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Research Article

Seasonal Inter-comparison of Fine Particulate Matter ($PM_{2.5}$) over Addis Ababa, Ethiopia

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Abstract

The seasonality of meteorology significantly influences the distribution of atmospheric pollution that have harmful effect on human, environment and economy. Similarly, Ethiopia has erratic seasons, this can impact air pollution. Thus, this study focused on intercomparison of PurpleAir $PM_{2.5}$ measurement at Addis Ababa city. The existing data processed by R software. Accordingly, the finding show that, during the rainy season, $PM_{2.5}$ levels exhibit a consistent pattern with concentrations peaking in the early night and reaching their lowest at midday. At Black Lion Hospital (BLH), peak concentrations extend to midday due to *due to heavy traffic and cross-sectional jams to travel commercial areas*. In contrast, during the semi-rainy and dry seasons, $PM_{2.5}$ levels peak in the early morning and decrease by midday. Hourly variations in $PM_{2.5}$ concentrations could be influenced by factors such as temperature inversion, wind, relative humidity, and solar intensity, alongside transportation and industrial activities. Analysis reveals that a significant proportion of the seasonal hourly mean trend during the rainy season, vary in between 30 µg/m3 to 50 µg/m3 of the hourly data while 15 µg/m3 to 40 µg/m3 of data in both the semi-rainy and dry seasons also surpass these guidelines. Despite the general reduction in pollution levels due to rain, the rainy season still contributes to elevated $PM_{2.5}$ concentrations, posing substantial risks to human health, the environment, and development activities. The monthly mean pattern further highlights a peak in $PM_{2.5}$ concentrations during the rainy season, underscoring the complex dynamics of air quality. This finding emphasizes the need for targeted strategies to manage pollution throughout the year. The finding suggest that, expand air quality monitoring, and reduce traffic emissions, strengthen industrial regulations and increase public awareness. It may relevance for air quality management strategies for local and regional governments.

Keywords

Seasonality, Comparison, PurpleAir, $PM_{2.5}$, Addis Ababa

1. Introduction

Pollution is the introduction of harmful substances into the environment, reducing its quality with high concentrations of harmful solids, liquids, or gases. Extensive studies have explored human interactions with their surroundings, where various activities impact the environment a blend of living organisms (biotic) and the non-living elements (abiotic) like atmosphere and air pollution is a significant problem affecting both climate change and public health through increased sickness and death rates [1].

In global regions with distinct wet and dry seasons, such as

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Southeast Asia, monsoon rains during wet seasons can drastically reduce pollution levels by washing pollutants out of the atmosphere, in contrast, dry seasons often experience elevated pollution levels due to reduced rainfall and increased biomass burning [2].

Seasonality significantly influences air pollution levels due to variations in weather patterns, temperature, human activities, and vegetation across different times of the year [3, 4]. During colder months, air pollution increases due to greater fossil fuel usage for heating, emitting more particulate matter, sulfur dioxide, and nitrogen oxides. Reduced solar radiation slows pollutant breakdown. Winter thermal inversions, where warm air traps cooler air near the ground, further worsen air quality by preventing pollutants from dispersing [5]. Higher temperatures in the summer increase the formation of ground-level ozone (O_3), a harmful air pollutant. Sunlight and heat catalyze chemical reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs), leading to elevated ozone levels [6]. Warmer weather often means better atmospheric mixing and higher wind speeds, which can disperse pollutants more effectively. However, in some regions, the stagnant air during heat waves can lead to elevated concentrations of pollutants [6]. In transitional seasons like spring and autumn, air pollution levels become more variable due to changing environmental factors. Spring often brings reduced pollution through increased vegetation and air circulation, but pollen spikes and biogenic emissions from plants can still contribute to particulate matter and ozone formation. Autumn sees rising pollution levels as heating starts. So that, these seasonal variations highlight the complexity of air quality management and the need for flexible strategies to address different pollutants [7]. However, the seasonal effects on air pollution can vary significantly depending on geographic region, type of pollutants, and local meteorological conditions. Global trends suggest that winter tends to exacerbate pollution problems, while summer increases ozone levels due to heat and sunlight.

Ethiopia experiences distinct seasonal variations, such as Kiremt (Rainy Season): June to September, Belg (Short Rainy Season): March to May and Bega (Dry Season): October to February that influence its climate, agriculture, and daily life [8-10]. The country's seasons are primarily shaped by the movement of the Intertropical Convergence Zone (ITCZ) and are defined by its geographical location within the tropics and highland topography. These seasonality might have an influence the distribution of air pollution by rising and sinking.

Addis Ababa, the capital of Ethiopia, experiences a temperate highland climate with distinct wet and dry seasons. Due to its high altitude (about 2,355 meters or 7,726 feet above sea level), the city enjoys mild temperatures throughout the year. The climate in Addis Ababa is largely influenced by the movement of the Inter-tropical Convergence Zone (ITCZ) and the surrounding mountainous topography [11-13, 9]. Therefore, this seasonality also plays a significant role in influencing air pollution patterns in the city's atmosphere. In the Bega season, Addis Ababa faces worsened air pollution due to increased dust, thermal inversions trapping pollutants, and biomass burning [14]. Addressing these issues requires improved road surfaces, stricter construction regulations, and cleaner alternatives for heating.

However, there is a limitation in studies that confirm the impact of meteorological seasonality on the seasonal distribution of pollutants. Thus, this study focused on analysis of seasonal inter comparison of PurpleAir fine particle matter ($PM_{2.5}$) over Addis Ababa. This study is important for providing information about the impacts of seasonality of meteorology on the seasonal distribution of $PM_{2.5}$. It also aims to identify advisory solutions to address the growing relationship between urban meteorology and air pollution. In addition, it offers recommendations for air pollution control strategies and management activities for local governments, the public, planners, and researchers, in response to the impact of air pollution on health, the environment, and ecology.

2. Data and Methodology

2.1. Study Area

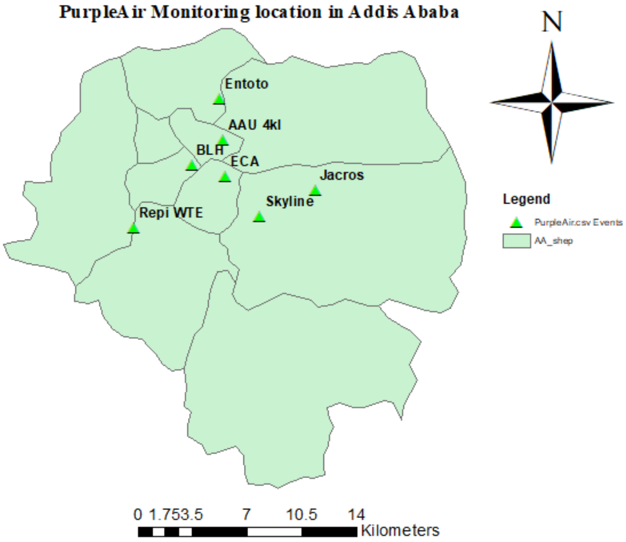

Figure 1. *Study area and PurpleAir monitoring locations.*

Addis Ababa, the capital city of Ethiopia, is situated in the central highlands of the country at an elevation of approximately 2,355 meters (7,726 feet) above sea level, has a latitude range of 8.833-9.01 N and longitude range of 38.64-38.9 E. This elevation can influence air quality by affecting atmospheric conditions such as temperature and wind patterns. Air pollution in Addis Ababa is primarily driven by emissions from vehicle traffic, industrial activities, and the burning of solid fuels. And also, the city's rapid urbanization and population growth have exacerbated pollution levels, contributing to health concerns among its residents. The sub-tropical climate sees average temperatures ranging from 10 ℃. Seasons fluctuate from cool (10-15 ℃) to warm (20-23 ℃). The wet season lasts from June to mid-September. Atmospheric conditions influence pollutant levels. Figure 1 shows the geographical location of Addis Ababa's city and the location of PurpleAir $PM_{2.5}$ monitoring device.

2.2. Data

Air quality monitoring in Ethiopia relies on Federal Reference Method (FRM), Federal Equivalent Method (FEM), and low-cost PurpleAir (PA) sensors. FRM and FEM are precise but expensive, while PA sensors, despite lower accuracy, provide useful data on $PM_{2.5}$, air temperature (^{0}F) and relative humidity (RH). This study analyzed minutely data from seven PA sensors in Addis Ababa, installed by NASA-MAIA, covering January 2022 to December 2023. Challenges like calibration issues and missing data were addressed using the Seasonal and Trend decomposition using Loess (STL) method, which handles seasonal variations and imputes missing values effectively. To enhance $PM_{2.5}$ measurement accuracy from PA sensors, data were calibrated using a regression model based on co-located PA and BAM data [15]. Applied to the model adjusted $PM_{2.5}$ concentrations for air temperature (Tair) and relative humidity (RH). Calibration improved 7.10 and R^2 from 70.2% to 75.6%, using calibration equation 1 developed by the NASA-MAIA project.

$$\text{PM2.5, calibrated} = 17.189 + 0.664 * \text{PM2.5row} + 8 * 10^{-3} * \text{Tair} - 0.153 * \text{RH} \quad (1)$$

2.3. Data Proses and Analysis

Air quality data processing and analysis require various tools across different stages, including data acquisition, cleaning, analysis, and visualization. This study utilized R statistical software (R 3.6.2; https://www.r-project.org/) for statistical processing and analysis of $PM_{2.5}$ concentrations.

2.4. Method

There are a lot of techniques to analysis atmospheric pollution, such as air quality index (AQI), air quality guideline (AQG), wind rose, wind direction, and time series analyses. However, this study examined the time series along with seasonal change and daily AQG level. Thus, the study examined seasonal variations in atmospheric $PM_{2.5}$ along with monitoring location in the city. It analyzed how seasonal changes impact $PM_{2.5}$ levels distribution. And also The World Health Organization's Air quality guidelines (AQG) set global targets for governments to improve citizen health by reducing air pollution. Clean air is a fundamental human right, yet global air pollution remains a major threat to health, causing non-communicable diseases like heart attacks and strokes [16]. Therefore, the study follows WHO 2021 guidelines for $PM_{2.5}$ levels: 15 μg/m^3 for 24 hours.

3. Result and Discussion

3.1. Hourly Mean of Rainy, Semi Rainy and Dry Season

Kampala's air quality fluctuates seasonally, with PM10 and $PM_{2.5}$ levels dropping during the rainy season, though pollutants from cooking and traffic remain steady [17]. Nairobi faces air pollution from particulate matter and NO_2, with the rainy season reducing but not eliminating traffic-related spikes. Tanzania's coastal city experiences air pollution from traffic and industry; rain lowers pollutant levels, but traffic peaks increase CO and NO_2 locally [18]. In Addis Ababa, vehicular emissions and industrial activities cause significant pollution. The rainy season reduces $PM_{2.5}$ and PM_{10} levels, but daily traffic peaks lead to temporary rises [19]. The semi-rainy season in Central and East Africa (March-May, October-December) can significantly impact air pollution. Rain generally reduces particulate matter and pollutants, but effectiveness varies with rain consistency and wind. Dust storms and biomass burning remain key pollution sources, especially in rural areas. Urban areas may still experience high pollution due to traffic and industry, while rural areas might see improved air quality offset by agricultural practices and biomass burning [20]. Air pollution in Ethiopia during the semi-rainy seasons (March-May, October-December) is influenced by rainfall, biomass burning, and urban emissions. Rain generally reduces pollutants, but biomass burning and traffic emissions persist, limiting overall improvements [21]. Typically, cities in Ethiopia experience a dry season (usually from October to May) and a wet season (from June to September). Air quality might vary between these seasons due to factors like dust during the dry season and increased pollution from biomass burning during the wet season [22]. World Health Organization (WHO) Air Quality Data). The local factors might be like traffic patterns, industrial activity, and biomass burning can also influence seasonal pollutant levels. Similarly, this research finds that during the rainy season (see Figure 2), hourly mean $PM_{2.5}$ distribution is consistent across all monitoring locations, with maximum concentrations observed in the early night and minimum concentrations at midday. However, at Black Lion Hospital (BLH), the peak extends to midday due to the area's commercial nature and heavy traffic congestion. In contrast, during the semi-rainy and dry seasons (see Figures 3 and 4), $PM_{2.5}$ distribution remains consistent, with maximum concentrations in the early morning and minimum concentrations at midday. In addition to activities like transportation and industrial processes, hourly variations during each season are influenced by factors such as temperature inversion, wind, relative humidity, and solar intensity.

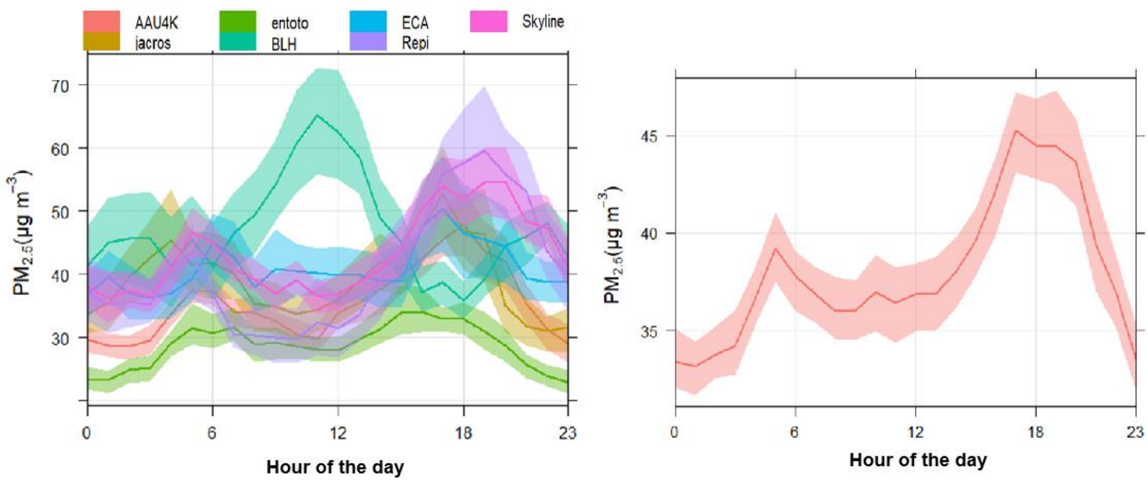

Figure 2. *Hourly mean concentrations of $PM_{2.5}$ rainy season (Jun to September): Individual sites (left) and overall average (right).*

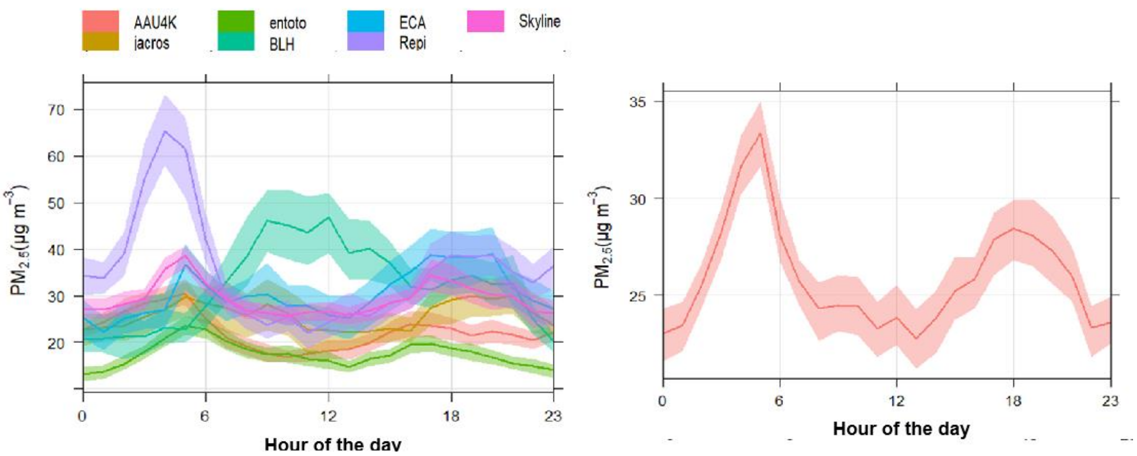

Figure 3. *Hourly mean concentrations of $PM_{2.5}$ during the semi-rainy season (February to May): Individual sites (left) and overall average (right).*

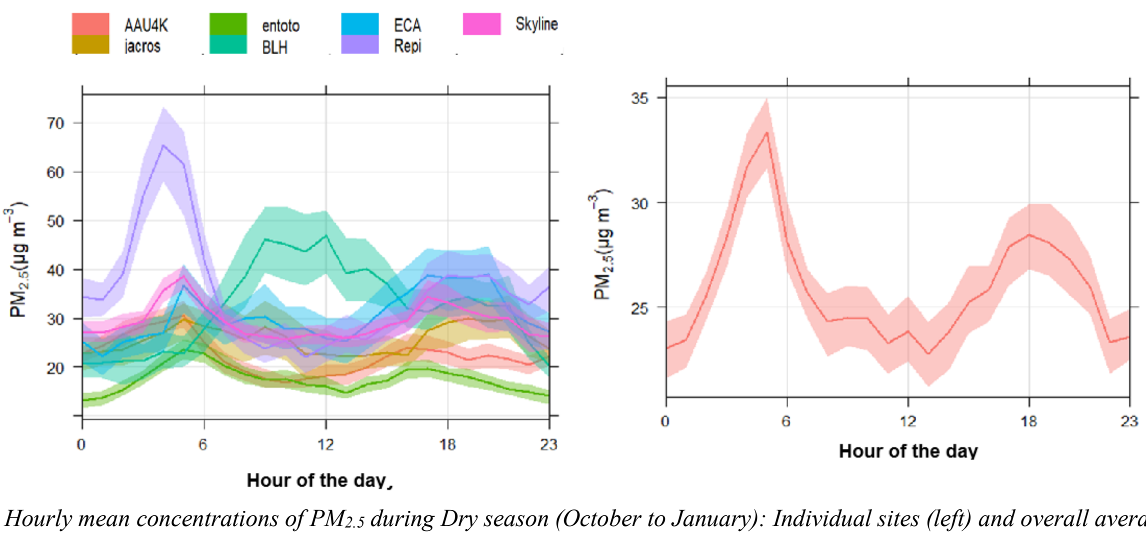

Figure 4. *Hourly mean concentrations of $PM_{2.5}$ during Dry season (October to January): Individual sites (left) and overall average (right).*

3.2. Seasonal Hourly Mean Trend

A limited number of short term $PM_{2.5}$ data sets in East Africa have shown concentrations nearly 10 times higher than the yearly average WHO guideline values (5 µg/m^3), and approximately 4 times higher than the 24-hour average (15 µg/m^3) [23, 24]. Similarly, figure 5 show that the seasonal hourly mean trend during the rainy season, vary in between 30 µg/m^3 to 50 µg/m^3 of the hourly data while 15 µg/m^3 to 40 µg/m^3 of data in both the semi-rainy and dry seasons also surpass these guidelines. This indicates that the rainy season may contribute to increased pollution. This poses a threat to human health, the environment, and ongoing development activities.

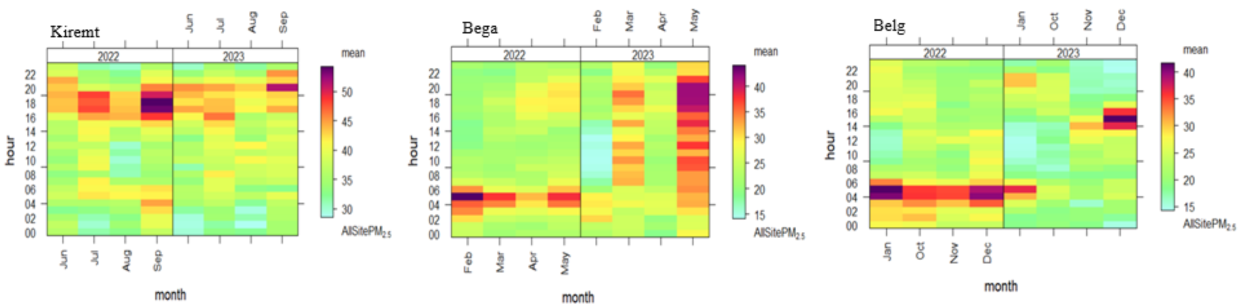

Figure 5. *Figure 1.Seasonal trend of $P_{2.5}$ Rainy season (left), semi-rainy season (middle) and dry season (right)*

3.3. Monthly Patterns

The monthly mean pattern of $PM_{2.5}$ concentrations, as illustrated in Figure 6, exhibits a notable peak during the rainy season (Jun, July, august and September) at individual monitoring sites and the monthly mean of all ministering site have shown similar patterns. This pattern aligns with findings from studies by [25-27] which reveal similar seasonal variations in $PM_{2.5}$ levels. These fluctuations are significantly influenced by temperature inversions and local climatic changes. During the rainy season, temperature inversions can trap pollutants near the surface, preventing their dispersion. This leads to an accumulation of particulate matter, such as $PM_{2.5}$, in the lower atmosphere. Additionally, local climatic factors, including changes in wind patterns and atmospheric stability during the rainy season, can further exacerbate the concentration of these fine particles. These meteorological conditions create an environment conducive to higher $PM_{2.5}$ levels, despite the common assumption that rain would naturally cleanse the atmosphere.

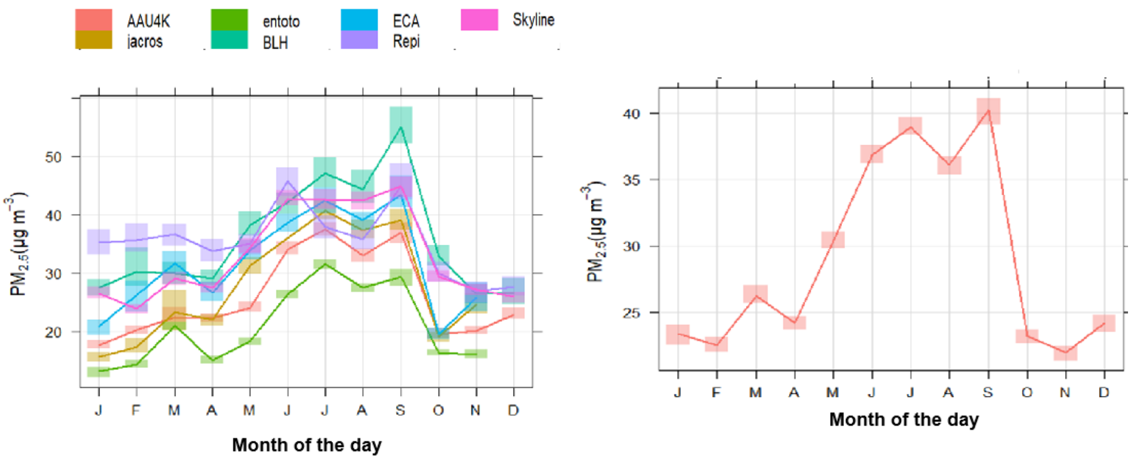

Figure 6. *Monthly mean variation of $PM_{2.5}$: Individual monitoring (left) and the average across all monitoring (right).*

4. Conclusion and Recommendation

4.1. Conclusion

This research reveals distinct patterns in the hourly mean distribution of $PM_{2.5}$ across different seasons: Rainy Season: $PM_{2.5}$ levels show a consistent distribution across all monitoring locations, with concentrations peaking in the early night and reaching their lowest point at midday. Notably, at Black Lion Hospital (BLH), the peak concentration extends to midday due to the area's heavy traffic and commercial activities. Semi-Rainy and Dry Seasons: $PM_{2.5}$ levels follow a similar distribution pattern as in the rainy season, with concentrations peaking in the early morning and reaching minimum levels at midday. Across all seasons, hourly variations in $PM_{2.5}$ concentrations are influenced by factors such as temperature inversion, wind, relative humidity, and solar intensity, in addition to transportation and industrial activities.

The monthly mean pattern of $PM_{2.5}$ concentrations reveals a peak during the rainy season. This finding underscores the complexity of air quality dynamics and the need for targeted strategies to manage pollution throughout the year, particularly during the rainy season.

Significant proportion of *the* seasonal hourly mean trend during the rainy season, vary in between 30 $\mu g/m^3$ to 50 $\mu g/m^3$ of the hourly data while 15 $\mu g/m^3$ to 40 $\mu g/m^3$ of data in both the semi-rainy and dry seasons also surpass these guidelines. This suggests that although rain season generally helps rise pollution levels, the rainy season still contributes to elevated $PM_{2.5}$ concentrations that pose substantial risks to human health, the environment, and ongoing development activities.

4.2. Recommendation

The finding suggest that, Expand air quality monitoring networks to capture more detailed data on $PM_{2.5}$ concentrations across different times of day and seasons. This will help in understanding and managing seasonal variations more effectively. Implement measures to reduce traffic congestion and emissions, particularly in areas like Black Lion Hospital (BLH) where peak $PM_{2.5}$ concentrations extend to midday due to heavy traffic. Promote public transportation and alternative modes of transport to alleviate traffic-related pollution. Strengthen regulations on industrial emissions to reduce the contribution of industrial activities to $PM_{2.5}$ concentrations. Encourage the adoption of cleaner technologies and practices. Raise awareness about the health impacts of high $PM_{2.5}$ levels and advise the public on protective measures, especially during periods of high pollution. Develop and implement strategies specifically targeting $PM_{2.5}$ reduction during the rainy season, where concentrations still peak despite rainfall. This may include addressing local sources of pollution and improving emission controls. Integrate air quality management into broader environmental and urban planning policies to address the complex dynamics of seasonal pollution and its impacts on health and development.

Abbreviations

BLH	Black Lion Hospital
CO	Carbon Monoxide
FRM	Federal Reference Method
ITCZ	Inter-Tropical Convergent Zone
NASA MAIA	NASA Melty Angular Imagery Aerosol
NO_X	Nitrogen Oxide
NO_2	Nitrogen Dioxide
O_3	Ozone
PA	PurpleAir
$PM_{2.5}$	Particulate Matter Aerodynamic Dimeter 2.5
PM_{10}	Particulate Matter Aerodynamic Dimeter 10
RH	Relative Humidity
STL	Season Trend Lose
T_{air}	Air Temperature
WHO	World Health Organization
VOCs	Volatile Organic Compound
$\mu g/m^3$	Microgram Per Meter Cube
^0F	Degree Fahrenheit

Ethical Approval Statement

The author affirm that the study titled "Seasonal Inter-comparison of $PM_{2.5}$" complies with ethical standards. The review relied solely on publicly available data from peer-reviewed sources, with no direct involvement of human or animal subjects. No conflicts of interest exist, and all funding sources, if applicable, are disclosed.

Declaration

The author, declare that the manuscript titled "Seasonal Inter-comparison of $PM_{2.5}$" is original, has not been previously published, and is not under consideration elsewhere. There are no conflicts of interest, and all funding sources have been disclosed.

Consent to Participate

Not relevant in the manuscript.

Consent for Publication

The author approve to publish the manuscript.

Competing Interests

The authors declare that there are no competing interests regarding the publication of the manuscript titled "Seasonal Inter-comparison of $PM_{2.5}$"

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Author Contributions

Tofikk Redi is the sole author. The author read and approved the final manuscript.

Data Availability Statement

Data is available on the hand of author.

Conflicts of Interest

The author declares no conflicts of interest.

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