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Seasonal Variation of Particulate Matter ($PM_{2.5}$ and PM_{10}) in Delhi

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Abstract- This study investigates the seasonal variability of particulate matter ($PM_{2.5}$ and PM_{10}) concentrations across three distinct sites in Delhi in the year 2024—Rohini (residential), Karol Bagh (heavy-traffic), and Wazirpur (industrial)—to assess the influence of meteorological conditions and localized emission sources. Results revealed a consistent seasonal trend of Winter > Post-Monsoon > Summer > Monsoon across both $PM_{2.5}$ and PM_{10}. The highest concentrations were observed in winter, with Rohini peaking at 211.14 µg/m³ ($PM_{2.5}$) and 314.27 µg/m³ (PM_{10}), indicating strong accumulation under low temperature and high humidity. In Karol Bagh, maximum winter values reached 158.72 µg/m³ ($PM_{2.5}$) and 275.58 µg/m³ (PM_{10}), while Wazirpur recorded 173.51 µg/m³ ($PM_{2.5}$) and 250.54 µg/m³ (PM_{10}). The pronounced winter peak can be attributed to temperature inversions, lower boundary layer height, and increased biomass burning, all of which restrict vertical mixing and trap pollutants near the surface. In contrast, higher temperatures and stronger winds in summer enhanced atmospheric dispersion, while monsoonal rainfall facilitated wet scavenging, thereby reducing particulate load. Seasonal minima were observed during the monsoon, with the lowest $PM_{2.5}$ at Karol Bagh (58.06 µg/m³) and the lowest PM_{10} at Karol Bagh (95.05 µg/m³), reflecting effective wet deposition. Wazirpur, however, maintained comparatively elevated monsoon levels (110.22 µg/m³ $PM_{2.5}$; 198.45 µg/m³ PM_{10}), suggesting persistent industrial emissions. Post-monsoon concentrations again increased, particularly at Rohini (160.57 µg/m³ $PM_{2.5}$) and Wazirpur (199.59 µg/m³ PM_{10}), consistent with regional biomass burning and reduced rainfall. This study demonstrates how temporal and spatial analysis of air quality data, supported by statistical techniques, is critical for formulating targeted, evidence-based policies that align with sustainable development goals and safeguard public health in megacities like Delhi.

Key words: Air Pollution, Particulate Matter, $PM_{2.5}$, PM_{10}, Seasonal Variations, Delhi

1. Introduction

Air pollution is a pressing global concern, with urban areas like Delhi experiencing severe challenges due to rapid industrialization and population growth. Exposure to fine particulate matter ($PM_{2.5}$ and PM_{10}) is linked to millions of premature deaths annually, impacting respiratory and cardiovascular health [1, 2]. Delhi consistently ranks among the world's most polluted cities, frequently exceeding National Ambient Air Quality Standards (NAAQS) due to factors like vehicular emissions, industrial activity, and seasonal crop residue burning [3, 4]. Particulate matter, suspended aerosols varying in size and origin, dominates urban pollution. $PM_{2.5}$, particles smaller than 2.5 µm, is particularly hazardous as it penetrates deep into the lungs and bloodstream [5]. In Delhi, $PM_{2.5}$ levels can surge to 8 times the permitted limit in winter, driven by meteorological conditions like temperature inversions and stagnant winds that trap pollutants near the surface [6, 7]. Conversely, monsoon rainfall facilitates wet scavenging, significantly reducing particulate concentrations [8]. Understanding seasonal aerosol dynamics is therefore crucial. Annual averages obscure drastic seasonal variations influenced by distinct meteorological and anthropogenic patterns—such as winter heating and post-monsoon agricultural burning [9]. A season-specific analysis is essential for predicting pollution peaks, issuing public alerts, and designing effective, targeted mitigation strategies for sustainable urban development [10].

Seasonal variations in particulate matter are well-documented in Indian cities, with consistent peaks in winter/post-monsoon and troughs in monsoon. Studies across diverse urban landscapes—from Raipur and Udaipur to Visakhapatnam—confirm this pattern, attributing winter highs to atmospheric stability, biomass burning, and low wind speeds, while monsoon lows are due to wet deposition [11-14]. In Delhi specifically, research highlights the acute winter pollution crisis. Gaur et al. (2020) observed $PM_{2.5}$ levels often surpassing 300 µg/m³ in winter, while Pandey et al. (2022) noted a significant drop during monsoon rains [15, 16]. The post-monsoon resurgence is strongly linked to regional crop residue burning [17]. Furthermore, source apportionment studies indicate that while vehicular emissions are a year-round contributor, colder months see increased contributions from biomass and coal burning [18]. These findings underscore the compounded impact of meteorological factors and seasonal emission sources, necessitating localized and temporal analysis for effective policy intervention.

2. Methodology

This study focuses on Delhi, India's capital and one of the most polluted and densely populated cities in the world. Situated in the Indo-Gangetic Plain, Delhi experiences distinct seasonal variations that strongly affect aerosol patterns. With over 20 million

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residents, the city faces persistent air pollution from traffic, industries, construction dust, open waste burning, and seasonal crop residue fires in nearby states. Its basin-like geography often traps pollutants, especially in winter under temperature inversions. These combined geographic and human factors make Delhi a critical case for studying seasonal aerosol variability in an urban Indian context. This study analyzed $PM_{2.5}$and PM_{10} concentrations across three representative sites in Delhi in 2024: Rohini (residential), Karol Bagh (heavy traffic), and Wazirpur (industrial). Daily 24-hour average pollutant concentration data and meteorological parameters (temperature, relative humidity, wind speed) were obtained from the AQI India portal for the full calendar year. Data were processed in Microsoft Excel to calculate monthly and seasonal averages. Seasons were defined as: Winter (December-February), Summer/Pre-Monsoon (March-May), Monsoon (June-August), and Post-Monsoon (September-November). This approach enabled the identification of seasonal pollution patterns and the assessment of meteorological influences.

Figure 1: Map showing the three study sites in Delhi: Rohini, Karol Bagh, and Wazirpur.

3. Results and Discussions

3.1. Seasonal Variation of $PM_{2.5}$ in the year 2024

Table 1: Seasonal Average Concentrations of $PM_{2.5}$ (in µg/m^3)

ason	hini	rol Bagh	azirpur
inter	1.14	8.72	3.51
mmer	.17	.47	.18
onsoon	.75	.06	0.22
st Monsoon	0.57	8.93	4.21

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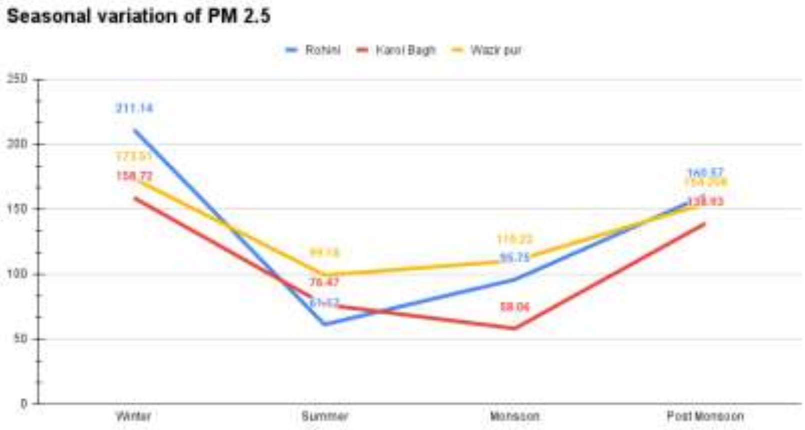

Figure 2: Seasonal Average Concentrations of $PM_{2.5}$

3.2. Seasonal Variation of PM_{10} in the year 2024

Table 2: Seasonal Average Concentrations of PM_{10} (in µg/m^3)

ason	hini	rol Bagh	azirpur
inter	4.27	5.58	0.54
mmer	8.67	0.68	3.31
onsoon	1.88	.05	8.45
st Monsoon	1.16	1.56	9.59

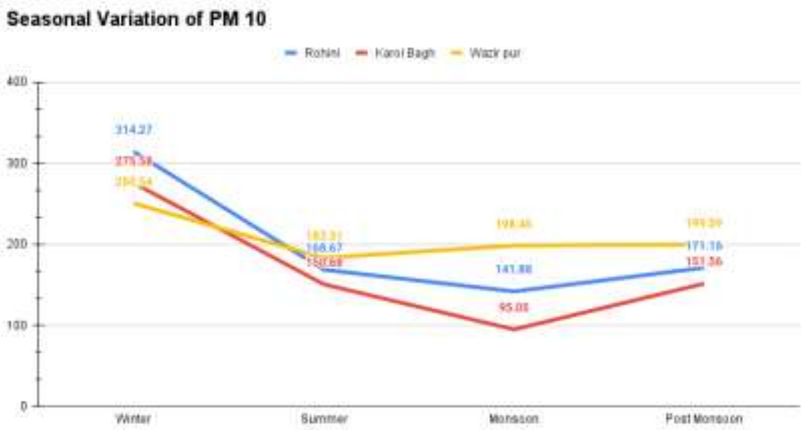

Figure 3: Seasonal Average Concentrations of PM10

The seasonal variation of $PM_{2.5}$ and PM_{10} across Rohini (residential), Karol Bagh (traffic

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dominated), and Wazirpur (industrial) is shown in Figures 2 and 3. Both $PM_{2.5}$ and PM_{10} concentrations were highest in winter across all sites. Rohini recorded the highest $PM_{2.5}$ (211.14 µg/m3) and PM10 (314.27 µg/m3), followed by Wazirpur ($PM_{2.5}$: 173.51 µg/m3; PM_{10}: 250.54 µg/m3) and Karol Bagh ($PM_{2.5}$: 158.72 µg/m3; PM_{10}: 275.58 µg/m3). Concentrations decreased sharply during summer, with Rohini showing the lowest PM2.5 (61.17 µg/m3), while Wazirpur recorded relatively higher values ($PM_{2.5}$: 99.18 µg/m3; PM_{10}: 183.31 µg/m3). The lowest PM_{10} levels were observed at Karol Bagh (95.05 µg/m3), while Rohini showed the lowest $PM_{2.5}$ (95.75 µg/m3) during the monsoon. Wazirpur exhibited the highest monsoon values for both fractions ($PM_{2.5}$: 110.22 µg/m3; PM_{10}: 198.45 µg/m3). Concentrations increased again after the monsoon, with Rohini ($PM_{2.5}$: 160.57 µg/m3; PM_{10}: 171.16 µg/m3) and Wazirpur ($PM_{2.5}$: 154.20 µg/m3; PM_{10}: 199.59 µg/m3) showing higher values than Karol Bagh. Overall, seasonal variation followed the trend: Winter > Post-Monsoon > Summer > Monsoon, consistent across all sites and both PM fractions. The seasonal and site-specific variations observed can be explained by a combination of meteorological factors and local emission sources. Low temperature and higher relative humidity in winter promote atmospheric stability and hinder vertical dispersion of pollutants. In addition, residential heating, increased biomass burning, and stagnant winds likely contributed to higher PM concentrations, with Rohini (residential) showing the highest winter values, possibly linked to local biomass combustion and domestic activities. In summer, higher temperature and stronger winds favored atmospheric mixing and dilution of pollutants. All three sites recorded a sharp drop, but Wazirpur maintained comparatively higher values, likely due to continuous industrial emissions. During the monsoon, wet deposition due to rainfall substantially reduced particulate matter concentrations. However, Wazirpur still showed elevated PM_{10} and $PM_{2.5}$ compared to Rohini and Karol Bagh, indicating persistent emissions from industrial activity that are less affected by washout. Post-monsoon concentrations increased again, likely due to crop residue burning in surrounding regions, reduced rainfall, and moderate winds. Both Rohini and Wazirpur exhibited higher post-monsoon PM levels compared to Karol Bagh, suggesting that local and regional emission sources reinforced background concentrations. Site-specific patterns were also evident: Rohini (residential) showed strong seasonal contrast with sharp winter peaks and summer lows, demonstrating greater sensitivity to meteorological changes; Karol Bagh (traffic-dominated) had the lowest monsoon values, reflecting effective washout of traffic-related dust and soot; while Wazirpur (industrial) maintained consistently higher background levels across all seasons, especially during monsoon, indicating the continuous impact of industrial emissions.

4. Conclusion

This study highlighted the pronounced seasonal variation of $PM_{2.5}$ and PM_{10} concentrations across three representative sites in Delhi—residential (Rohini), traffic-dominated (Karol Bagh), and industrial (Wazirpur). Results consistently showed the highest concentrations during winter due to unfavorable meteorological conditions and increased emissions, while the lowest levels were recorded in the monsoon owing to rainfall-induced washout. Wazirpur exhibited persistently elevated concentrations across seasons, underscoring the continuous influence of industrial activity, whereas Rohini and Karol Bagh displayed stronger seasonal contrasts influenced by local domestic and traffic-related sources. The study reinforces the importance of temporal and spatial statistical analysis of air quality in identifying critical pollution periods and site-specific vulnerabilities. Such insights are crucial for evidence-based policy interventions aimed at sustainable urban development and protecting public health in megacities like Delhi.

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