanding the dispersion patterns of pollutants and their seasonal variations. The meteorological data collected during the study period (2021-2022) were analysed in correlation with pollutant levels to assess how weather conditions influenced the spread and concentration of pollutants.

2.5 Statistical Analysis

The primary dataset was processed and analysed using the Data Analysis Tool pack in MS Excel 2021 to obtain the average mean values, and standard deviation. All experimental data were expressed as mean ± standard deviation based on six replicates. To evaluate the relationship between increasing concentrations of air pollutants over different years and seasons, Correlation analysis was conducted using SPSS software (IBM SPSS Statistics v 25). Given the nature of the data—small sample size, potential outliers, and likely non-linear relationships—Spearman correlation provides a more reliable and interpretable measure of association in this context. Statistical significance was determined at three levels: $p < 0.05$, $p < 0.01$, and $p < 0.001$. Correlation heatmaps were generated for better visualization of the results, and the findings were cross-verified using Python's MatPlotLib library.

2.6 Quality Control and Calibration

To ensure the accuracy and reliability of the data:

- Calibration of sampling instruments was performed before and after each sampling campaign to confirm their proper functioning.
- Field blanks were used to detect contamination during sample collection, and replicates were taken for each pollutant to check for consistency in the measurements.
- Filter handling was conducted in a controlled environment to minimize the risk of contamination.

Laboratory analysis of filters for particulate matter and gaseous pollutants followed standard protocols. For lead analysis, filters were acid-digested and analysed in the laboratory using ICP-MS, ensuring high sensitivity and accuracy.

2.7 Limitations

- The study focused on only two sites in Panipat, and findings may not be applicable to other areas without similar industrial or vehicular activity.
- Seasonal variation in meteorological conditions could have influenced pollutant dispersion, which requires further exploration in future studies.
- The study did not account for local topographical variations, which could influence pollutant distribution patterns.

3. RESULTS AND DISCUSSION

This section presents the results of air quality monitoring conducted at two distinct sites in Panipat: the industrial site (near the Panipat Thermal Power station and adjacent Industrial Area) and the vehicular site (near the NH-44 L&T Toll Plaza). The data was collected over a two-year period (2021-2022) during three key seasons: Winter, Pre-monsoon, and Post-monsoon. The pollutants measured include SO_2, NO_2, $PM_{2.5}$, PM_{10}, CO, and Pb. Seasonal variations and differences between the two sites are discussed below.

3.1 Pollutant Concentration at the Industrial Site (2021-2022)

At the industrial site, pollutant concentrations exhibited seasonal variations in both years.

SO_2 Levels

The concentration of SO_2 at the industrial site was highest during the post-monsoon period in both 2021 and 2022. In 2021, SO_2 levels were 54.77 ± 9.33 μg/m³ during Winter, decreasing to 42.86 ± 16.82

µg/m³ in Pre-monsoon, and rising to 68.87 ± 23.79 µg/m³ in Post-monsoon as shown in figure 2. In 2022, SO_2 levels were 44.84 ± 14.34 µg/m³ during Winter, 37.15 ± 9.50 µg/m³ during Pre-monsoon, and 53.59 ± 12.31 µg/m³ during Post-monsoon. These fluctuations indicate that Post-monsoon season sees a significant spike in industrial emissions, which could be exacerbated by decreased rainfall and atmospheric conditions that trap emissions near the ground.

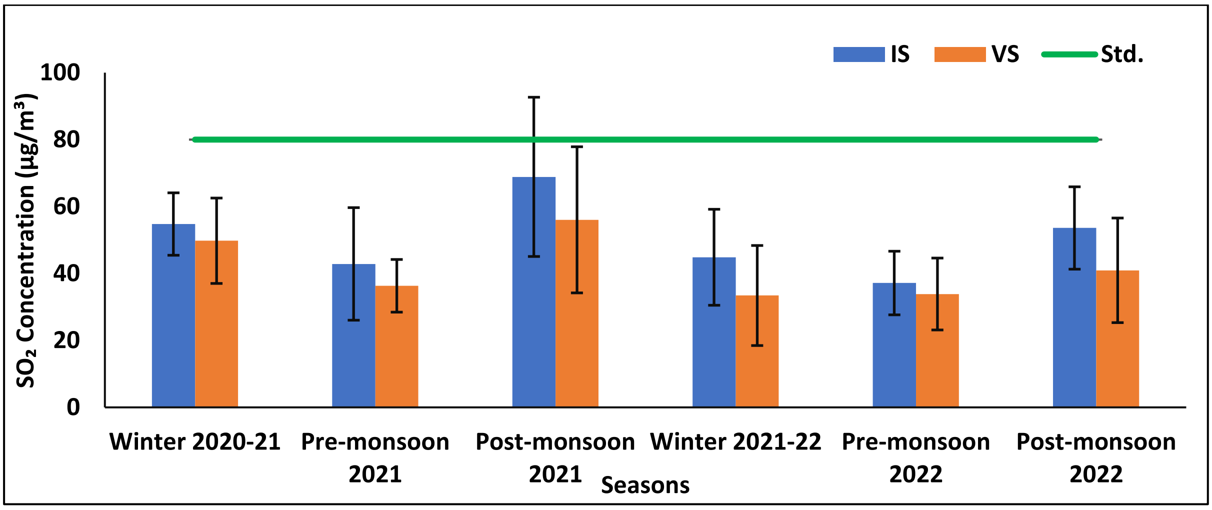

Figure 2: Seasonal Variations in SO_2 Concentrations at Industrial and Vehicular Sites in Panipat (2021-2022) Compared to CPCB NAAQS Permissible Limit

Figure 1 Seasonal variations in SO_2 concentrations at the Industrial Site (IS) and Vehicular Site (VS) in Panipat from 2020 to 2022, compared with the NAQMS permissible limit. The bars represent the average concentrations for each season, with error bars showing the standard deviations. The green line denotes the permissible limit for SO_2 as per CPCB NAAQS.

NO_2 Levels

NO_2 levels were also higher during the Post-monsoon season. In 2021, the levels were 58.39 ± 17.81 µg/m³ during Winter, 40.49 ± 14.75 µg/m³ during Pre-monsoon, and 66.60 ± 12.63 µg/m³ during Post-monsoon as shown in figure 3. In 2022, the concentrations were 50.21 ± 10.53 µg/m³ during Winter, 36.48 ± 7.63 µg/m³ during Pre-monsoon, and 81.76 ± 24.92 µg/m³ during Post-monsoon. The Post-monsoon spike could be linked to the higher levels of vehicular emissions, as well as increased industrial activities in that period. This suggests that NO_2 concentrations in the industrial area are influenced by both industrial and vehicular emissions, which peak during Post-monsoon due to favourable conditions for air stagnation.

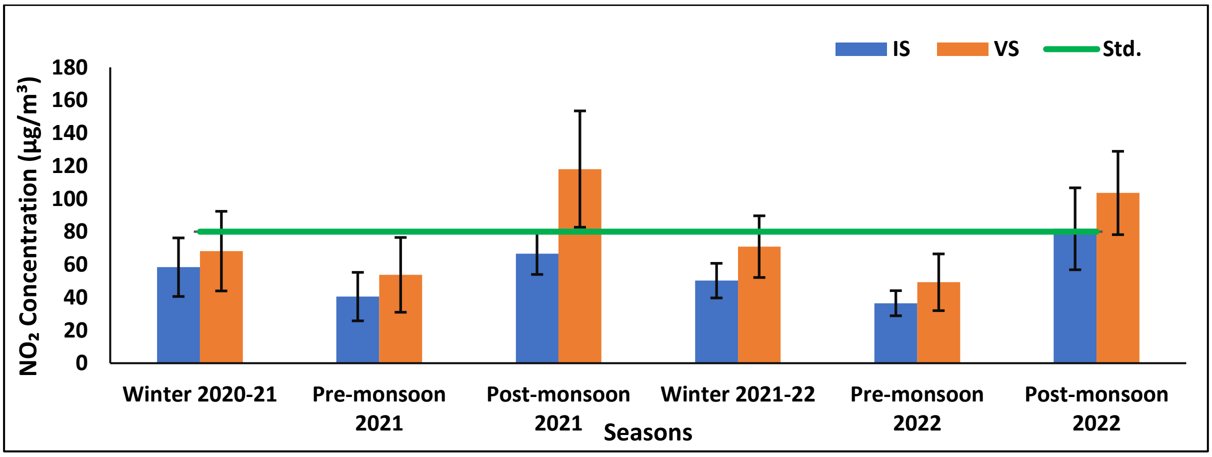

Figure 3: Seasonal Variations in NO_2 Concentrations at Industrial and Vehicular Sites in Panipat (2020-2022) Compared to CPCB NAAQS Permissible Limit

Figure 2 Seasonal variations in NO_2 concentrations at the Industrial Site (IS) and Vehicular Site (VS) in Panipat from 2020 to 2022, compared with the NAQMS permissible limit. The bars represent the average concentrations for each season, with error bars showing the standard deviations. The green line denotes the permissible limit for NO_2 as per CPCB NAAQS standards.

$PM_{2.5}$ and PM_{10} Levels

Both $PM_{2.5}$ and PM_{10} levels were highest during the Post-monsoon period. In 2021, $PM_{2.5}$ levels were 77.73 ± 19.72 µg/m³ during Winter, 51.36 ± 12.30 µg/m³ during Pre-monsoon, and 69.48 ± 18.41 µg/m³ during Post-monsoon as shown in figure 4. For PM_{10}, the concentrations were 112.83 ± 28.40 µg/m³ in Winter, 83.52 ± 21.59 µg/m³ in Pre-monsoon, and 130.15 ± 51.48 µg/m³ in Post-monsoon as shown in figure 5. In 2022, $PM_{2.5}$ levels were 63.05 ± 16.84 µg/m³ in Winter, 47.10 ± 9.86 µg/m³ in Pre-monsoon, and 92.61 ± 26.93 µg/m³ in Post-monsoon. Similarly, PM_{10} levels were 94.72 ± 15.36 µg/m³ in Winter, 82.28 ± 13.88 µg/m³ in Pre-monsoon, and 119.77 ± 32.95 µg/m³ in Post-monsoon. The high levels of PM in Post-monsoon are likely due to a combination of agricultural residue burning and stagnant atmospheric conditions, trapping pollutants near the surface. This is in line with studies showing the correlation between post-monsoon conditions and increased particulate matter in the Indo-Gangetic Plain, influenced by crop residue burning and vehicular emissions.

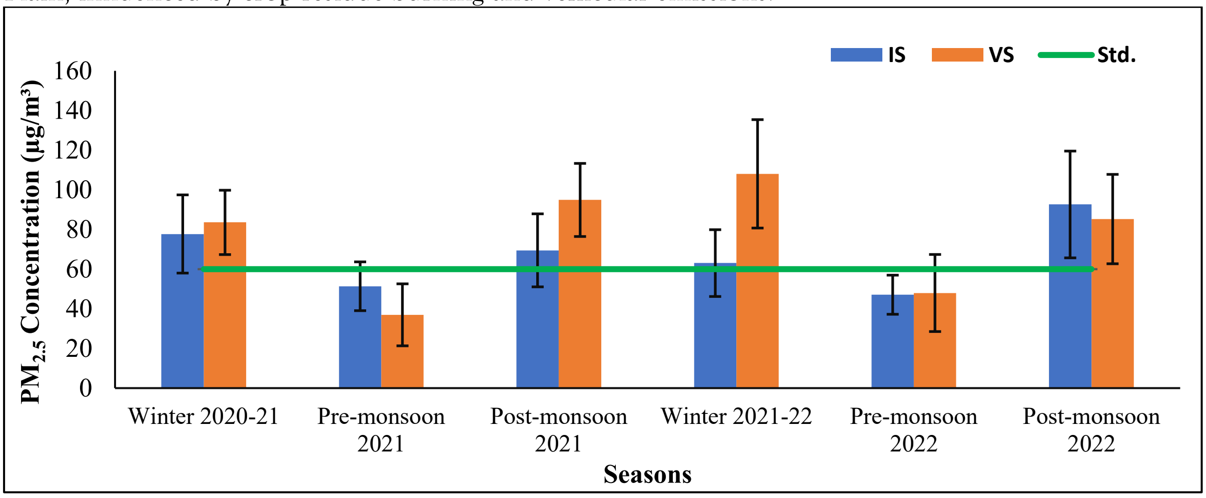

Figure 4: Seasonal Variations in $PM_{2.5}$ Concentrations at Industrial and Vehicular Sites in Panipat (2021-2022) Compared to CPCB NAAQS Permissible Limit

Figure 3. Seasonal variations in $PM_{2.5}$ concentrations at the Industrial Site (IS) and Vehicular Site (VS) in Panipat during 2021-2022, compared with the CPCB NAAQS permissible limit. The bars represent the mean concentrations for each season, with error bars showing the standard deviations. The green line indicates the CPCB NAAQS permissible limit for $PM_{2.5}$.

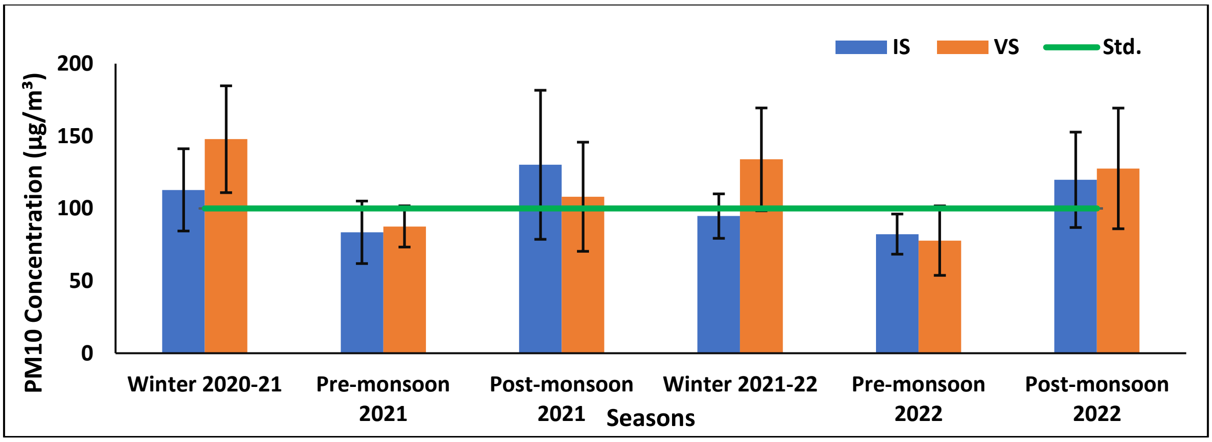

Figure 5: Seasonal Variations in PM_{10} Concentrations at Industrial and Vehicular Sites in Panipat (2021-2022) Compared to CPCB NAAQS Permissible Limit

Figure 4 Seasonal variations in PM 10 concentrations at the Industrial Site (IS) and Vehicular Site (VS) in Panipat from 2021 to 2022, compared with the NAQMS permissible limit. The bars represent the average concentrations for each season, with error bars showing the standard deviations. The green line denotes the permissible limit for PM 10 as per NAQMS standards.

CO and Pb Levels

CO levels remained relatively stable over the seasons, with the highest values observed in Post-monsoon. In 2021, CO concentrations were 1.26 ± 0.13 µg/m³ during Winter, 0.82 ± 0.13 µg/m³ during Pre-monsoon, and 1.92 ± 0.33 µg/m³ during Post-monsoon as shown in figure 6. In 2022, CO levels were 1.06 ± 0.11 µg/m³ in Winter, 0.86 ± 0.09 µg/m³ in Pre-monsoon, and 1.88 ± 0.27 µg/m³ in Post-monsoon. Similarly, Pb levels varied slightly across the seasons, with the highest Pb levels observed in Post-monsoon 2021 at 0.39 ± 0.21 µg/m³.

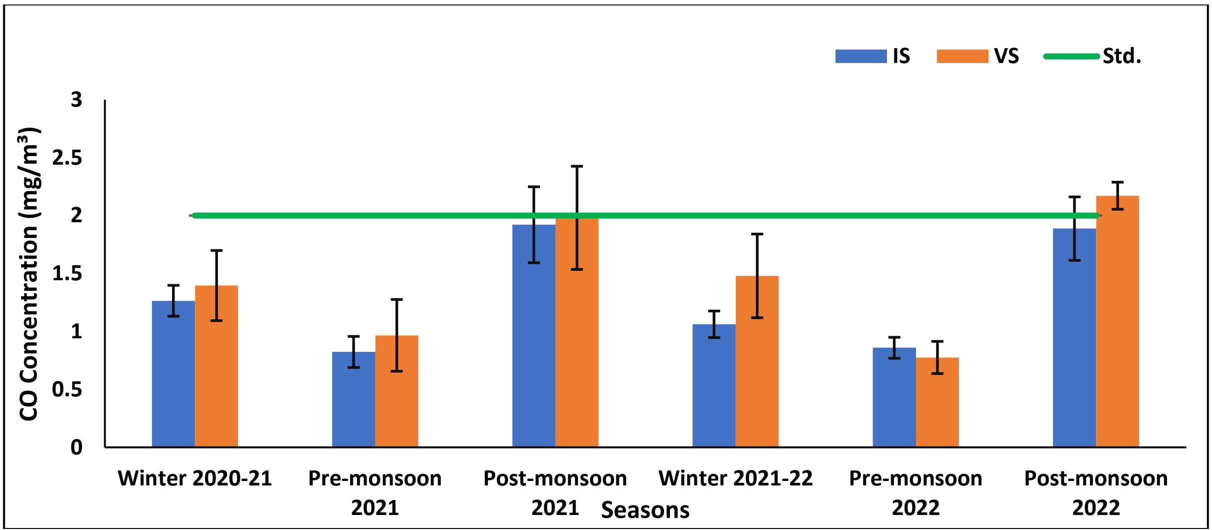

Figure 6: Seasonal Variations in CO Concentrations at Industrial and Vehicular Sites in Panipat (2021-2022) Compared to CPCB NAAQS Permissible Limit

Figure 5 Seasonal variations in CO concentrations at the Industrial Site (IS) and Vehicular Site (VS) in Panipat from 2021 to 2022, compared with the CPCB NAAQS permissible limit. The bars represent the average concentrations for each season, with error bars showing the standard deviations. The green line denotes the permissible limit for CO as per CPCB NAAQS standards.

3.2 Pollutant Concentration at the Vehicular Site (2021-2022)

SO_2 Levels

At the vehicular site, SO_2 levels were consistently lower than at the industrial site. In 2021, the levels were 49.77 ± 12.76 µg/m³ in Winter, 36.32 ± 7.86 µg/m³ in Pre-monsoon, and 56.03 ± 21.83 µg/m³ in Post-monsoon. In 2022, SO_2 concentrations were 33.41 ± 14.94 µg/m³ during Winter, 33.86 ± 10.74 µg/m³ in Pre-monsoon, and 40.94 ± 15.63 µg/m³ in Post-monsoon. The results suggest that vehicular emissions do not contribute significantly to SO_2 levels compared to industrial sources.

NO_2 Levels

NO_2 concentrations at the vehicular site were notably higher during Post-monsoon. In 2021, the levels were 68.17 ± 24.22 µg/m³ in Winter, 53.73 ± 22.75 µg/m³ in Pre-monsoon, and 118.08 ± 35.38 µg/m³ in Post-monsoon. In 2022, NO_2 levels were 70.89 ± 18.76 µg/m³ in Winter, 49.21 ± 17.26 µg/m³ in Pre-monsoon, and 103.53 ± 25.35 µg/m³ in Post-monsoon. The increase in NO_2 concentrations during Post-monsoon suggests that traffic emissions play a significant role in NO_X related pollution during this period.

$PM_{2.5}$ and PM_{10} Levels

$PM_{2.5}$ and PM_{10} concentrations at the vehicular site also showed seasonal variations, with the highest levels observed during Post-monsoon. In 2021, $PM_{2.5}$ concentrations were 83.57 ± 16.23 µg/m³ in Winter, 36.96 ± 15.63 µg/m³ in Pre-monsoon, and 94.89 ± 18.43 µg/m³ in Post-monsoon. For PM_{10}, concentrations were 147.81 ± 36.90 µg/m³ in Winter, 87.58 ± 14.25 µg/m³ in Pre-monsoon, and 108.08 ± 37.70 µg/m³ in Post-monsoon. In 2022, $PM_{2.5}$ levels were 108.07 ± 27.34 µg/m³ in Winter, 47.96 ± 19.43 µg/m³ in Pre-monsoon, and 85.25 ± 22.54 µg/m³ in Post-monsoon. PM_{10} concentrations were 133.91 ± 35.50 µg/m³ in Winter, 77.78 ± 24.00 µg/m³ in Pre-monsoon, and 127.65 ± 41.68 µg/m³ in Post-monsoon. These increases in particulate matter during Post-monsoon highlight the contribution of vehicular emissions to particulate pollution, especially during the pre-monsoon when vehicular traffic is at its peak.

CO and Pb Levels

CO concentrations at the vehicular site were highest during Post-monsoon, with values of 1.40 ± 0.30 µg/m³ in Winter, 0.97 ± 0.31 µg/m³ in Pre-monsoon, and 1.98 ± 0.45 µg/m³ in Post-monsoon in 2021. In 2022, the CO concentrations were 1.48 ± 0.36 µg/m³ in Winter, 0.78 ± 0.14 µg/m³ in Pre-monsoon, and 2.17 ± 0.12 µg/m³ in Post-monsoon. Pb levels were relatively consistent, but the highest levels were noted during Post-monsoon 2021 at 0.29 ± 0.12 µg/m³ as shown in figure 7.

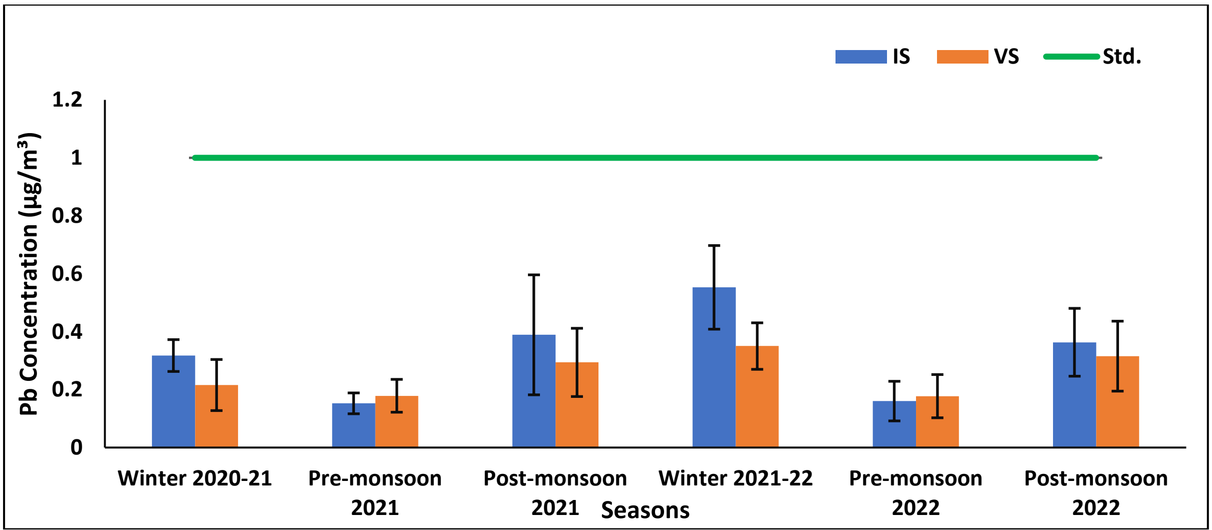

Figure 7: Seasonal Variations in Pb Concentrations at Industrial and Vehicular Sites in Panipat (2021-2022) Compared to CPCB NAAQS Permissible Limit

Figure 6 Seasonal variations in Pb concentrations at the Industrial Site (IS) and Vehicular Site (VS) in Panipat from 2021 to 2022, compared with the CPCB NAAQS permissible limit. The bars represent the average concentrations for each season, with error bars showing the standard deviations. The green line denotes the permissible limit for Pb as per CPCB NAAQS standards.

3.3 Meteorological Data and Its Influence on Pollutant Dispersion

The meteorological variables, including boundary layer height (BLH), relative humidity, wind speed, wind direction, temperature, and precipitation, play a significant role in the dispersion and accumulation of pollutants. The data collected from Panipat for the years 2021-2022 reveals distinct patterns across different seasons, influencing air quality. The boundary layer height (BLH), a key parameter that dictates pollutant dispersion, was highest during the Pre-monsoon season in 2021 and 2022, reaching values of 818.77 m and 713.58 m, respectively, allowing for greater vertical mixing and better dispersion of pollutants. In contrast, the Winter and Post-monsoon seasons, with BLH values of 197.7 m and 217.3 m in 2021, and 241.4 m and 217.3 m in 2021-22, showed significantly lower values, indicating restricted pollutant dispersion and higher pollutant accumulation near the surface, particularly in the Post-monsoon period.

Relative humidity was highest in Winter 2021-22 at 81.31%, likely contributing to the agglomeration of particulate matter such as $PM_{2.5}$ and PM_{10}, which could further exacerbate pollution. Lower humidity values in Pre-monsoon 2022 (37.63%) and 2021 (49.07%) likely contributed to drier conditions, which suspended dust and fine particles, particularly from agricultural activities. In contrast, Post-monsoon showed moderate humidity, potentially increasing particle aggregation, but not to the extent seen during Winter.

Wind speed is another critical factor affecting pollutant dispersion. The Pre-monsoon season exhibited the highest wind speeds in 2021 (0.76 m/s) and 2022 (0.69 m/s), facilitating better pollutant dispersion compared to the Post-monsoon and Winter seasons, where wind speed was as low as 0.52 m/s and 0.41 m/s in Winter 2021 and 2021-22 respectively while 0.46m/s and 0.58 m/s in Post-monsoon 2021 and 2022 respectively, leading to stagnant air and higher pollutant concentrations in post-monsoon seasons and winters

Wind direction indicated a consistent pattern of westerly winds during Winter (around 239° in 2021 and 192.82° in 2021-22), which may have carried pollutants from industrial sources towards residential areas. During the Post-monsoon periods, south-westerly winds (around 214.95° in 2021 and 205.45° in 2022, respectively) influenced pollutant transport over longer distances, depending on the proximity to pollution sources. During the pre-monsoon seasons, the wind direction was easterly to south-easterly (162.72° in 2021 and 187° in 2022).

Input of temperature was critical in air quality patterns. The Pre-monsoon temperatures were higher with a maximum of 36.03 °C in 2021 and 35.89 °C in 2022, which allowed industrial and vehicular emissions to be even higher when secondary pollutants such as ozone are produced. Also, high temperatures may stimulate the volatility of particulate matter, increasing the problems of air quality. In Winter, the temperature decrease (e.g., 13.31 °C in 2021) could have cooled down the activity of secondary pollutants; however, reduced BLH and less wind speed promoted the accumulation of the pollutant at the boundary layer, exacerbating the air quality situation.

The meteorological data suggests that the most polluted season in Panipat is during the Pre-monsoon and Post-monsoon, which is mainly because of raised temperatures, drop in humidity and wind direction shifts. These aspects, along with the low level of BLH increase the accumulation of pollutants especially $PM_{2.5}$ and PM_{10}. The evidence shows that the relative humidity, wind speed & direction, BLH and temperature are the key factors affecting the quality of air and outlines the necessity of the specific strategies of managing the air quality taking into consideration the meteorological settings and even human-made conditions.

3.4 Correlation Analysis of Meteorological Parameters and Air Pollutants

Spearman correlation analysis was performed (Figure 8 & 9) to determine the meteorological variables and air pollutants relationship of the Industrial Site (IS) and Vehicular Site (VS), Panipat. The NO_2 and $PM_{2.5}$ were found to be very strongly positively correlated ($r = 0.94$ with $p < 0.01$) at the Industrial Site implying both the pollutants concentrate in the same time and in similar periods indicating that the respiratory disease hazard increases in the Post-monsoon period with increased industrial activities. On the same note, both SO_2 ($r = 0.94$) and NO_2 ($r = 0.94$) correlating strongly and significantly ($p < 0.01$) with PM_{10} supports the argument that industrial emissions contribute to particulate and gaseous pollutants. There was an inverse correlation between wind speed and pollutant levels at the two sites since the strongest negative correlation was at the Vehicular Site with significant one was with $PM_{2.5}$. There were lower wind speeds during the Post-monsoon period at the Vehicular site which resulted in an increase in the concentrations of $PM_{2.5}$ ($r = -0.94$ with $p < 0.01$) because there was inability to pollute other locations. This observation demonstrates the fact that stagnant conditions of air increase the number of pollutants in those sections of infrastructure where there is extensive movement of traffic. A positive effect between relative humidity and PM_{10} was found at both sites, which was significant at the Vehicular Site with $p < 0.05$. Such indicates higher humidity might be a reason causing agglomeration of particulate matter. Also, the humidity and CO were found to show statistically insignificant correlation with $p > 0.05$. There was significant and negative correlation between temperature and PM_{10} ($r = -0.89$ at $p < 0.05$) at the Vehicular Site, therefore this indicated that a higher temperature may play a role in suspending the particulate matter in the air. This can be especially relevant in times, when there is less atmospheric mixing, during colder months.

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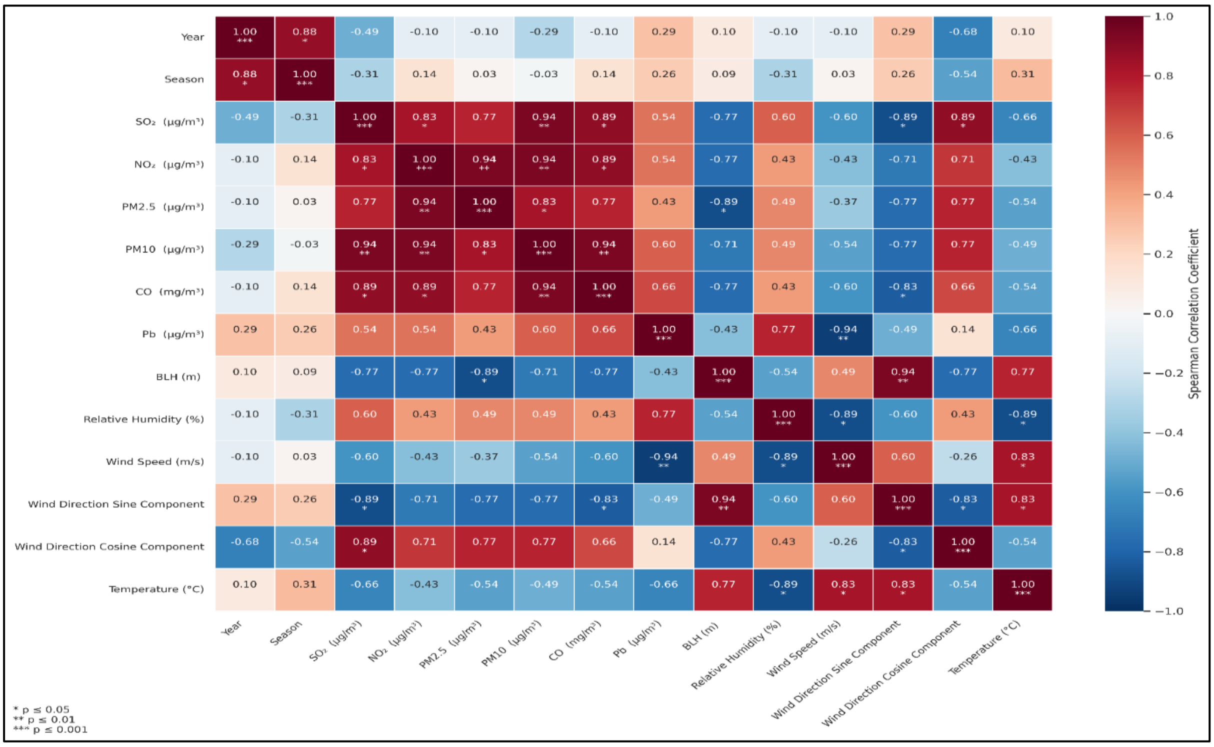

Figure 8: Correlation Matrix of Meteorological Parameters and Air Pollutants at Industrial Site in Panipat (2021-2022)

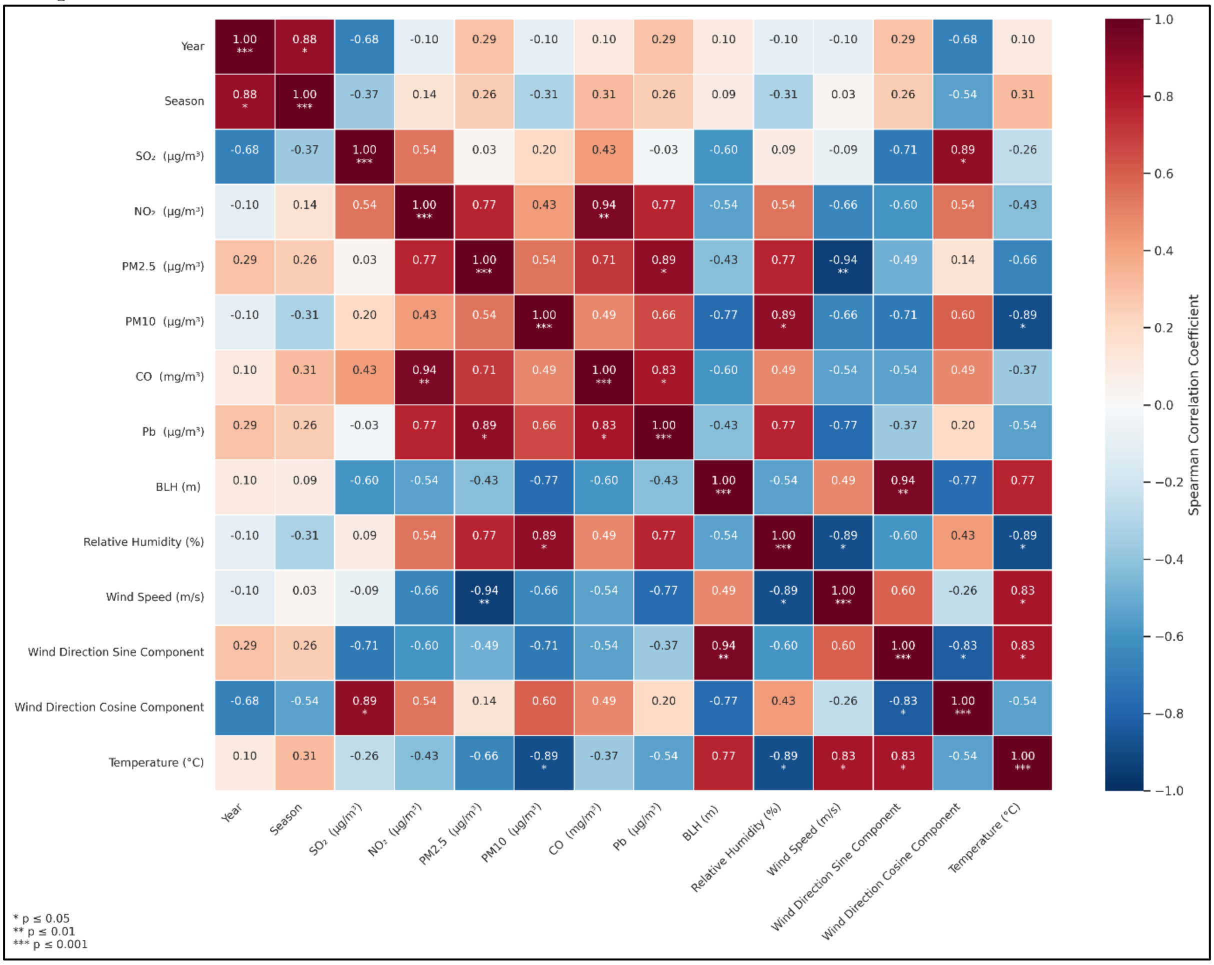

Figure 9: Correlation Matrix of Meteorological Parameters and Air Pollutants at Vehicular Site in Panipat (2021-2022)

Figure 7&9 Correlation matrices showing the relationships between various meteorological parameters and air pollutants (SO_2, NO_2, $PM_{2.5}$, PM_{10}, CO, and Pb) at the Industrial Site (IS) and Vehicular Site (VS) in Panipat from 2021 to 2022. The colour scale represents the strength of correlation, with red indicating a strong positive correlation and blue indicating a strong negative correlation. The values indicate the strength of the correlation between each pair of variables, with significant relationships marked by star annotations between meteorological factors and pollutant concentrations

The Boundary Layer Height (BLH) showed a negative correlation with both PM_{10} and $PM_{2.5}$ at the Industrial Site, highlighting that lower BLH values during the Winter and Post-monsoon seasons result in the trapping of pollutants near the surface, worsening air quality. Lastly, the wind direction components had a positive but insignificant correlation with NO_2 but significant and positive correlation between SO_2 and wind direction cosine component was observed at vehicular site indicating that wind direction influences the transport of pollutants, particularly from industrial and vehicular sources, like SO_2 pollution can be seen associated with winds blowing from the east direction (or towards the west). In conclusion, the correlation analysis demonstrates the significant impact of meteorological factors such as temperature, wind speed & direction, relative humidity, and boundary layer height on the dispersion and accumulation of air pollutants. These findings suggest that air quality management strategies for Panipat should consider the seasonal variations in meteorological conditions alongside the primary sources of pollution.

3.5 Discussion of Key Findings

The trend in air quality and meteorological measurements in the industrial site and vehicular site within Panipat depicts some important seasonal trends which have a bearing on pollutant measurements. The post-monsoon conditions that are represented by the lower winds, higher temperatures and humidity have a strong correlation with high concentration of PM_{10}, $PM_{2.5}$, and NO_2. This weather situation led to ineffective expenditure and elevated levels of atmospheric stagnation making air contamination levels high in the season. The conditions during post-monsoon are also characterized by scarce vertical mixing, as the conditions associated with a low boundary layer height (BLH) trap contaminants close to the ground, as the air quality continues to worsen further (Kumar et al., 2020; Ravish & Chaudhry, 2024). The Post-monsoon season in the industry site showed seasonal emissions of industrial activities which were in conjunction with meteorological conditions that enhanced pollution. High concentration of SO_2 and PM was especially prominent, because Post-monsoon is a time of enhanced production in the industries, along with calm air situation. Here, the issue of temperature inversion and trapping of pollutants can be further experienced as these led to an increased concentration of industrial emissions. At the vehicular location, the contribution of vehicles emission to the NO_2, $PM_{2.5}$, and CO pollution was more evident, especially in the Post-monsoon season. The sensitivity of traffic growth to influential factors during this period such as medium temperatures and low wind speeds, was aligned with the elevated levels of pollutants. The low winds speeds of Post-monsoon did not give time to disperse the emission, and the pollutants were accumulated close to the ground and it is also likely that the low to medium temperatures promoted the reaction with secondary pollutants such as NO_2 and CO. Also, low relative humidity observed during the Pre-monsoon is credited in rising the amount of particulate matter owing to suspension of dust at both the sites thus aggravating the overall air quality at the sites. Crop residue burning during the Winter months did contribute a minor part to increasing the particulate matter concentrations. Although Winter is not usually a high season of crop residue burning, the agricultural waste that remains are still burnt especially in Indo-Gangetic Plain region, including Panipat and its surrounding districts. This combustion adds to the presence of PM_{10} and $PM_{2.5}$ particularly when weather conditions, including low BLH and calm air, do not allow the productive activity of smoke. Although burning of crop residues in Winter is not as major a contributor to particulate matter levels as during the Post-monsoon period, it still contributes significantly when combined with industrial and vehicular emissions. Bio decomposers are a sustainable means of handling agricultural wastes as an alternative to open burning of crop remnant (Ravish & Chaudhry, 2025). This process helps eradicate the burning process which in effect reduces the emission of PM and becomes more helpful in terms of soil health. With the promotion of bio-decomposers for sustainable agriculture, the impact of crop residue burning on air quality in areas like Panipat where this practice is widespread could be significantly reduced. The results underscore the importance of meteorological variables, namely, wind speed, temperature and relative humidity, in dispersion and accumulation of pollutants. The movement of pollutant was directly dependant on the wind speed and the conditions were particularly unfavourable during Post-monsoons since the wind was stagnant and the BLH was low with little possibility of the pollutants escaping by rise to higher altitudes (Garsa et al., 2023; Soni et al., 2024). The Pre-monsoon heat also contributed to the production of pollutants, especially those from vehicle emissions and industrial operations. Additionally, fine particles agglomerated due to higher humidity levels in Winter, which increased $PM_{2.5}$ and PM_{10} concentrations. There were strong correlations between air pollutants and meteorological parameters. Temperature showed a positive correlation with $PM_{2.5}$ and PM_{10}, contributing to increased pollutant formation, especially during the Post-monsoon season. Wind speed was negatively associated with pollutant levels, as lower wind speeds in the Post-monsoon period led to poor dispersion and higher pollutant accumulation. Relative humidity showed a positive relationship with $PM_{2.5}$, promoting the agglomeration of fine particles, particularly during Winter and Post-monsoon. These observations highlight the critical role of meteorological conditions in determining air quality. The results underscore the urgent need for action, particularly by focusing on interventions such as regulating industrial emissions, improving traffic management, and investing in green infrastructure. Additionally, promoting the use of bio-decomposers as an alternative to crop residue burning is a key strategy to mitigate seasonal pollution peaks in Panipat. The findings further emphasize the importance of incorporating meteorological factors into the development of air quality management and climate action plans. Understanding seasonal patterns and the meteorological drivers of pollution enables the implementation of more targeted and effective measures to combat poor air quality in Panipat. Strategies should particularly account for factors such as seasonal low wind speeds, high temperatures, agricultural burning, and industrial emissions, which tend to be most prominent during the Post-monsoon and Pre-monsoon periods. In conclusion, Panipat requires a holistic approach to achieving cleaner air, one that integrates meteorological insights with pollution control measures such as reducing emissions from industries and heavy vehicles, and adopting sustainable practices like use of electrical vehicles. To reduce air pollution in Panipat, it is important to encourage the use of electric vehicles (EVs) and improve fuel efficiency standards for vehicles to lower emissions. Industries should also adopt green technologies and cleaner fuels, such as renewable energy, to reduce harmful emissions and improve air quality. This integrated strategy will help foster a cleaner and greener environment for the community.

CONCLUSION

The aim of the present study was to assess the spatial and seasonal variations in air pollution severity and their correlation with meteorological factors across two locations in Panipat: The Industrial Site (IS) and the Vehicular Site (VS), during the period from 2021-2022. The findings reveal significant seasonal fluctuations in pollutant levels, with the highest concentrations of $PM_{2.5}$, $PM_{10,}$ NO_2, and SO_2 observed during the Post-monsoon season. These results align with meteorological conditions typical of that period, such as low wind speeds, elevated temperatures, and high humidity, which hinder pollutant dispersion and cause accumulation near the surface. Emissions from anthropogenic activities particularly at the Industrial Site were identified as major contributors to elevated levels of SO_2, PM_{10}, and $PM_{2.5}$ during the Post-monsoon period. Similarly, the Vehicular Site showed a higher contribution from traffic-related emissions, with NO_2, CO, and $PM_{2.5}$ exhibiting pronounced seasonal variation, especially in the Post-monsoon season. Correlation analysis demonstrated the significant role of meteorological factors such as wind speed, temperature, and relative humidity in influencing the dispersion and accumulation of pollutants. For instance, low wind speeds and warm conditions were found to be strongly associated with elevated pollutant levels, particularly between the Post-monsoon and Pre-monsoon seasons. Another crucial factor was the Boundary Layer Height (BLH), with lower BLH values during these seasons leading to greater stagnation of pollutants. These findings underscore the need for targeted air quality management policies in Panipat, addressing both industrial and vehicular pollution sources. Strengthening regulatory mechanisms to control emissions from these sectors while accounting for meteorological influences could significantly improve air quality in the region. In summary, this study highlights the dynamic relationship between meteorological conditions and air pollution in Panipat. The results can serve as a framework for more effective air quality management and public health protection. Integrating meteorological data into decision-making processes for pollution control will be essential for addressing the air pollution challenges faced by medium-sized cities like Panipat and for achieving cleaner air for the city and its surroundings.

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