FIVE-YEAR $PM_{2.5}$ TRENDS IN LAHORE: A MONTHLY AND ANNUAL OVERVIEW (2019–2023)

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ABSTRACT: This study presents a comprehensive analysis of monthly and yearly average $PM_{2.5}$ concentrations in Lahore, Pakistan, from 2019 to 2023, utilizing data sourced from IQAir. The research aims to understand the influence of meteorological parameters on air quality trends and to identify significant patterns and shifts in pollution levels over the five-year period. Results reveal a distinct seasonal cycle, with peak pollution occurring during the colder, stagnant winter months (October-February) characterized by lower temperatures, reduced wind speeds, and frequent temperature inversions. Conversely, the lowest $PM_{2.5}$ concentrations are observed during the warmer, rainy summer months (May-August) due to enhanced atmospheric dispersion and wet deposition. Year-on-year comparisons indicate a persistent air quality challenge, with a concerning escalation in peak pollution levels observed in November 2023, recording the highest monthly average in the dataset. The analysis also highlights the temporary air quality improvements during the COVID-19-induced economic slowdown in 2020, followed by a rebound and increase in pollution levels as economic activity resumed. This study underscores the critical need for more aggressive and sustained emission control measures in Punjab to mitigate the adverse impacts of air pollution on public health and the environment.

Key words: $PM_{2.5}$, COVID, Economic Activity, Meteorology, Lahore.

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INTRODUCTION

Air pollution, particularly fine particulate matter ($PM_{2.5}$), poses a significant environmental and public health challenge in Lahore, Pakistan. The city frequently experiences severe air quality degradation, especially during specific seasons. Lahore has consistently ranked among the world's most polluted cities over the last decade (Khan *et al*., 2023; Majeed *et al*., 2024). Globally, poor atmospheric quality critically impacts human health, biodiversity, ecosystems, and regional climate (Kim *et al*., 2015; Monks *et al*., 2009; Allabakash *et al*., 2022). The World Health Organization (WHO) reports that metropolitan areas are at higher risk, with respiratory ailments accounting for a large percentage of chronic diseases (Jahanzaib *et al*., 2023; Sharma *et al*., 2022; Asif *et al*., 2018). This alarming air quality significantly impacts human health, contributing to respiratory ailments, cardiovascular diseases, and other chronic conditions (Kampa & Castanas, 2008). Developing nations like Pakistan are at higher risk due to rapid industrial and urban growth, vehicular exhaust, insufficient air quality standards, and reliance on obsolete technology in high-density population areas (Butt *et al*., 2018; Kermani *et al*., 2021). The Pakistan Air Quality Index (AQI) in cities like Lahore often does not meet WHO air quality guidelines, particularly during winter and autumn seasons (Farrow *et al*., 2020; PAQI, 2018).

The problem is particularly acute in South Asia, which has officially outpaced other regions as the world's most polluted (Majeed *et al*., 2024). Intense air pollution episodes have become so frequent and pervasive that they are colloquially referred to as "the fifth season" (Majeed *et al*., 2024). These episodes are characterized by high concentrations of air pollutants and low visibility, leading to severe socio-economic disruptions. Despite the recognized severity, comprehensive, granular, and real-time understanding of pollution levels, their drivers, and the efficacy of mitigation strategies across the entire province remains a significant research gap, partly due to limited ground-based monitoring stations (Khan *et al*., 2023; Majeed *et al*., 2024).

This analysis provides an in-depth examination of Lahore's monthly and yearly average $PM_{2.5}$ concentrations from 2019 to 2023, with a focus on understanding the influence of meteorological parameters and identifying trends over time. The data utilized for this analysis was sourced from IQAir, a widely recognized platform for real-time and historical air quality

information, aiming to contribute to the understanding of this critical environmental issue in Lahore.

METHODOLOGY

The $PM_{2.5}$ concentration data for Lahore, covering the period from January 2019 to December 2023, was extracted from the IQAir historical data archives. This dataset comprises monthly average concentrations expressed in micrograms per cubic meter (µg/m3). The data was then organized into a tabular format to facilitate direct comparison across months and years. For visual representation, a bar chart was generated to illustrate monthly variations for each year, alongside a polynomial trendline for the year 2023 to highlight the seasonal pattern. The analysis of meteorological influence is based on general knowledge of Lahore's climate patterns, including seasonal temperature variations, wind speeds, precipitation (monsoon), and the occurrence of temperature inversions. Statistical comparisons involve observing the magnitude and consistency of $PM_{2.5}$ levels across different periods.

RESULTS AND DISCUSSION

The analysis of Lahore's $PM_{2.5}$ data from 2019 to 2023 reveals a pronounced seasonal pattern and notable year-on-year variations, largely influenced by prevailing meteorological conditions.

Seasonal $PM_{2.5}$ Trends and Meteorological Influence:

- **Winter (October - February):** Peak Pollution Period $PM_{2.5}$ concentrations are consistently highest during these months, with peaks typically observed in November and December. For instance, December 2023 recorded the highest monthly average at 251 µg/m3, while November 2021 and 2022 also showed concentrations exceeding 190 µg/m3. January consistently registers high levels, often above 130 µg/m3. This period aligns with Lahore's winter, characterized by lower temperatures which lead to a reduced mixing layer height, effectively trapping pollutants closer to the ground. Reduced wind speeds further limit the horizontal dispersion of pollutants, allowing them to accumulate. The frequent occurrence of temperature inversions acts as an atmospheric lid, preventing vertical mixing and exacerbating pollutant concentration. These stagnant atmospheric conditions, combined with increased emissions from residential heating (biomass burning), agricultural stubble burning (especially in October/November), and persistent vehicular/industrial emissions, contribute to the severe "smog" phenomenon.

- **Spring (March - April): Transition and Improvement** A significant decline in $PM_{2.5}$ levels is observed from March to April. Monthly averages in March range from 47 to 85.6 µg/m3, further dropping in April to between 31.4 and 69.3 µg/m3. This improvement is primarily due to **rising temperatures** and changing wind patterns that facilitate better atmospheric dispersion.

- **Summer (May - August): Lowest Pollution Period** The lowest $PM_{2.5}$ concentrations are consistently recorded during these months, often falling below 50 µg/m3. July and August frequently represent the cleanest months, with July 2021 recording a low of 27.9 µg/m3. This cleaner air is attributed to high temperatures promoting atmospheric instability and vertical mixing, stronger winds aiding pollutant transport, and crucially, monsoon rains (July-August) which effectively wash pollutants out of the atmosphere through wet deposition.

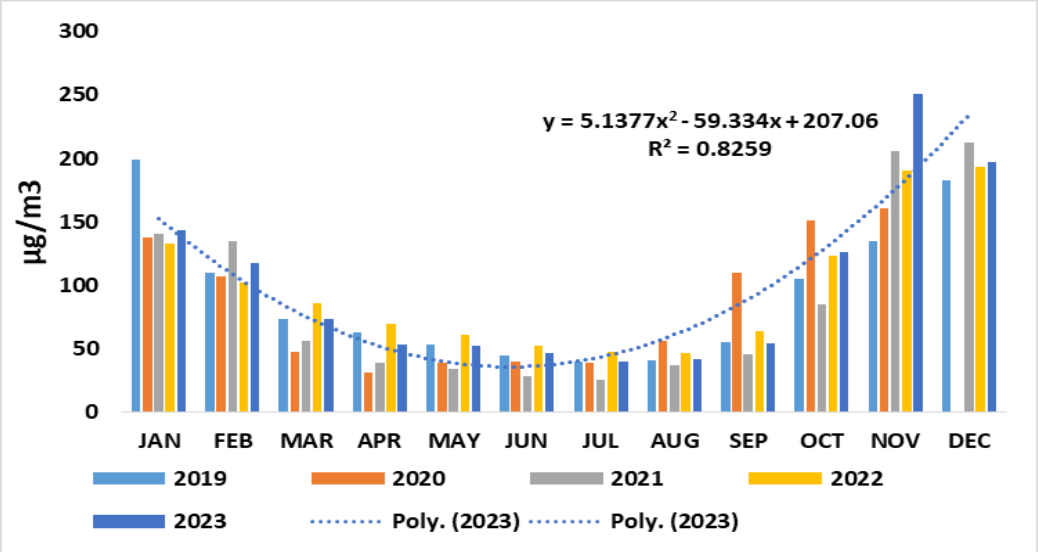

Figure 1: Monthly trend of $PM_{2.5}$ in Lahore (2019-2023)

Autumn (September - October): Gradual Increase $PM_{2.5}$ levels begin to rise gradually in September and accelerate sharply in October. October averages range from 85.1 to 151.3 µg/m3. This period marks the transition from the monsoon to winter, where decreasing temperatures, reduced rainfall, and weakening winds create conditions conducive to pollutant accumulation, often compounded by the onset of agricultural residue burning.

Annual $PM_{2.5}$ Trends and Socio-Economic Influences (2019-2023): The annual average $PM_{2.5}$ concentrations for Lahore show a fluctuating but generally upward trend over the five-year period, with a notable dip in 2020 that can be directly linked to the global COVID-19 pandemic and its associated economic slowdown.

- **2019: Baseline (91.8 µg/m³)** This year serves as a pre-pandemic baseline, showing a high annual average $PM_{2.5}$ concentration, indicative of Lahore's persistent air quality challenges even before the widespread impact of COVID-19.

- **2020: The COVID-19 Effect (83.6 µg/m³)** Lahore experienced its lowest annual average $PM_{2.5}$ concentration in this dataset during 2020, dropping to 83.6 µg/m³ from 91.8 µg/m³ in 2019. This significant decline is largely attributable to the strict and moderate lockdowns implemented globally and within Pakistan in response to the COVID-19 pandemic. These measures led to a substantial decline in economic activity, resulting in:

  - **Reduced Vehicular Activity:** Restrictions on movement and public transport significantly decreased tailpipe emissions.

  - **Industrial Shutdowns/Slowdowns:** Many factories and industrial units either ceased operations or ran at reduced capacities, leading to a drop in industrial emissions.

  - **Decreased Commercial Activity:** General economic slowdown meant less energy consumption from commercial sectors. This period demonstrated a clear, albeit temporary, improvement in air quality directly linked to the sharp decline in anthropogenic activities, highlighting the substantial contribution of human-related emissions to Lahore's air pollution.

- **2021: Partial Rebound and Continued Impact (86.8 µg/m³)** The annual average $PM_{2.5}$ concentration slightly increased in 2021 to 86.8 µg/m³. This suggests a partial rebound in economic activity as lockdown measures eased and life began to return to some semblance of normalcy. However, the concentration remained lower than the 2019 baseline. This could be due to lingering economic impacts, persistent behavioral changes (e.g., increased remote work), or a delayed recovery in certain economic sectors.

- **2022: Significant Increase (97.4 µg/m³)** $PM_{2.5}$ levels saw a substantial jump in 2022, reaching 97.4 µg/m³. This indicates a more robust and widespread resumption of economic activity across all sectors (vehicular, industrial, commercial) as pandemic-related restrictions were largely lifted. This figure surpasses the 2019 baseline, suggesting that while the pandemic offered a temporary reprieve, the underlying emission sources quickly regained or even exceeded their previous intensity once economic activity normalized.

- **2023: Highest Recorded (99.7 µg/m³)** The trend of increasing pollution continued into 2023, with the annual average reaching 99.7 µg/m³, the highest in the observed five-year period. This reinforces the notion that the temporary reduction in emissions during the peak of COVID-19 was not sustained. As economic activity fully recovered and potentially expanded, the emission load from various sectors also increased, leading to a worsening of the annual average air quality.

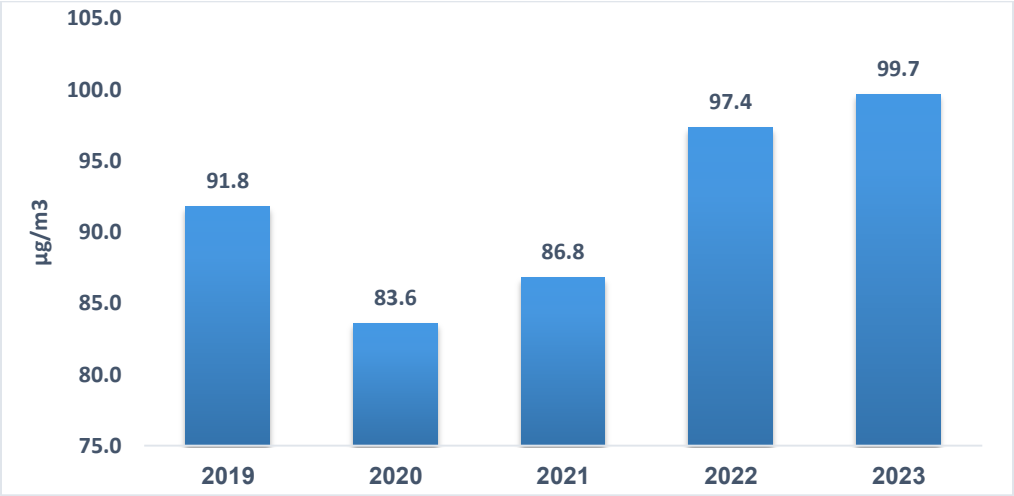

Figure 2: Annual Trend of $PM_{2.5}$ in Lahore (2019-2023)

Conclusion: The analysis of IQAir $PM_{2.5}$ data for Lahore from 2019 to 2023 unequivocally demonstrates a strong seasonal pattern, with severe air pollution episodes occurring during the colder, stagnant winter months and significantly lower levels during the warmer, rainy summer. While year-to-year variations exist, the data, particularly from 2023, indicates a worrying trend of increasing peak pollution levels, underscoring the urgent need for more aggressive and sustained emission control measures in Punjab to mitigate the adverse impacts of air pollution. The temporary air quality improvement observed during the COVID-19-induced economic slowdown in 2020 highlights the direct link between anthropogenic activities and air pollution, emphasizing the critical need for sustainable development strategies that decouple economic growth from environmental degradation.

Recommendations: Based on the observed trends and the persistent air quality challenges in Lahore, the following recommendations are put forth to improve air quality management in Punjab:

- **Strengthen Emission Control Measures:** Implement and rigorously enforce stricter emission standards for industrial, vehicular, and agricultural sources throughout the year, with particular emphasis during the winter months. This includes promoting cleaner technologies, improving fuel quality, and regulating agricultural burning.
- **Expand and Modernize Monitoring Network:** Invest in expanding the network of ground-based air quality monitoring stations across Lahore and other major cities in Punjab to provide more comprehensive and real-time data. This will enable better source apportionment and more accurate forecasting.
- **Enhance Public Awareness and Education:** Launch targeted public awareness campaigns about the health impacts of air pollution and the importance of individual and community-level actions to reduce emissions.
- **Promote Green Infrastructure and Urban Planning:** Encourage urban planning strategies that reduce reliance on private vehicles, promote public transport, and increase green spaces to help absorb pollutants and improve microclimates.
- **Foster Regional Cooperation:** Given the transboundary nature of air pollution in South Asia, collaborate with neighboring regions and countries to develop joint strategies for emission reduction, particularly concerning agricultural burning and industrial emissions.
- **Support Research and Development:** Continue to fund and encourage research into air pollution sources, atmospheric dynamics, health impacts, and the effectiveness of mitigation strategies specific to the regional context of Punjab.

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