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Long-range Transport, Regional Forest Fire Events and Meteorological Influences on $PM_{2.5}$ in Western Nepal

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Abstract

$PM_{2.5}$ pollution is a major global environmental concern, upsetting human as well as ecosystem health. This study examines the long-range transport and effects of meteorological factors on $PM_{2.5}$ concentration, utilizing data from a real-time air quality monitoring station established in the Rara National Park in 2020 and satellite data. Similarly, the influence of forest fire events on $PM_{2.5}$ levels were also assessed. $PM_{2.5}$ concentration at the Rara Station showed bimodal pattern, higher during early morning and late night, with peak levels in March and April, particularly due to forest fires in regional geographical extent. The correlation between $PM_{2.5}$ and meteorological factors showed a moderate negative relationship with humidity, and weak negative and positive correlation with temperature and wind speed, respectively. Wind direction analysis indicated that southern and southwestern air masses significantly contributed to elevated $PM_{2.5}$ levels, suggesting regional and transboundary transport of pollutants. The strong correlation between fire frequency and $PM_{2.5}$ concentration was observed around 100-200 km at 2-day time lag emphasizing the long-range transport of pollutants. Linear regression model indicated that forest fires had a significant impact on air quality, explaining about 74% of the variance in $PM_{2.5}$ levels. Linear regression analysis further indicated that forest fire frequency explained a substantial portion of $PM_{2.5}$ variability, with each additional fire within 100 km increasing $PM_{2.5}$ by 0.4 µg m^{-3}. The findings highlight regional approach and transboundary cooperation for research and policy interventions to mitigate regional forest fire events and improve regional and local air quality.

Keywords: *long-range transport, forest fire, meteorological factors, Rara National Park.*

Introduction

Air pollution is one of the major global environmental issues, causing serious threats to human health and ecosystems (Bolaño-Diaz *et al*., 2022; Wei *et al*,, 2023;). Among various air pollutants, particulate matter (PM) in ambient air is of particular concern because of its substantial implications in public health and safety (Portier *et al*., 2010). Fine particulate matter specially $PM_{2.5}$ is very harmful because of its small size which can penetrate deep into the respiratory system, leading several respiratory problems (Dunea *et al*., 2016; Guaita *et al*., 2011; Xing *et al*., 2016), cardiovascular effects (Hayes *et al*., 2020; Kirrane *et al*., 2019; Schneider *et al*., 2010; Sharma *et al*., 2020) and reduction of lung function (Chen *et al*., 2019; Downs *et al*., 2007; Fillion *et al*., 2006; Guo *et al*., 2019). Vulnerable populations including children, elderly, and individuals with pre-existing health complications are particularly more susceptible to the harmful effects of $PM_{2.5}$ (Bell & Holloway, 2007; Matus & Oyarzún, 2019). Exposure to $PM_{2.5}$ during pregnancy may adversely affect fetal development, potentially leading to low birth weight and other complications (Leung *et al*., 2022; Sun *et al*., 2016). People in low and middle-income countries are disproportionately affected by air pollution levels that exceed WHO air quality limits (WHO, 2022). In addition, $PM_{2.5}$ emissions from forest fire increases the risk of various human diseases (Kuikel *et al*., 2025; Reddington *et al*., 2021).

Air pollution occurs as a results of various natural and anthropogenic factors (Cheng & Li, 2010; Yang *et al*., 2018). Chemical reactions in the atmosphere, volcanic eruptions, dust storms, wildfires are some of the natural factors (Barman *et al*., 2008; Pope *et al*., 1995) whereas population density, urbanization (Han *et al*., 2014), economic conditions, transportation (Titos *et al*., 2015), agricultural practices (Singh *et al*., 2021), waste management (Peter & Nagendra, 2021) and industrial activities (Ren & Matsumoto, 2020) are some of the anthropogenic factors causing air pollution. Similarly, the meteorological factors play a crucial role in formation, dispersion and dilution of air pollutants. Variables such as wind speed, wind direction (Liu *et al*., 2020), atmospheric stability, relative humidity (Li *et al*., 2017), precipitation (Mahapatra *et al*., 2019) and solar radiation significantly influence $PM_{2.5}$ concentration. Temperature and humidity contribute to the formation of $PM_{2.5}$ (Portier *et al*., 2010), while wind speed and direction play a key role in the dispersion of pollutants (Koe *et al*., 2001). Studies indicate that $PM_{2.5}$ concentration is positively correlated to temperature and negatively correlated to precipitation and wind speed (Wang & Li, 2022).

Both natural and anthropogenic forest fire, emitting high concentration of $PM_{2.5}$ (Sahu *et al*., 2022; Sapkota *et al*., 2005; Shrestha *et al*., 2025) along with toxic gases (Abdurrahman *et al*., 2020). Biomass burning release wide range of pollutants, including particulate matter, carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs), aldehydes, and semi volatile and volatile organic compounds (VOCs) (Urbanski *et al*., 2008). During atmospheric transport such pollutants undergo physical and chemical transformations (WHO, 1999). Biomass derived PM has been shown to stimulate oxidative stress, inflammation and genotoxicity in lungs (Suriyawong *et al*., 2023). It is estimated that nearly 90% of the carbon released during forest fires is converted to either CO_2 or CO and 5% to PM in the atmosphere (Reid *et al*., 2005). Typically, fire generated aerosols rise 200 to 500 m from sources under normal conditions and may increase up to 2 km or more under favorable meteorological conditions (Mehra *et al*., 2019) facilitating long-range transport and affecting regional air quality. Studies on impacts of forest fire on PM concentration in ambient air are limited in Nepal. Some researches have explored the relationship between PM level and cook stove emission (Adhikari *et al*., 2020; Johnston *et al*., 2021; Pokhrel *et al*., 2015) and the long-range transport of PM from its source (Khuzestani *et al*., 2017; Liao *et al*., 2017). Researches from other countries show a clear positive relationship between forest fire and PM concentration. Significant increase in PM concentration during episodes of large forest fires have been documented in India (Sahu *et al*., 2022), Colombia (Bolaño-Diaz *et al*., 2022), and Thailand (Suriyawong *et al*., 2023). It is reported that the composition of biomass burning in general affects composition of the atmosphere (Putero *et al*., 2014), affecting the overall quality of air (Bali *et al*., 2017). In this context, the present study investigates the effects of forest fires on $PM_{2.5}$ concentration with perticular emphasis on the long-range transport of PM over hundred of kilometers away from the study area, the Rara National Park. The research has attempted to address existing knowledge gap regarding fluctuation of $PM_{2.5}$ levels and their long-range transport during forest fire events in Nepal. The local and regional effects of forest fires on air quality, particularly in the protected areas like Rara National Park, remain largely unexplored. The study also aims to estimate the time required for PM to travel a specific distance from its source to understand the pollutant transport dynamics.

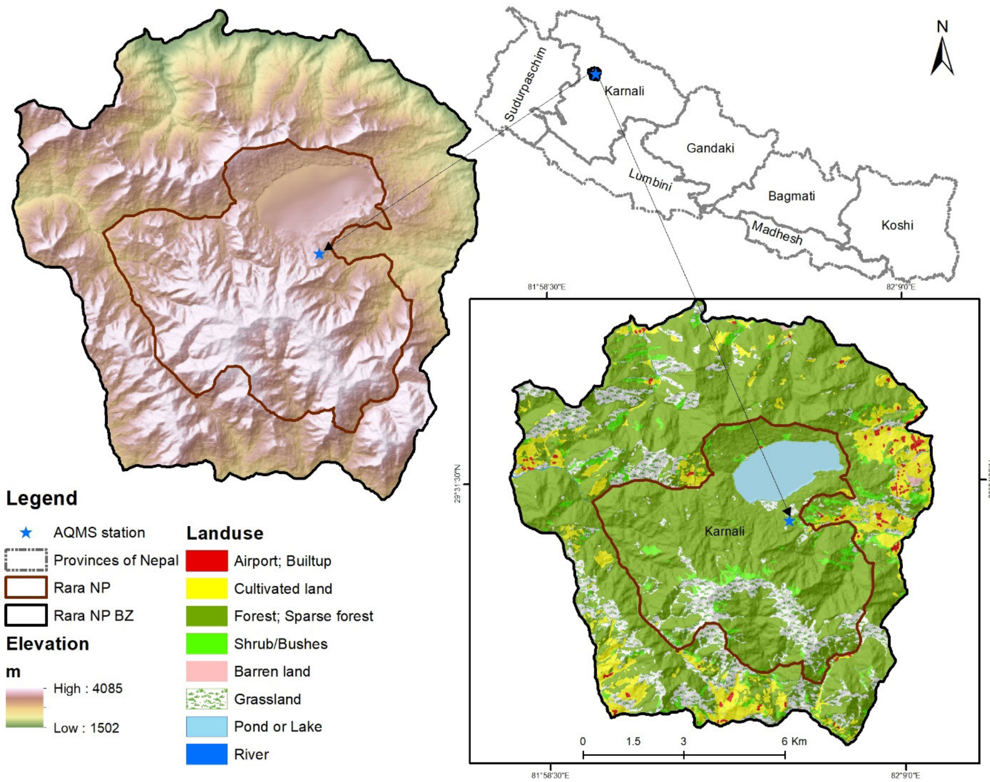
Materials and Methods

Study Area

Rara National Park is located in the north-western high mountains of Mugu and Jumla districts in Karnali Province, Nepal (Figure 1). The park was established in 1976 for the conservation, and management of the natural highland environment, including its unique wildlife, vegetation, and landscapes (DNPWC, 2024). National Parks and Wildlife Conservation Act 1973 of Nepal restrict various human activities inside the Park to ensure the protection and conservation of natural resources.

Figure 1

Location of Rara Air Quality Monitoring Station at Milichaur Area.



Rara National Park is the smallest national park in Nepal, covering an area of 106 km² with an additional buffer zone of 198 km² (DNPWC, 2024). Rara Lake - a Ramsar site, is the major attraction of the park characterized by conifer forests and grasslands, habitat of various endangered species of flora and founa. The study area experiences pleasant summers and freezing cold winters. In 2020, the Department of Environment, Government of Nepal, established a real-time air quality monitoring station at the grassland of Milichaur, at an elevation of 2,990 m above sea level. As this station is located within the national park's boundary, it is exposed to minimal anthropogenic activities and is considered as a reference station (a station with very low background pollution levels) for air quality measurement in Nepal. This makes the study area an ideal site for studying influence of meteorological factors in $PM_{2.5}$ concentration and its long-range transport in relation to local and regional forest fire events.

Methods of Data Collection and Analysis

$PM_{2.5}$, Meteorological and Fire Frequency Data Collection

The data for fine particulate matter ($PM_{2.5}$) concentration and meteorological data from the Rara Monitoring Station, spanning the period from January to December 2021, was obtained from the Department of Environment, Government of Nepal. The station at Rara National Park is equipped with a Grimm EDM 180+ Environmental Dust Monitor, which uses laser light-scattering technology to measure particle counts and calculate PM levels based on size. The data, recorded at a minute resolution, was averaged into hourly and daily values, with an 80% data availability threshold applied at each stage. Diurnal variation in $PM_{2.5}$ concentration was assessed by calculating hourly averages for each month. This approach allowed for identifying both diurnal and monthly trends. Meteorological data, including temperature (°C), relative humidity (%), wind speed (m/s), and wind direction, were collected from the same station using a Lufft Sensor. Per minute data from the sensor were averaged hourly for the analysis.

The regional fire event data were obtained from NASA's Fire Information for Resource Management System (FIRMS), which provides near-real-time active fire detections derived from both the Moderate Resolution Imaging Spectroradiometer (MODIS: ~1 km spatial resolution) and the Visible Infrared Imaging Radiometer Suite (VIIRS: ~375 m spatial resolution). The combined MODIS–VIIRS active fire dataset available through FIRMS was downloaded and used directly in this study. This product integrates fire detections from both sensors into a unified dataset. Fire detections were extracted within concentric zones of 10 km, 50 km, 100 km, 200 km, and 500 km centered on the Rara Monitoring Station to evaluate the influence of local and regional fire events. Daily fire frequency was calculated by summing all detected fire pixels within each zone for each day. Hourly $PM_{2.5}$ measurements from the Rara Monitoring Station were aggregated to daily averages to ensure temporal consistency. The daily fire counts and daily $PM_{2.5}$ concentration temporally matched and used to compute the Pearson correlation coefficients. Statistical significance was evaluated at the 95% confidence level ($p < 0.05$). The resulting correlation matrix was visualized as a heat map.

Data Analysis

Pollution rose diagrams were drawn using the "openair" package (Carslaw, 2019) in R to visualize the relationship between $PM_{2.5}$ concentration and wind direction. Hourly $PM_{2.5}$ concentration was plotted against corresponding wind speed and direction to identify linkage between wind patterns and elevated pollution levels. Daily averaged $PM_{2.5}$ concentration was compared with Nepal's National Ambient Air Quality Standard (NAAQS) of 40 µg/m³. A histogram of daily averaged data was generated to analyze data distribution. Pearson correlation coefficients were calculated to assess relationships between $PM_{2.5}$ concentration and meteorological parameters, viz. temperature, relative humidity, and wind speed. To evaluate the impact of regional fire events on $PM_{2.5}$ concentration, fire frequency data at various distances from the station were correlated with $PM_{2.5}$ concentration over different time lags (same day to 5 days). For instance, the $PM_{2.5}$ concentration on a particular day was compared with the fire frequency from the previous day for a 1-day lag analysis. Similarly, Pearson correlation coefficients were calculated for each distance-time lag combination. Linear regression was performed for different scenario, using $PM_{2.5}$ concentration as the dependent variable and fire event frequency as the independent variable. Model performance was assessed using R^2 and p-values. Data analysis was carried out in R (R Core Team, 2024).

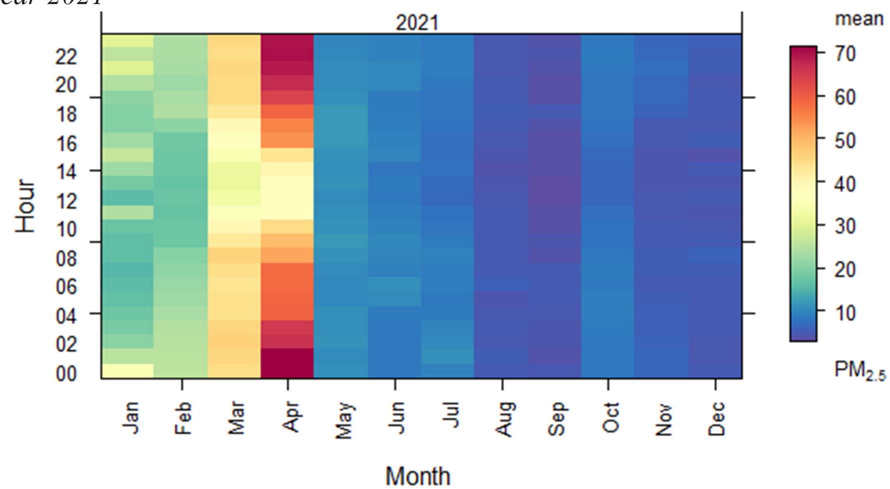
Results and Discussion

Variation of Air Quality

The diurnal variation in $PM_{2.5}$ concentration showed bimodal distribution, lower concentration during mid-day and higher concentration during early morning and late night. This pattern is particularly evident during January to April months with elevated $PM_{2.5}$ concentration, and can be attributed to variations in wind speed and atmospheric mixing. Notably, $PM_{2.5}$ concentrations were significantly higher during January to April, with April recording the highest monthly concentration (Figure 2).

Figure 2

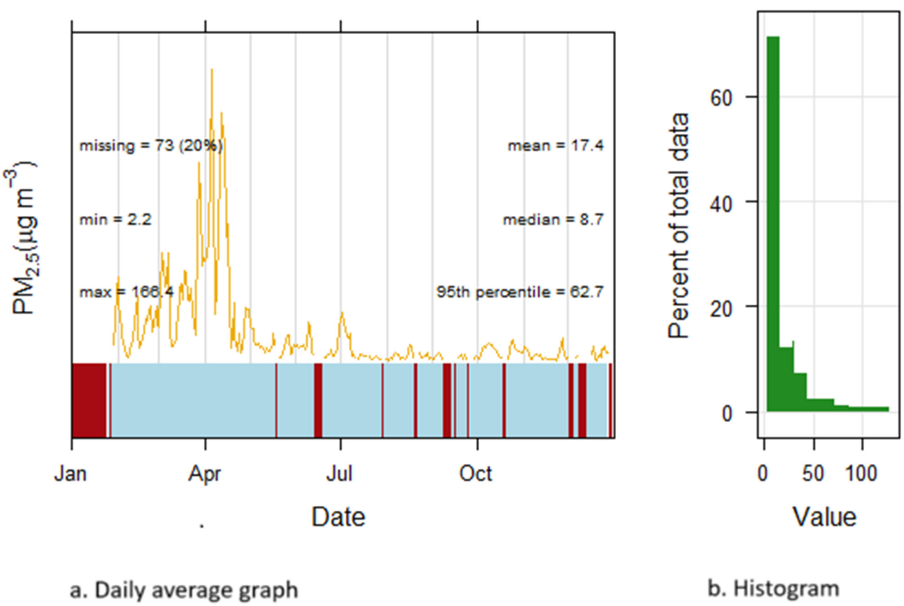
Diurnal Variation of $PM_{2.5}$ at the Rara Monitoring Station in Different Months of the Year 2021



Pre-monsoon season (March and April) were observed with high $PM_{2.5}$ concentration compared to other months. The highest daily average $PM_{2.5}$ concentrations were observed in April, with notable data gaps in January (Figure 3). The overall mean $PM_{2.5}$ concentration was 17.4 µg m^{-3}. While daily average concentrations ranged from as low as 2.2 µg m^{-3} during the monsoon season to as high as 166.4 µg m^{-3} during the pre-monsoon period. However, the median for daily averaged concentration was 8.7 µg m^{-3}, suggesting substantial influence of few high values on the overall mean. In 2021, 340 days of $PM_{2.5}$ data were available of which only 9.4% of the days (i.e., 32 days) exceeded NAAQS. However, in March and April, the percentage of days exceeding NAAQS was found to be 51.6% and 45.2%, respectively. The histogram exhibits decline in frequency of $PM_{2.5}$ as the concentration increases.

Figure 3

Daily Average PM2.5 (µg m-3) at the Rara Monitoring Station During 2021. The maximum concentration of PM2.5 was observed during pre-monsoon (a). Majority of the data points were observed with low value of PM2.5 at the station (b).



Influence of Meteorological Factors on $PM_{2.5}$ Concentration

The relationship between hourly average $PM_{2.5}$ and key meteorological parameters-temperature, relative humidity and wind speed, was examined using the Pearson correlation coefficient. The results indicate a moderate negative correlation (r=-0.315) with relative humidity followed by weak negative correlation with temperature (r =

-0.166). The wind speed whereas had a weak positive correlation (r = 0.194) with $PM_{2.5}$. The negative association with relative humidity may be attributed to enhanced wet scavenging and hygroscopic growth processes that facilitate the removal of airborne particles under high humidity conditions (Li, Feng, *et al*., 2017; Mahapatra *et al*., 2019). Similarly, temperature influences atmospheric mixing and secondary particle formation, thereby affecting $PM_{2.5}$ levels. Although wind speed generally promotes pollutant dispersion, its weak positive correlation in this study may reflect the role of regional transport, where stronger winds facilitate the inflow of polluted air masses from distant sources (Koe *et al*., 2001; Wang & Li, 2022).

Wind direction plays a critical role in transport and dispersion of pollutants. The air mass originated from southern region contributed most significantly to elevated $PM_{2.5}$ concentration (Figure 4) suggesting the influence of regional and transboundary pollution sources, including forest fire events. During March and April, higher $PM_{2.5}$ concentrations were predominantly associated with winds from the south and southwest directions, whereas lower concentration was linked to northerly winds (Figure 5). This seasonal pattern is consistent with previous studies demonstrating that prevailing wind direction strongly influences the spatial distribution and long-range transport of particulate matter (Sahu *et al*., 2022). These findings highlight the combined influence of local meteorology and regional air mass movement in determining ambient $PM_{2.5}$ levels in high-altitude and relatively pristine environments.

Figure 4

Pollution Rose Diagram of Hourly Average $PM_{2.5}$ at the Rara Monitoring Station.

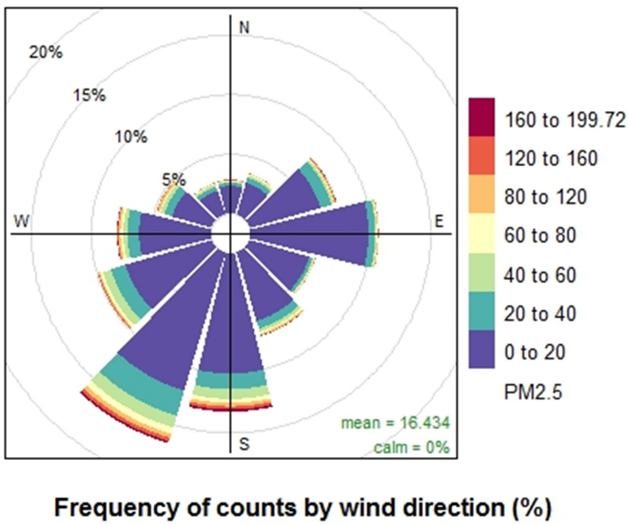
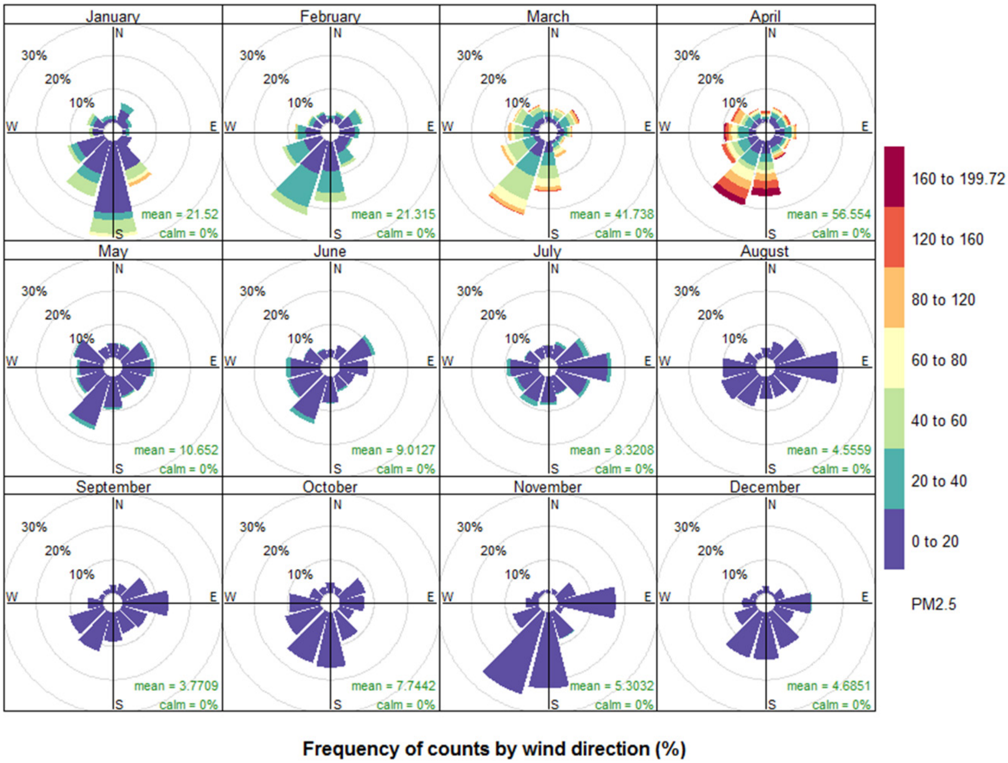


Figure 5

Pollution Rose Diagram of Hourly Averaged $PM_{2.5}$ Across Months at the Rara Monitoring Station.



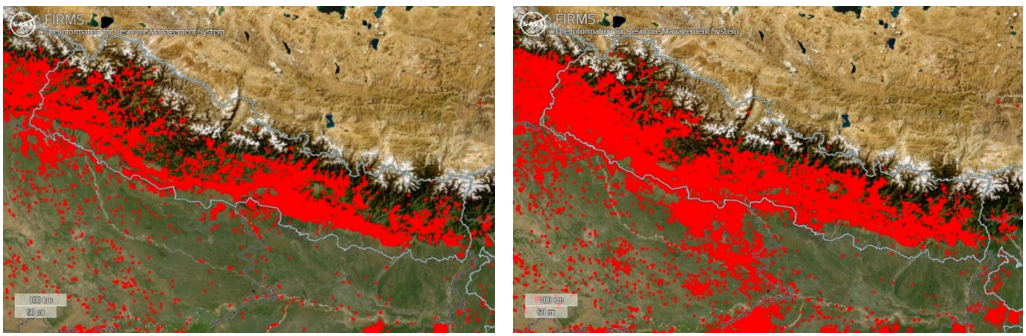
Fire Events and $PM_{2.5}$ Concentration

Numbers of local as well as regional fire events were observed particularly in the southern region of study area especially during March and April (Figure 6). The number of wildfire incidents were rising globally (Pechony & Shindell, 2010), and this trend is projected to continue in future (Yaoxian *et al*., 2015), releasing various gases along with particulate pollutants (Abdurrahman *et al*., 2020; Kuikel *et al*., 2024).

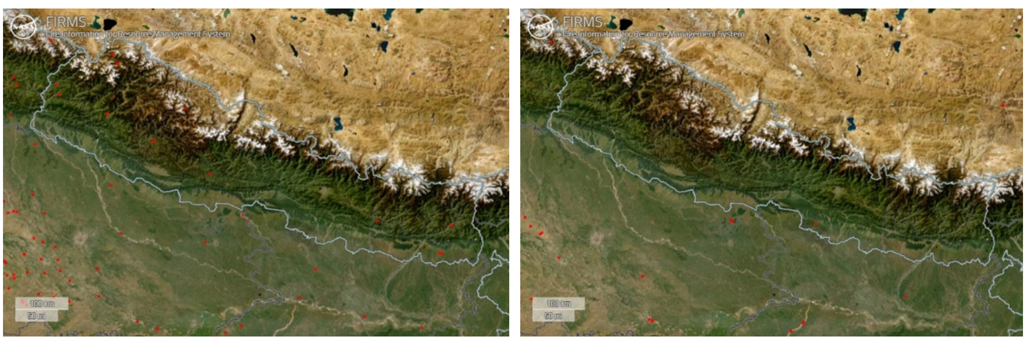
November to May is generally considered as burning season in northern hemisphere (WHO, 1999), while in tropical region it is considered to be during February to May (Bali *et al*., 2017). In Nepal, all physiographic regions are vulnerable to forest fire but western and lowland areas of the country are more susceptible to forest fires (Bajracharya, 2002; Bhujel *et al*., 2022). Forest fire incidents in Nepal also occurs from January to June, where the highest frequency recorded during March-April (Bhujel *et al*., 2022; Parajuli *et al*., 2015; Shrestha *et al*., 2025) which can be attributed to low rate of precipitation and high temperature (Mishra *et al*., 2023). A similar forest fire season in January to June month has been recorded in India (Sahu *et al*., 2022). The regional fire events, particularly from the southern part of the station which is contributing to elevated $PM_{2.5}$ levels during March and April, is further supported by the pollution rose diagram (Figure 5). Biomass burning on $PM_{2.5}$ concentration has been estimated to contribute between 9%-70% (Abdurrahman *et al*., 2020). Previous research using Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model suggested that pollution generated form fire events can be translocated as far as the upper Himalayan area under southwesterly wind (Bali *et al*., 2017). The spatial distribution of fire events within a 100 km radius of the Rara Station during 2021 (Figure 7) shows significant fire activities during March and April, coinciding with periods of elevated $PM_{2.5}$ concentration. In 2021, fire occurrences were reported on 164 days. On average, satellites observation detected 17.85 fire events per day, with 347 being the maximum number of fire events detected in a single day. The daily fire frequency was highest for April 2021 (Figure 7).

Figure 6

Fire Events Detected by Satellite for Different Months in Nepal (Source: FIRMS, 2021).



a) March, 2021 b) April, 2021



c) June, 2021 d) July, 2021

Figure 7

Distribution of Fire Events within 100 km Radius of the Rara Monitoring Station

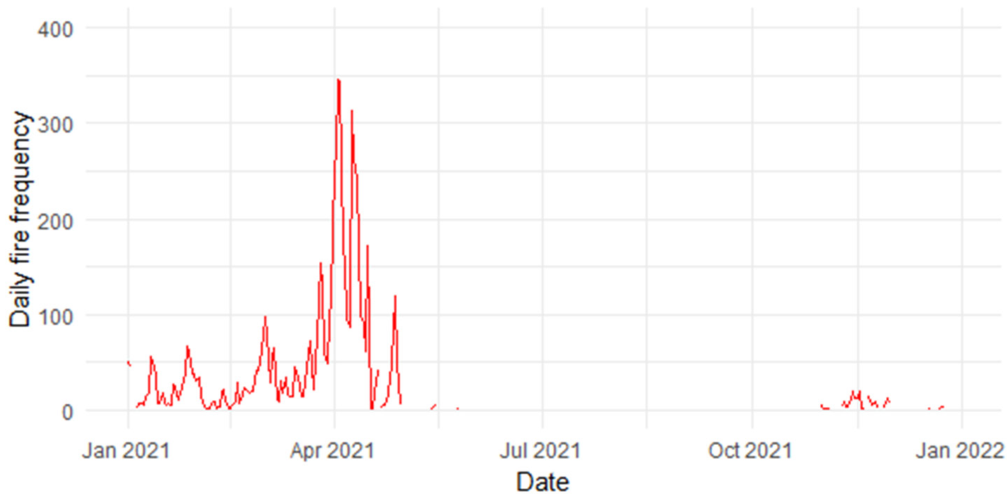


Figure 8 illustrates the correlation between the daily average $PM_{2.5}$ concentration with daily fire event frequencies within different aerial distance from the study site across different time lag. The analysis shows a clear pattern in which the strength of association between $PM_{2.5}$ and fire events depends on both distance from the source and time lag. At shorter distances, such as within a 10 km radius of the fire events, the Pearson correlation coefficient is relatively low, ranging from 0.17 to 0.28 across different time intervals indicating a weaker association between fire events and $PM_{2.5}$ concentration close to the source.

As the distance increases, the correlation between $PM_{2.5}$ concentration and fire event frequencies strengthen considerably. Between 50 and 100 km, there is a notable rise in the Pearson correlation coefficients for almost all-time lags, with a particularly strong correlation observed around a 2-day time lag. This increase in correlation at mid-range distances likely reflects the cumulative transport of $PM_{2.5}$, which remains suspended in atmosphere for extended periods. At distances beyond 100 km, the correlation peak, with coefficients as high as 0.86 to 0.87 at 100 km, 200 km, and 500 km again most pronounced at 2-day time lag. This pattern suggests that the highest impact of $PM_{2.5}$ emissions from forest fires is observed 2-3 days after the events, particularly at greater distances. This observation aligns with the well-documented behavior of fine particulate matter, which can stay suspended in the atmosphere for extended periods, allowing for long-range transport before settling or being deposited (Pfeiffer, 2015). The correlation between $PM_{2.5}$ concentration and fire events strengthen with distance from the source, peaking at a 2-day time lag for distances over 200 km. A linear regression analysis further conformed these findings, showing the relationship between $PM_{2.5}$ concentration at the Rara Station with distances of forest fires events at various time lag. Although Pearson correlation coefficients were similar across certain conditions, the linear regression model provided quantitative contribution of regional fire events to observed $PM_{2.5}$ concentration.

Figure 8

Pearson Correlation Coefficient Between $PM_{2.5}$ Concentration and Number of Forest Fire within Different Distances at Different Time Lags.

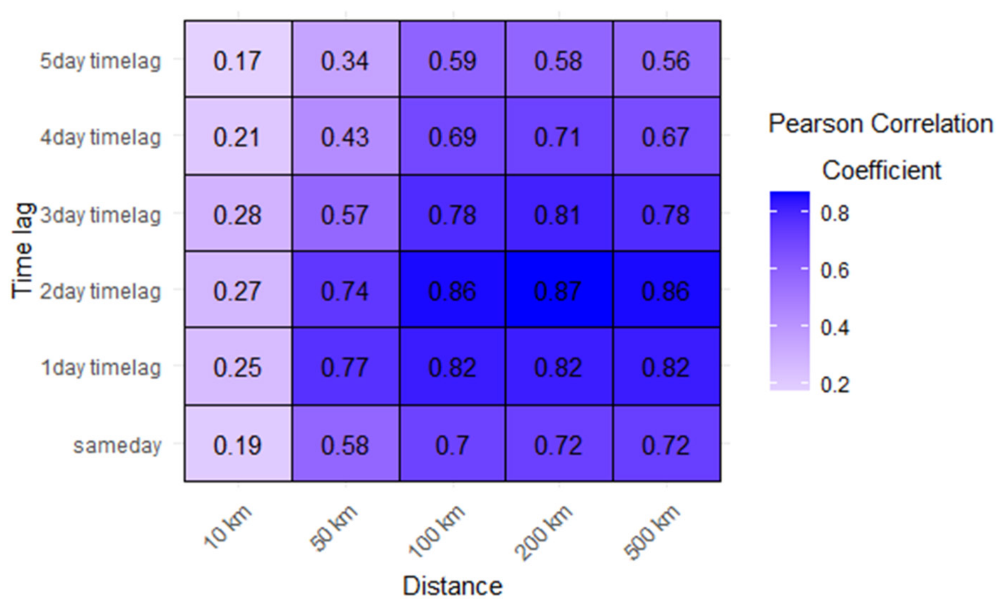
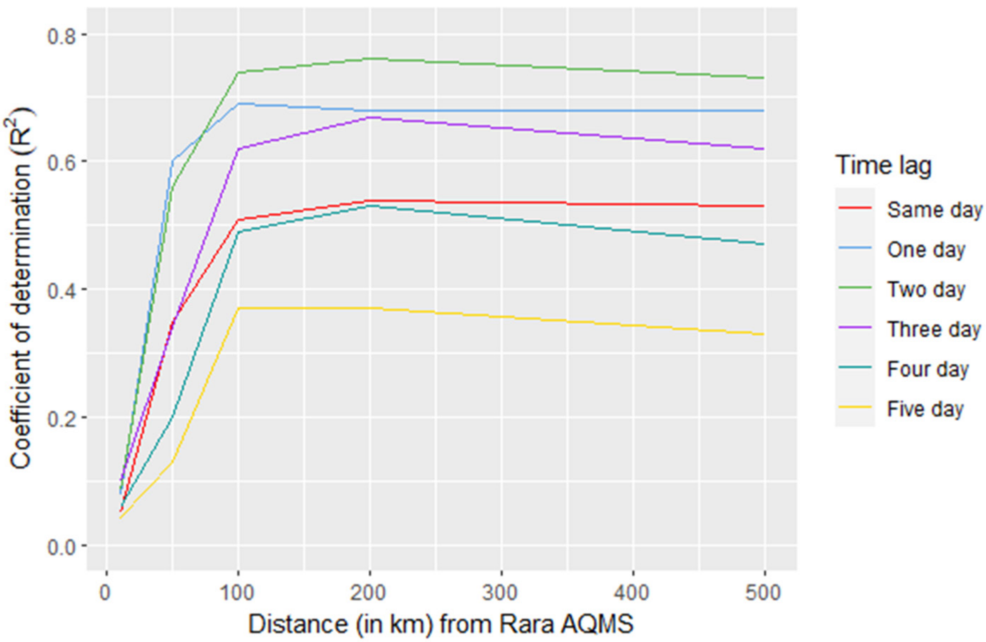


Figure 9 shows a significant increase in the R^2 values of linear regression model increase with distance from the station, peaking around 100 km. Beyond this distance, the R^2 values remain high but do not increase rapidly. The highest R^2 value occurs at a 2 days' time lag for distances greater than 100 km indicating that the linear regression model best captures the impact of forest fire events on $PM_{2.5}$ concentration when a 2-day lag is considered. Therefore, this condition was selected as the optimal setting for further analysis. Figure 10 illustrates the relationship between daily average $PM_{2.5}$ concentration and the number of fires within a 100 km radius, using a 2-day time lag. The regression model explains approximately 74% of the variance in $PM_{2.5}$ concentration demonstrating that the model provides a strong fit ($p < 0.001$) between the $PM_{2.5}$ concentration and frequency of fire events. The model intercept of 9.24 µg/m³ represents the baseline $PM_{2.5}$ concentration when no fires occur, while the coefficient of 0.4 µg/m³ per fire indicates that each additional forest fire increases $PM_{2.5}$ concentration by 0.4 µg/m³.

Figure 9

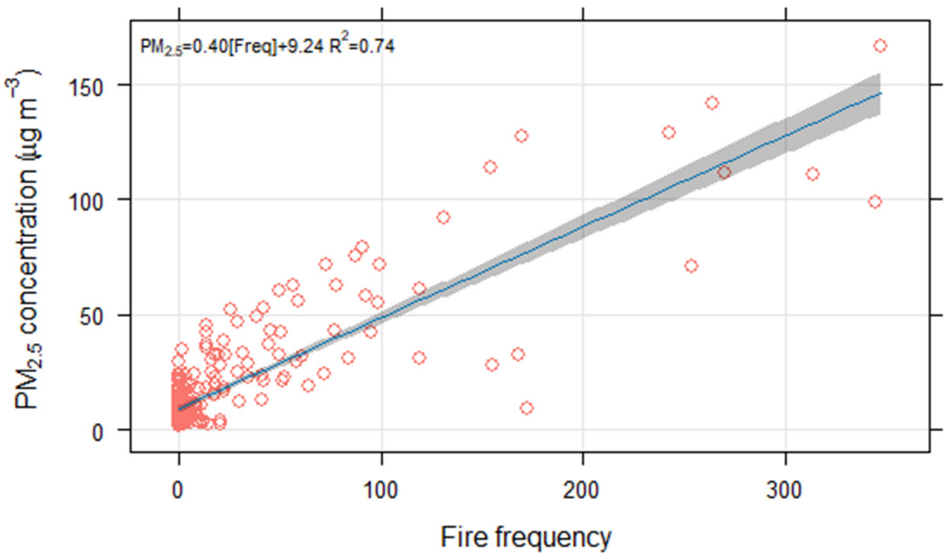
R^2 Value Between $PM_{2.5}$ Concentration and Number of Forest Fires within Different Distances at Different Time Lags.



Under favorable atmospheric circulation, air pollutants can travel long distances (Oakes, 2007). R^2 value slightly increases to 0.76 for fires within 200 km and decreases to 0.73 for fire within 500km, highlighting a strong influence of fire within 100-200 km on local $PM_{2.5}$ concentration. These findings indicate that the impact of forest fires on $PM_{2.5}$ concentration peaks two days after the fire event and gradually decreases afterwards. Increase in particulate matter concentration in ambient air is usually claimed to be from vehicles and various local point sources (Singh *et al*., 2019), but as the Rara National Park is pristine and far from local well-known sources of particulate pollution, the pollution at the study area can be confirmed from the contribution from regional wildfires as shown in various other studies (Begum *et al*., 2013; Mahapatra *et al*., 2019; Reddington *et al*., 2021).

Figure 10

Daily Average $PM_{2.5}$ and Number of Fires within 100 km at 2 Days' Time Lag.



Conclusion

This study investigated the influence of regional fire events on $PM_{2.5}$ concentration along with their relation with meteorological parameters at Milichaur of Rara National Park, Nepal. $PM_{2.5}$ concentration exhibited bimodal diurnal pattern peaking in early morning and late night. Higher $PM_{2.5}$ concentration during March and April reflects the significant contribution of seasonal factors, such as dry conditions and fire events. $PM_{2.5}$ concentration was influenced by both meteorological and regional air mass movement. Significant relationships between $PM_{2.5}$ concentration and relative humidity having the moderate negative correlation, and temperature and wind speed exhibiting weak negative and weak positive correlation, respectively. The southern and southwestern winds played crucial role to elevate $PM_{2.5}$ concentration especially during March and April, emphasizing the influence of fire events on local air quality. Analysis of satellite data and forest fire records provided that the fire events around 100-200 km radius form the study area exhibited the highest correlation with $PM_{2.5}$ concentration at a 2-day time lag. This highlights the most significant impact of forest fires on air quality occurs 2-3 days after the fire event further proving its sustained presence in the atmosphere and hence the long-range transport of air pollutants. Similarly, the forest fire frequency was observed to account for a substantial variation in the $PM_{2.5}$ concentration, emphasizing the significant impact of fire events on regional air quality. The findings are particularly significant for understanding air pollution dynamics in pristine protected areas like Rara National Park, where direct sources of anthropogenic emissions, except wildfires, are limited. The influence of regional fire events coupled with transboundary pollution highlight the need of coordinated efforts in forest fire management and reduction in particulate matter emissions to protect environmental quality.

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