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Research Article

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Investigation of Air Pollution in Al Bayda, Libya: Exposure Levels, Temporal Variability and Potential Sources

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Abstract

The association between exposure to high levels of $PM_{2.5}$ and health impacts is extensively studied and well-documented. Al Bayda, Libya, faces recurring air quality issues due to open waste burning, particularly during nighttime hours. To date, no comprehensive assessment of $PM_{2.5}$ concentrations has been conducted in this area. This study aims to characterize $PM_{2.5}$ concentrations in Al Bayda, Libya, by assessing exposure levels, temporal variability, and potential sources. Concentrations of $PM_{2.5}$ were recorded every minute during 2023 and 2024 using PurpleAir-II-SD air quality monitors. For the same period, meteorological hourly data were also obtained from Al Bayda Weather Station. The data were analyzed to assess temporal variability and were compared with WHO guidelines and US-EPA standards. The WHO 24-hr standard was exceeded on 118 days (41%) in 2023 and 144 days (44%) in 2024. Annual average $PM_{2.5}$ concentrations were 15.4 $\mu g/m^3$ and 17.4 $\mu g/m^3$ in 2023 and 2024, respectively, exceeding both the WHO air quality guidelines and the US-EPA standards. Diurnal trends of $PM_{2.5}$ concentrations and wind speed indicate that $PM_{2.5}$ levels are strongly influenced by meteorological conditions. Monthly $PM_{2.5}$ concentrations and weekday boxplots suggest that the timing of elevated concentrations does not follow a consistent or systematic pattern. Together, the observed nighttime increases are consistent with intermittent local emission activities, most likely open waste burning. The findings indicate that $PM_{2.5}$ concentrations in Al Bayda frequently exceeded WHO guidelines and US-EPA standards and were strongly influenced by meteorological conditions. Chemical composition analyses are recommended to further investigate the potential sources of $PM_{2.5}$.

Keywords: Fine Particulate Matter, Air Pollution, Meteorology, Temporal Variability, Libya.

INTRODUCTION

The association between exposure to high levels of $PM_{2.5}$ and health impacts is extensively studied and well-documented. Exposure to $PM_{2.5}$ is linked to acute and chronic bronchitis, asthma, and reduced lung function growth (U.S. Environmental Protection Agency 2008; Health Effects Institute, 2010; Laumbach & Kipen, 2012; Batterman et al., 2014; Karagulian et al. 2015). Moreover, long-term $PM_{2.5}$ exposure causes 40% of the premature mortality worldwide (Wang et al., 2012; Sarpong et al., 2021).

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According to the United States Environmental Protection Agency (US-EPA), $PM_{2.5}$ represents airborne particles with aerodynamic diameters of 2.5 μm or less, which are divided into primary PM and secondary PM. Primary $PM_{2.5}$ is directly emitted into the atmosphere while secondary $PM_{2.5}$ is a result of photochemical processes that convert gas-phase emissions to particles (Guzman-Gonzalez et al., 2024).

The World Health Organization (WHO) and the US-EPA established standards of $PM_{2.5}$ to protect human health by limiting exposure to fine particulate matter and to reduce the effects of $PM_{2.5}$. Tables 1 and 2 list the WHO standards and US-EPA standards for 24-hour mean and annual mean.

Table: (1). World Health Organization (WHO) Guidelines (2021 revision)

Averaging time	$PM_{2.5}$ limit	Notes
24-hour mean	15 $\mu g/m^3$	Should not be exceeded more than 3-4 times per year
Annual mean	5 $\mu g/m^3$	Long-term exposure guideline

Table: (2). US-EPA (National Ambient Air Quality Standards – NAAQs)

Averaging time	$PM_{2.5}$ limit	Notes
24-hour mean	35 $\mu g/m^3$	In compliance if 98^{th} percentile, averaged over 3 years meets standard
Annual mean	9 $\mu g/m^3$	In compliance if annual mean, averaged over 3 years meets standard

Many cities in North Africa frequently experience Saharan dust, open waste burning, in addition to traffic, and other sources; however, studies of $PM_{2.5}$ concentrations remain largely underrepresented in this region because of data scarcity and the unavailability of a dense network of air quality monitoring stations.

Al Bayda, a mid-sized city in northeastern Libya, faces recurring air quality issues due to open waste burning, particularly at night. Such episodes are exacerbated by calm meteorological conditions, which may include temperature inversions. Despite these concerns, little is known about the city's air pollution levels, as formal monitoring is lacking.

Study objectives

This study aimed to characterize $PM_{2.5}$ concentrations in Al Bayda, Libya, by assessing exposure levels, temporal variability, and potential sources. The study also examined the influence of meteorological conditions on $PM_{2.5}$ concentrations, with particular attention to daily, monthly, weekday, and diurnal patterns. In addition, $PM_{2.5}$ concentrations were compared with the WHO air-quality guideline and US-EPA standards.

Statement of the study

Air pollution, particularly exposure to fine particulate matter ($PM_{2.5}$), is an important environmental and public-health concern. Although $PM_{2.5}$ concentrations have been studied extensively in many regions, air-quality information remains limited in North Africa, including Libya, due in part to the scarcity of monitoring stations and available data. Al Bayda, a mid-sized city in northeastern Libya, has experienced recurring air-quality concerns, with residents frequently reporting degraded conditions, particularly during nighttime hours. However, comprehensive information on $PM_{2.5}$ concentrations, their temporal variability, and the factors influencing their levels in Al Bayda remains limited.

The central research question of this study is: What are the levels and temporal patterns of $PM_{2.5}$ concentrations in Al Bayda, and what factors and potential local emission sources may contribute to elevated concentrations? Addressing this question is important because establishing baseline information on $PM_{2.5}$ exposure and understanding its temporal behavior can improve the scientific understanding of air quality in this resource-limited region and provide a basis for future air-quality monitoring and source-investigation efforts.

Study location

Al Bayda (the White City) is a mid-sized city in the northeast of Libya with unique geographical and environmental characteristics. The city (about 250,000 residents) is situated at approximately 32.76° N latitude and 21.76° E longitude in the elevated terrain of Al Jabal Al Akhdar (Green Mountain) district, approximately 600 m above sea level. Unlike the rest of Libya, the region of Al Jabal Al Akhdar is a heavily forested region with evergreen trees. The city's elevation and surrounding topography can influence air circulation patterns, potentially affecting the dispersion and concentration of air pollution. Residents of Al Bayda are frequently exposed to smoke plumes from the open burning of waste, particularly during nighttime hours when wind speeds are low and there are indications that the city experiences temperature inversions. Due to a lack of adequate waste disposal infrastructure, solid waste is being burned in the main disposal site on the southwest side of the city. Figure 1 shows Al Bayda city with the location of the west campus of Omar Al Mukhtar University and the location of the main solid waste disposal site.

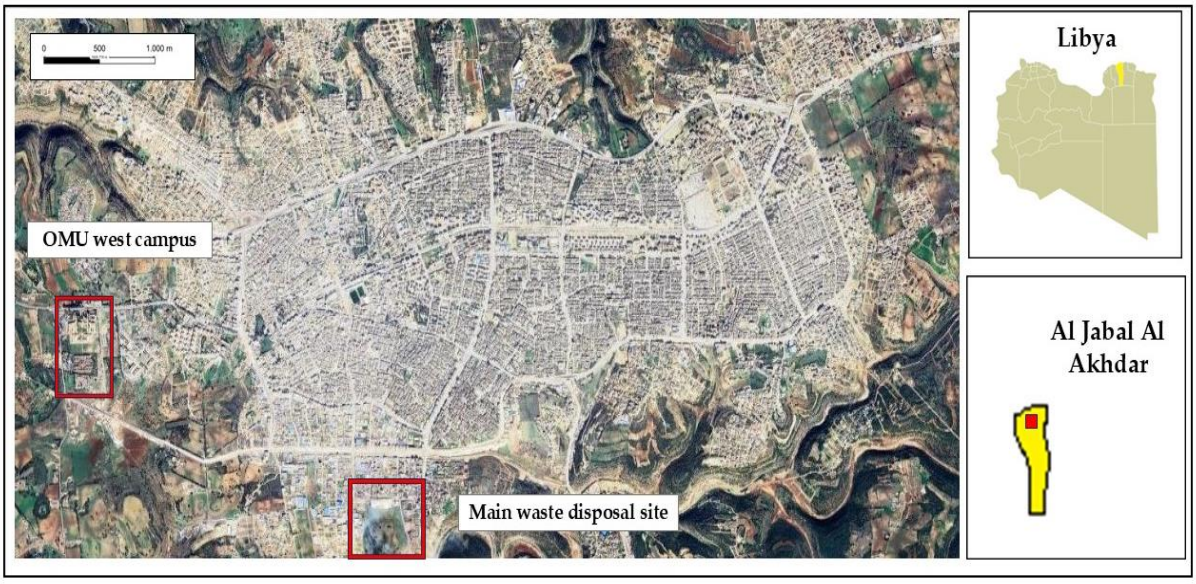

Figure: (1). Figure 1 Map of study area with location of Omar Al Mukhtar University (West campus) and the main waste disposal site in the south of the city.

A closer look at the main solid waste disposal site is shown in Figure 2. Smoke plumes from the open burning of waste on the site are visible. In addition to the main disposal site, solid waste often accumulates in various locations due to the poor management of local solid waste companies and municipalities. To avoid the odors of rotten food from such accumulations, residents often burn the collections of solid waste.

Figure: (2). The main solid waste disposal site in the south of Al Bayda, Libya.

The city also experiences heavy traffic, especially near downtown. It is important to note that there is no actual car emission testing in the city, and many cars are being driven without catalytic converters. Like any North African city, Al Bayda frequently experiences Saharan dust events from the south. Together, these and other factors could lead to low air quality in the city of Al Bayda.

MATERIALS AND METHODS

Data collection and description

Concentrations of $PM_{2.5}$ were recorded every minute during 2023 and 2024 using PurpleAir-II-SD air quality monitors deployed on Omar Al Mukhtar University campus, and subsequently aggregated into hourly data. For the same period, meteorological hourly data were also obtained from Al Bayda Weather Station, which is located on Omar Al Mukhtar University campus. The hourly $PM_{2.5}$ concentration readings were combined with weather data from the Al Bayda station. After missing data were removed, the data consisted of 10 variables (time, date, temperature, relative humidity, air quality index (AQI), $PM_{2.5}$, dew point temperature, wind speed, wind direction, pressure, and weather condition). The hourly dataset for 2023 contained 6214 records, while the 2024 dataset contained 6886 records. Daily averages were also prepared, yielding 289 days in 2023 and 326 days in 2024. These correspond to data completeness levels of 79% and 89%, respectively, relative to the total number of days in each year.

Literature Review

Kumar et al. (2020) investigated the temporal variability of particulate matter in Hyderabad, India, using hourly $PM_{2.5}$ and PM_{10} measurements collected from six monitoring stations over a two-year period (2018–2020). The study examined diurnal, monthly, and seasonal variations and found clear temporal patterns in particulate matter concentrations. $PM_{2.5}$ concentrations showed elevated levels during the morning and evening hours, with a minimum during the afternoon, while concentrations were generally higher during winter than during the monsoon season. The authors attributed these variations partly to differences in atmospheric dispersion conditions. These findings highlight the importance of examining temporal patterns and meteorological conditions when characterizing urban $PM_{2.5}$ pollution.

Awokola et al. (2022) investigated $PM_{2.5}$ concentrations across 15 monitoring sites in 11 cities in eight sub-Saharan African countries using a network of low-cost PurpleAir-II-SD sensors. The study assessed annual concentrations, seasonal variability, and diurnal patterns and reported annual $PM_{2.5}$ concentrations ranging from 10 to 116 μg/m³, with all study sites exceeding the WHO annual mean guideline of 5 μg/m³. Seasonal differences were particularly pronounced in Nigeria, where $PM_{2.5}$ concentrations were higher during the dry season than during the wet season. Diurnal variability was observed across all sites, with two major concentration peaks occurring around 06:00 and 18:00 local time. The authors associated these peaks with rush-hour periods and highlighted traffic-related emissions as an important potential source of $PM_{2.5}$.

Onyango et al. (2024) investigated ambient $PM_{2.5}$ concentrations in Mbarara, Uganda, and compared them with measurements from Kampala and WHO air-quality guidelines. They reported a daily mean $PM_{2.5}$ concentration of 26.7 μg/m³ in Mbarara, with concentrations exceeding WHO guidelines on 58% of days. $PM_{2.5}$ concentrations were significantly higher during the dry season than during the rainy season (30.8 versus 21.3 μg/m³), indicating an important influence of seasonal conditions on particulate pollution. The study also found no significant difference in $PM_{2.5}$ concentrations between weekdays and weekends, suggesting that temporal patterns cannot necessarily be attributed to weekday traffic activity alone.

As mentioned in the studies above, day-of-week variability in $PM_{2.5}$ concentrations is often attributed to variations in traffic and other human activities. Other studies have also reported lower $PM_{2.5}$ concentrations during weekends compared with weekdays (Tavella et al., 2023; Batterman et al., 2014; Zabalza et al., 2006; Krasnov et al., 2016).

Ramadan also provides an opportunity to examine the influence of human activity and traffic on air pollution because daily activity patterns change substantially during this period. In Yanbu, Saudi Arabia, increased nighttime activity during Ramadan was associated with changes in air-pollutant patterns, with the study reporting enhanced nighttime emissions and identifying traffic as an important contributor to the morning particulate peak (Khalil et al., 2016). In addition to traffic-related sources, $PM_{2.5}$ concentrations can be influenced by multiple sources such as Saharan dust, open waste burning, and other anthropogenic and natural sources (Moiwo et al., 2026; Zhou et al., 2014).

In Al Bayda, Libya, residents frequently report exposure to smoke from the open burning of waste, particularly during nighttime hours when wind speeds are low. Traffic emissions, particularly in the city center, and dust from Saharan Desert may also contribute to $PM_{2.5}$ concentrations. Despite these observations, no systematic scientific investigation has previously assessed $PM_{2.5}$ exposure levels, compared concentrations with international air-quality guidelines and standards, characterized their temporal variability, or investigated the potential contribution of different sources to $PM_{2.5}$ pollution in the city.

RESULTS AND DISCUSSION

The US-EPA 24-hour standard of 35 $\mu g/m^3$ was exceeded 25 times (9%) in 2023 and 46 times (14%) in 2024. The WHO 24-hour standard of 15 $\mu g/m^3$ was exceeded on 118 days (41%) in 2023 and 144 days (44%) in 2024. Annual average $PM_{2.5}$ concentrations were 15.4 $\mu g/m^3$ and 17.4 $\mu g/m^3$ in 2023 and 2024, respectively, exceeding both the WHO guideline (5 $\mu g/m^3$) and the US-EPA standard (9 $\mu g/m^3$). Figure 3 shows daily $PM_{2.5}$ levels compared to both the WHO and US-EPA standards. Tables 3 and 4 compares annual mean $PM_{2.5}$ concentrations in 2023-2024 with the WHO and US-EPA air quality standards while Figure 4 compares daily $PM_{2.5}$ concentrations in 2023–

2024 with the WHO (24-h guideline: 15 µg/m³) and US-EPA (24-h standard: 35 µg/m³) air quality standards.

These results are comparable to previous studies conducted across North Africa and sub-Saharan Africa, which have reported that annual average $PM_{2.5}$ concentrations often exceed both US-EPA and WHO standards. Katoto et al. (2019) reported annual averages ranging from 19 to 170 µg/m³ in Cameroon, Kenya, Madagascar, Mauritius, Nigeria, Senegal, South Africa, Uganda, and Tanzania. Similarly, Awokola et al. (2022), using low-cost sensors, found annual averages of 10–116 µg/m³ across eleven cities in eight countries: Nigeria, Sudan, Burkina Faso, Gambia, Benin, Cameroon, Uganda, and Kenya.

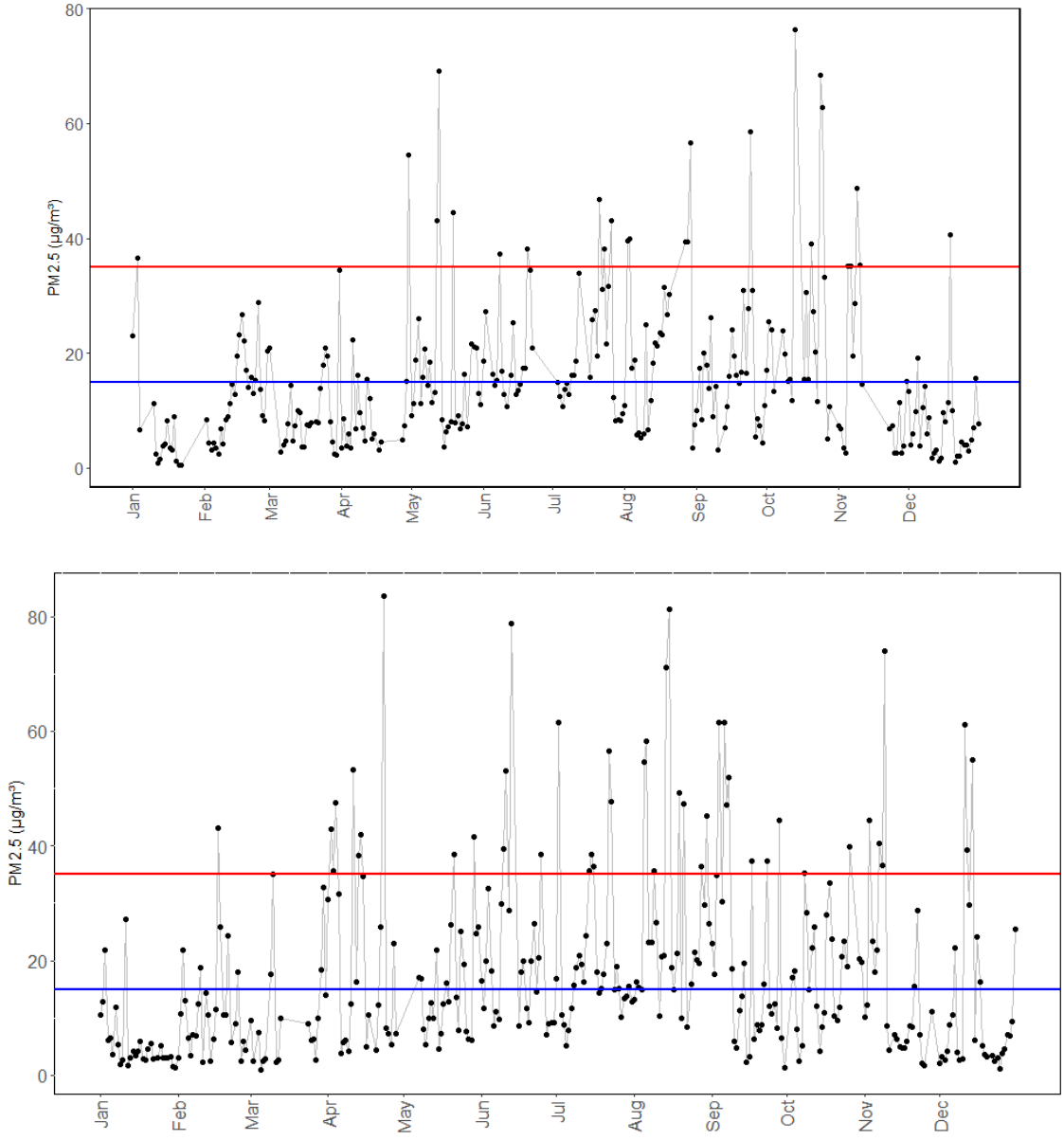

Figure: (3). Daily $PM_{2.5}$ concentrations compared to the WHO guidelines & US-EPA standards for (a) 2023 and (b) 2024

Table: (3). Annual mean $PM_{2.5}$ concentrations from the present study compared with the World Health Organization (WHO) air quality guidelines and United States Environmental Protection Agency (US-EPA) standards.

	Study data	WHO limit	US-EPA limit
Annual mean 2023	15.4	5	9
Annual mean 2024	17.4	5	9

Table: (4). Daily $PM_{2.5}$ concentrations from the present study compared with the World Health Organization (WHO) air quality guidelines and United States Environmental Protection Agency (US-EPA) standards.

	WHO limit	US-EPA limit	WHO Exceedances (%)	EPA Exceedances (%)
Daily averages 2023	15	35	41	9
Daily average 2024	15	35	44	14

Figure 4 shows the monthly averaged $PM_{2.5}$ concentrations in 2023 and 2024, indicating higher concentrations during warmer months. However, February and October in 2023 show relatively higher concentrations than other cold months and April and August in 2024 are elevated compared to adjacent months. The red curve represents the average monthly temperature given on the right y-axis. The temperature curve did not explain the increase in concentration in February and October of 2023 nor concentrations in April and August of 2024.

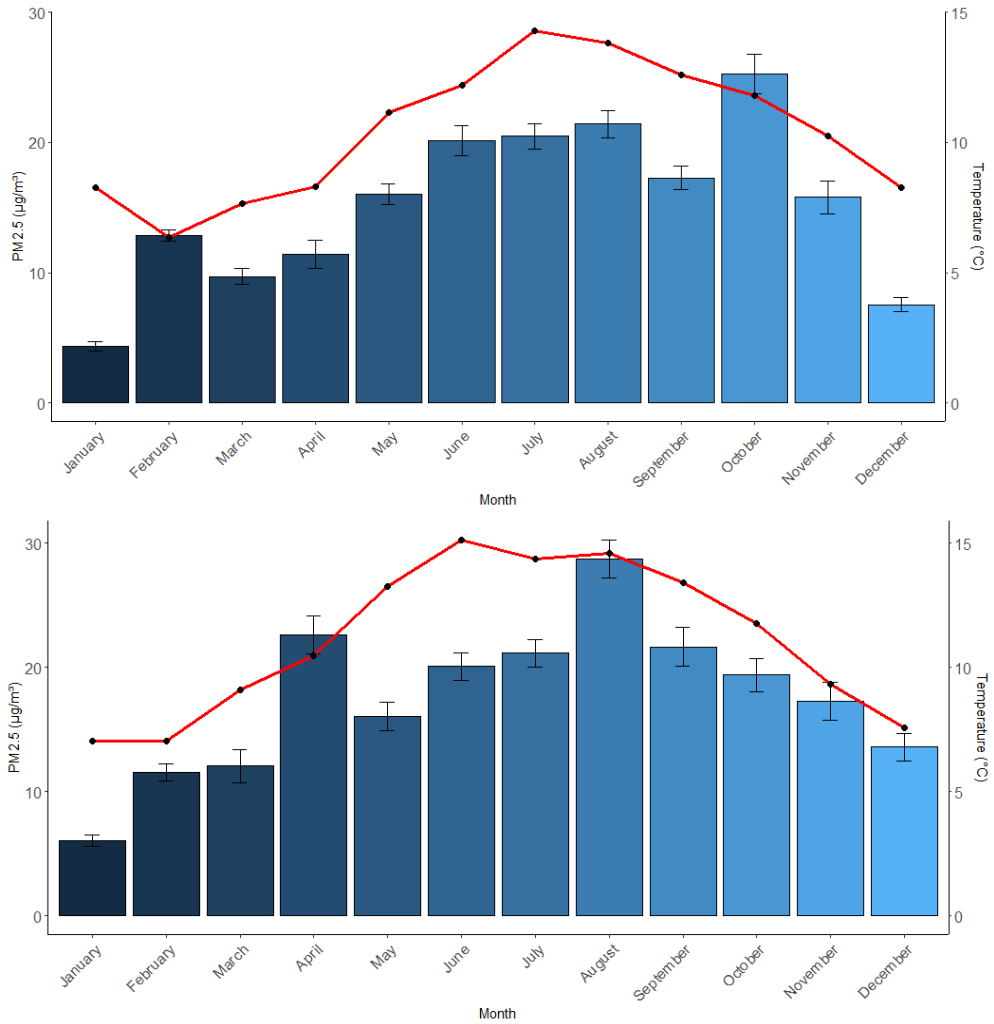

Figure: (4): Monthly averages of $PM_{2.5}$ measured in Al Bayda over the course of the study. Error bars are one standard deviation of the hourly measurements in each month.

To explore any seasonal variability, boxplots of $PM_{2.5}$ were generated for each day of the week and quarter of the year, as shown in Figure 5 (2023) and Figure 6 (2024). In 2023, the $PM_{2.5}$ data did not meet the assumptions of normality based on the Shapiro-Wilk tests and visual inspection; as a result, one-way ANOVA was not applicable. The Shapiro-Wilk test indicated that $PM_{2.5}$ concentrations for all days of the week significantly deviated from normality ($W = 0.495 - 0.655$, $p < 0.001$). This non-normality was also confirmed by histograms and Q-Q plots (see Supplementary Figure S1).

Since the normality assumption was violated, the nonparametric Kruskal–Wallis test was used instead. Results indicated a statistical difference in $PM_{2.5}$ concentrations between days of the week for January-March (Chi-square = 25.75, $p < 0.001$, df = 6), April-June (Chi-square = 61.15, $p < 0.01$, df = 6), and October-December (Chi-square = 58.29, $p < 0.01$, df = 6). No statistically significant difference was found for July-September (Chi-square = 12.49, $p > 0.05$, df = 6).

The results of the post hoc Dunn's test with Bonferroni correction show that, in the first quarter, Wednesday concentrations are significantly lower than Sunday and Monday. In the second quarter, Monday and Tuesday are statistically lower than almost all other days. The fourth quarter shows that Thursday, Friday, and Saturday are statistically different from Tuesday and Sunday.

Batterman et al. (2014), in their Near-Roadway Exposure and Urban Air Pollutant Study conducted in Detroit, Michigan, reported that $PM_{2.5}$ concentrations were significantly lower during weekends, particularly on Sundays. Similarly, Zabalza et al. (2006) observed in Alsasua, Spain, that particulate matter contributions were higher on weekdays, mainly attributed to traffic patterns. Krasnov et al. (2016) also found that both PM_{10} and $PM_{2.5}$ levels were reduced during weekends. In contrast, our findings showed that $PM_{2.5}$ concentrations during weekends (Friday and Saturday) did not exhibit the expected decrease, except during the fourth quarter. The results suggest that traffic has only a limited impact on $PM_{2.5}$ concentrations in the study area.

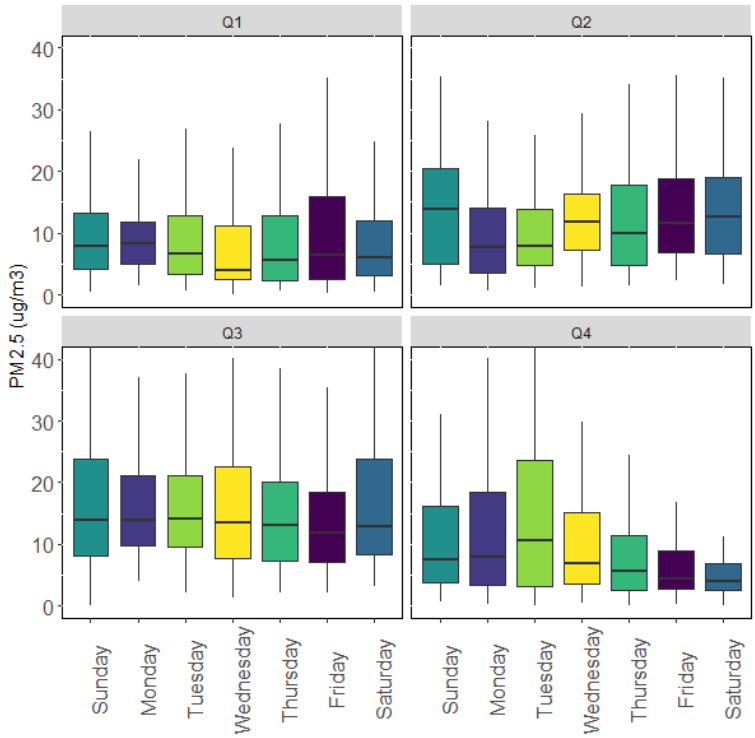

Figure: (5). Boxplots showing days-of-the-week variation of *$PM_{2.5}$* concentrations for four quarters of the year 2023.

Similarly, for 2024, the Shapiro-Wilk test showed the data for all days of the week did not meet the normality assumption (W = 0.475 - 0.517, $p < 0.001$). In Supplementary S2, Q-Q plots and histograms for 2024 $PM_{2.5}$ concentrations data are provided.

The Kruskal-Wallis test indicates a significant difference in $PM_{2.5}$ levels between at least two of the days of the week for every quarter of the year. More specifically, the test results are January-March (Chi-square = 61.71, $p < 0.001$, df = 6), April-June (Chi-square = 25.58, $p < 0.001$, df = 6), July-September (Chi-square = 17.47, $p = 0.008$, df = 6) and October-December (Chi-square = 38.67, $p < 0.001$, df = 6). The detailed pairwise comparisons between all possible pairs of days of the week within each quarter of the year are provided in Table S2 (Supplementary Material)

While the first quarter showed higher concentrations on weekends, the second and third quarters showed lower concentrations on Friday compared to some days. This again suggests that the observed variation is not systematic, and traffic is not likely to be a potential source.

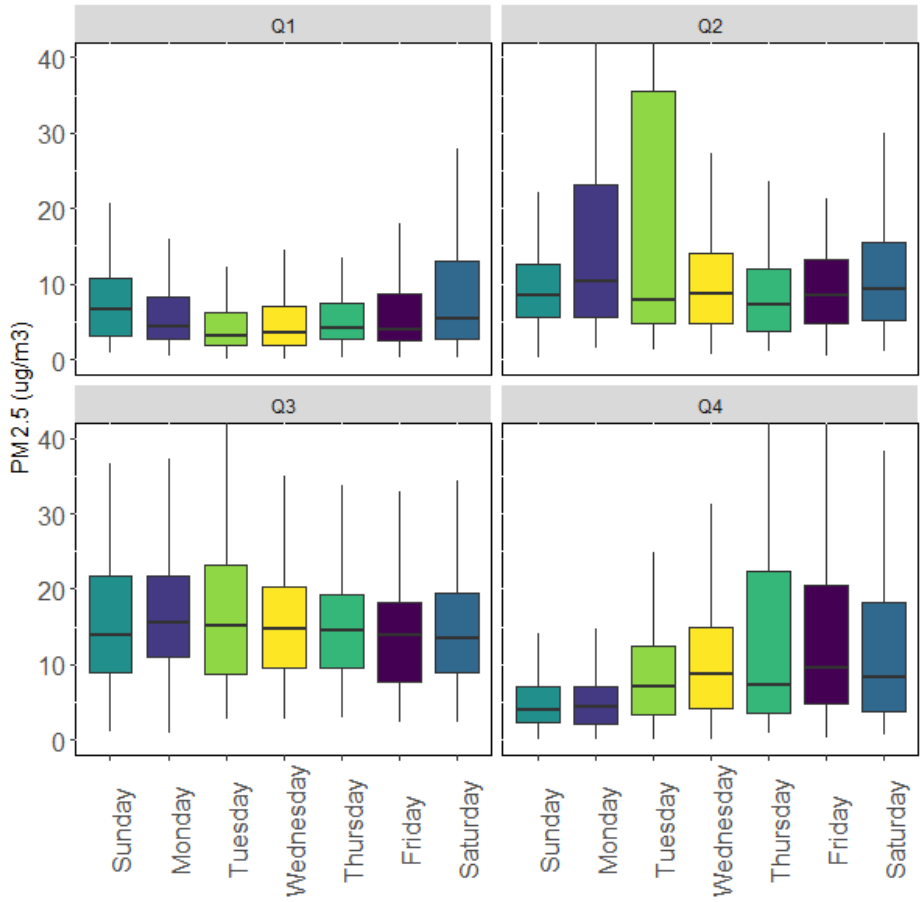

Figure: (6). Boxplots showing days-of-the-week variation of *$PM_{2.5}$* concentrations for four quarters of the year 2024.

It was hypothesized that higher $PM_{2.5}$ concentrations would occur at night, when winds tend to be calmer and temperatures are typically lower (Tunno et al., 2016; Shmool et al., 2014; Yang et al., 2017). Figure 7 presents hourly $PM_{2.5}$ concentrations along with the hourly air temperature (point size) and dew point temperature (point color) for 2023 and 2024. However, the figure does not clearly indicate that the high concentrations are associated with lower nighttime temperatures. Instead, the results suggest that seasonal temperature differences (summer vs. winter) are much

larger than daily variations, and these seasonal differences obscure the expected day-night temperature effect.

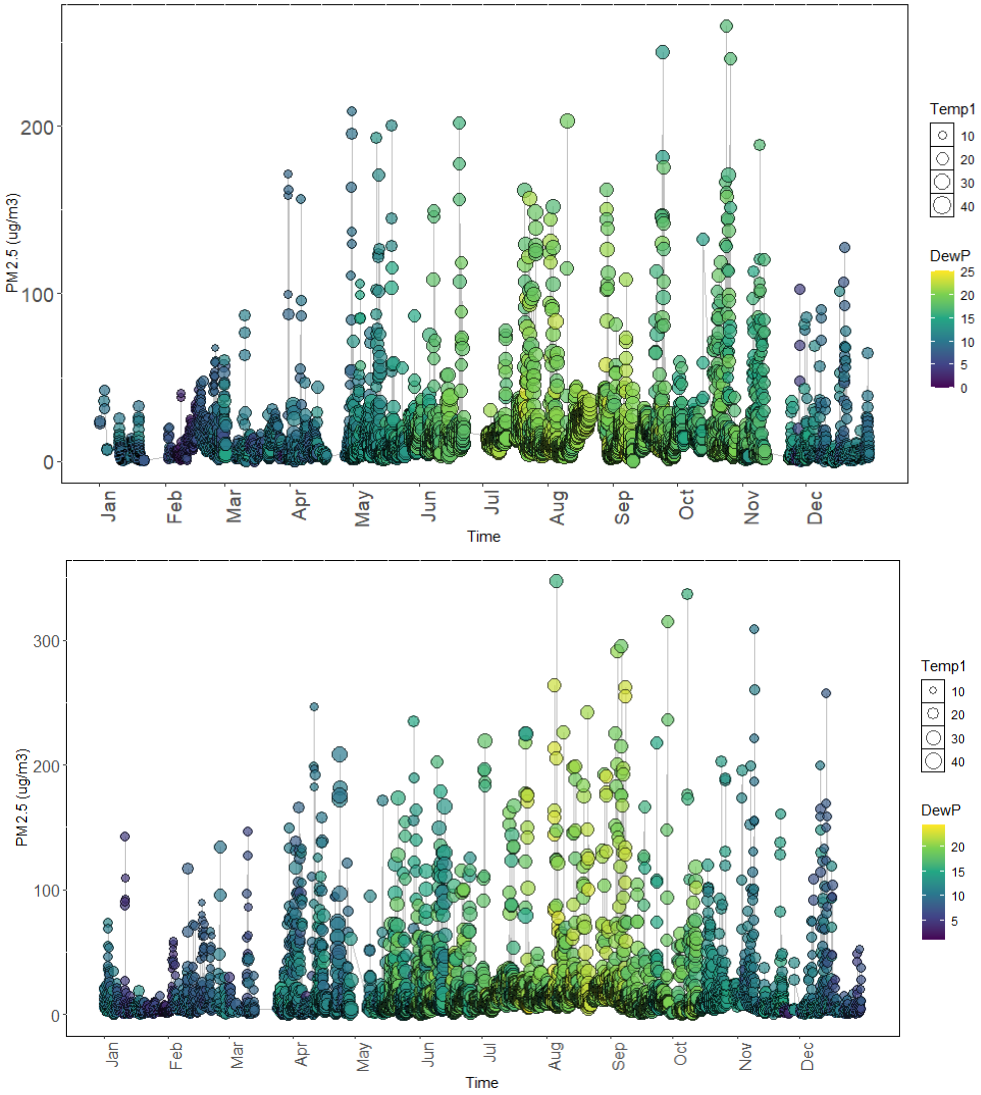

Figure: (7). Hourly *PM2.5* concentrations with point size indicating daily average air temperature and point color representing daily average dew point temperature in (a) 2023 and (b) 2024.

Diurnal $PM_{2.5}$ trends for each quarter of the year show elevated concentrations around midnight, which then begin to fluctuate during the pre-dawn period. During the morning, concentrations drop to very low levels throughout the day. In the afternoon, concentrations rise again until they peak at night (Figure 8 (2023) and Figure 9 (2024)).

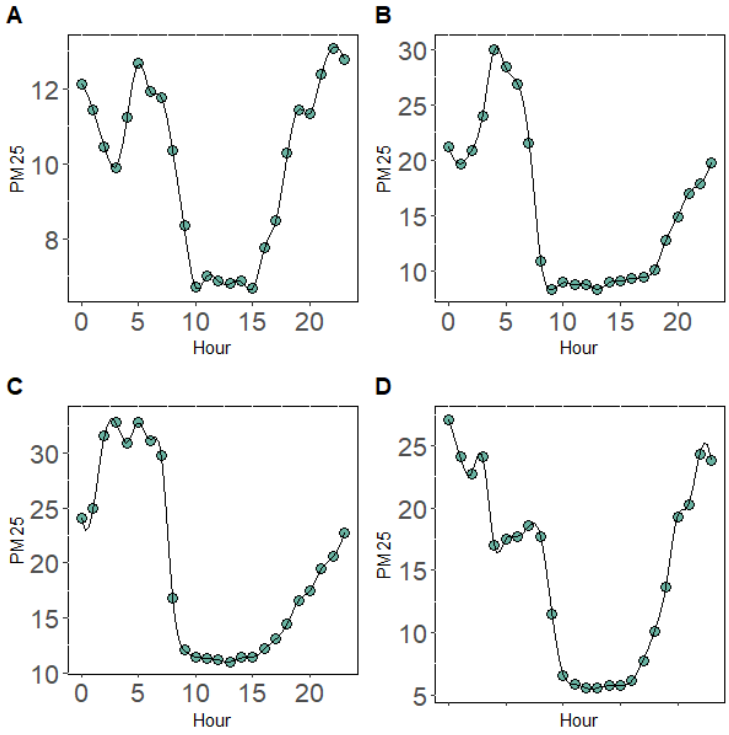

Figure: (8). Diurnal trends of $PM_{2.5}$ for each quarter of the year 2023

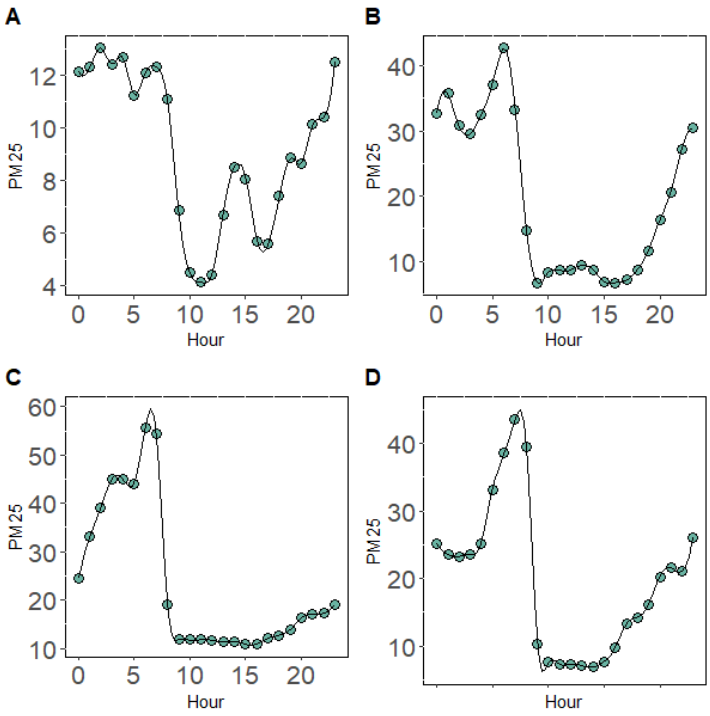

Figure: (9). Diurnal trends of $PM_{2.5}$ for each quarter of the year 2024.

Meteorological factors, especially wind speed, may explain these diurnal patterns. Reduction in $PM_{2.5}$ concentrations between 10 AM to 6 PM is likely due to favorable dispersion conditions (Kumar et al., 2020). Several studies have also reported that wind speed is negatively correlated with $PM_{2.5}$ (Li et al., 2015; Yang et al., 2017; Li et al., 2017; Tunno et al., 2016). In the study area,

daytime winds are stronger and more active during the day, while nighttime winds are weaker and often calmer. Diurnal wind speed graphs from 2023 and 2024 are shown in Figure 10 and Figure 11, respectively. The two figures 8 and 10 clearly show the inverse impact of wind on the $PM_{2.5}$ concentrations as well as figures 9 and 11. These findings are consistent with the above-mentioned studies that show a negative impact of wind speed on $PM_{2.5}$ concentrations.

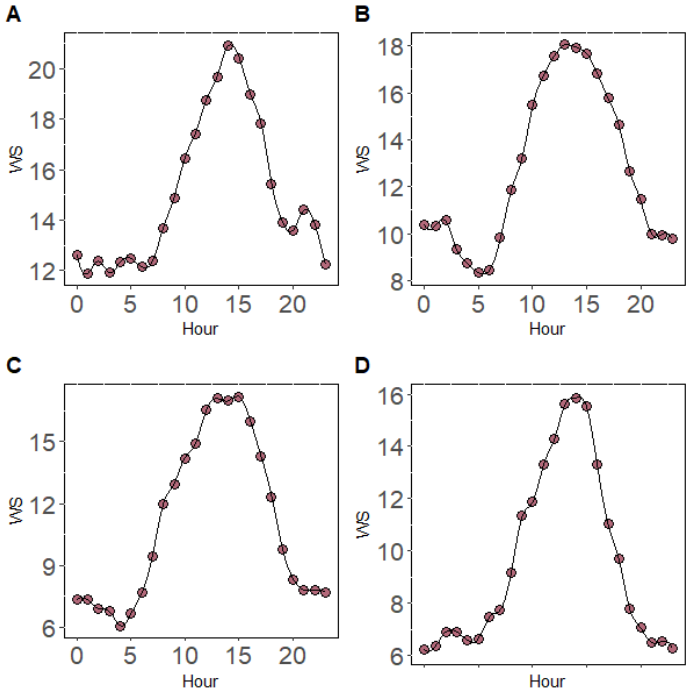

Figure: (10). Diurnal trends of wind for each quarter of the year 2023

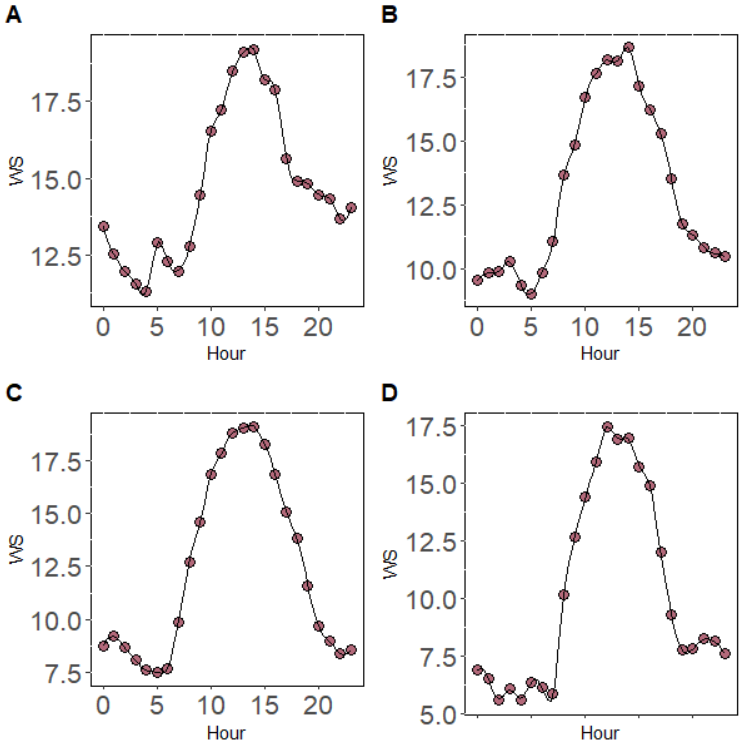

Figure: (11). Diurnal trends of wind for each quarter of the year 2024

Figure 12 shows the linear relationship between wind speed and $PM_{2.5}$ concentrations for the years 2023 and 2024. A negative correlation is observed, indicating that higher wind speeds are generally associated with lower $PM_{2.5}$ concentrations.

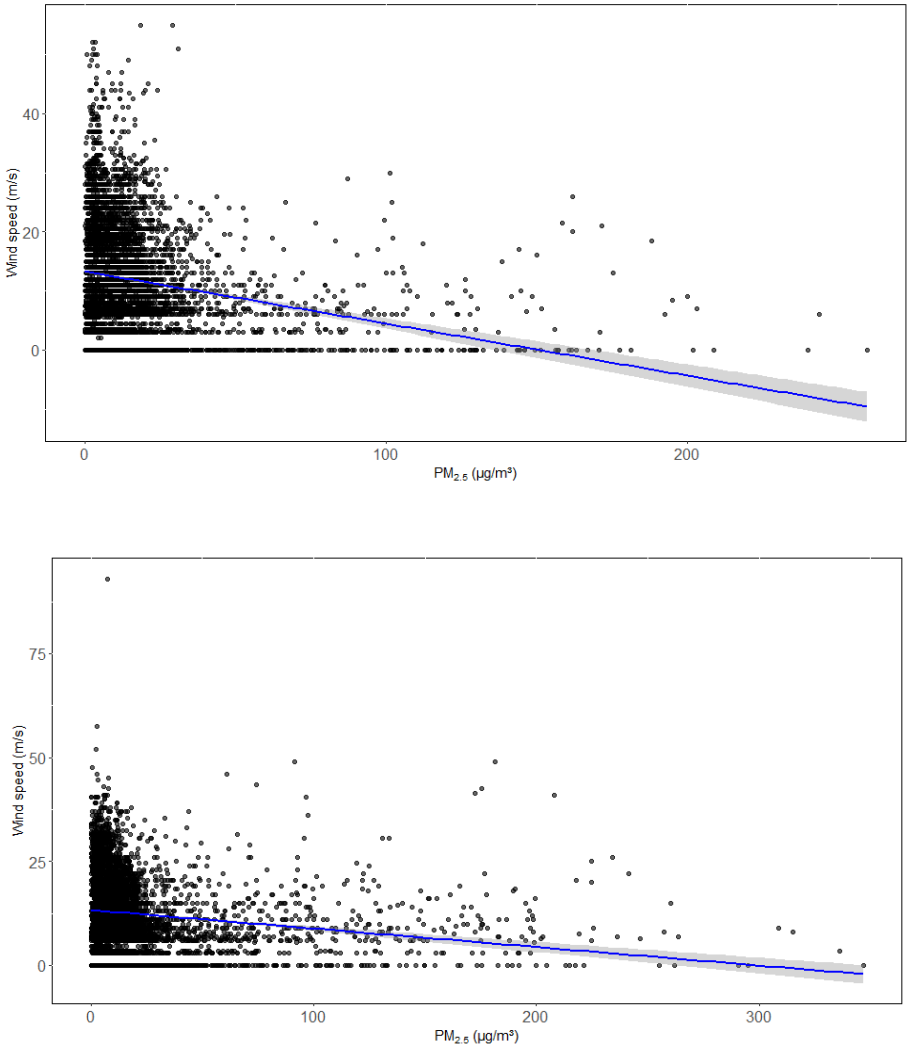

Figure: (12). Linear correlation between wind speed and $PM_{2.5}$ concentrations for the years 2023 and 2024.

Figure 13 shows the time series of the $PM_{2.5}$ concentrations incorporating the effect of wind speed and the hour of the day. The size of the data points reflects wind speed, with larger points indicating higher wind speeds. On the other hand, the hour of the day is indicated by the color of the points. With a few exceptions, most high-concentration events were associated with low wind speed, indicated by small-sized points. The yellow and very dark colors of the points indicate that the high $PM_{2.5}$ concentrations occurred around midnight. The observed nighttime increases are consistent with intermittent local emission activities, such as open waste burning, which are known to occur irregularly and predominantly at night.

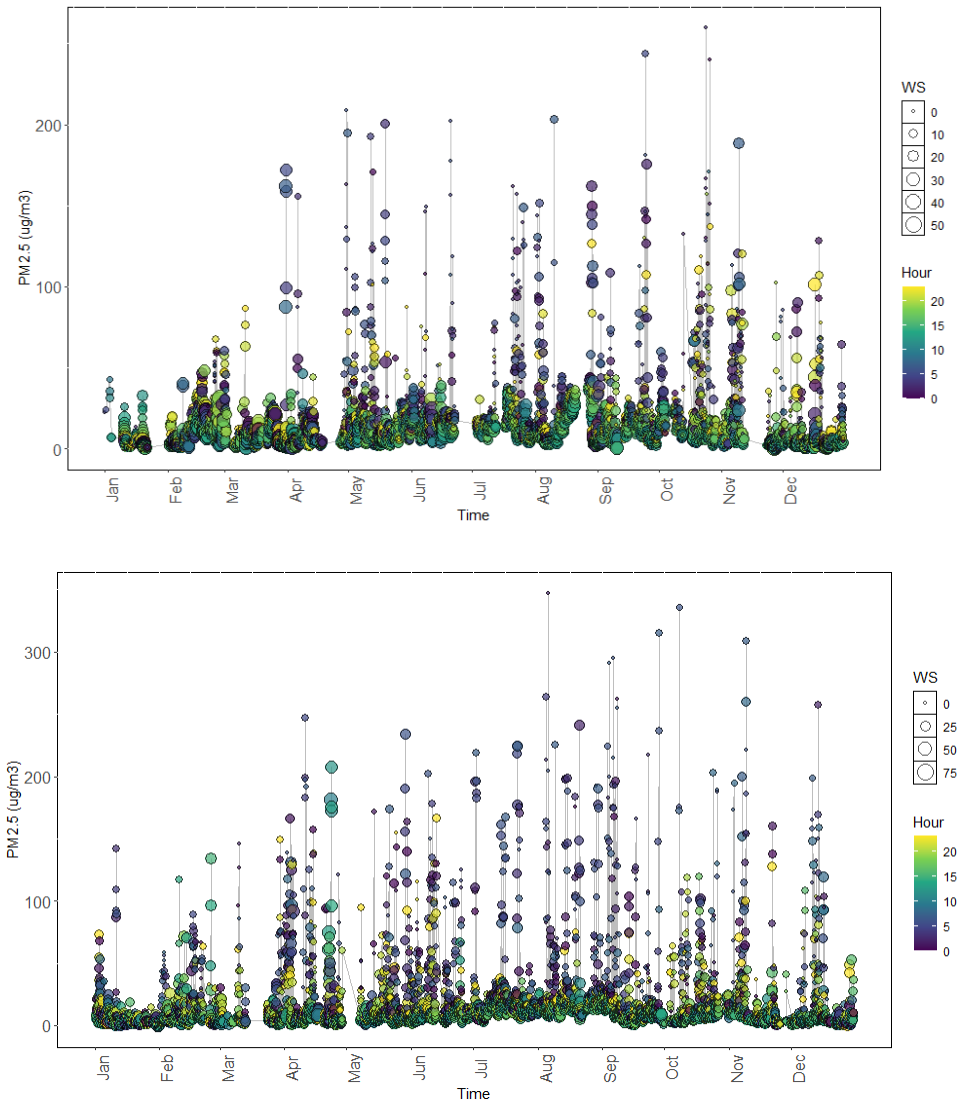

Figure: (13). Presents the time series of $PM_{2.5}$ concentrations, incorporating the effect of wind speed and the hour of the day. The size of the data points reflects wind speed, with larger points indicating higher wind speeds. The hour of the day is indicated by the color of the points: (a) 2023 and (b) 2024.

Another variable of interest is the weather condition, categorized as fair, fair/windy, cloudy, mostly cloudy/windy, and rainy. Figure 14 presents diurnal $PM_{2.5}$ concentrations grouped by weather condition for (a) 2023 and (b) 2024. The data indicate that both rain and wind are associated with lower $PM_{2.5}$ concentrations. Awokola et al. (2022) reported that $PM_{2.5}$ concentrations were higher during the dry season than during the wet season and suggested that rainfall could be responsible for this reduction in concentrations. According to Zabalza et al. (2006), the lower $PM_{2.5}$ concentrations observed in fall and winter may be attributed to the higher rainfall during these seasons. Similarly, a number of studies have reported a negative correlation between rainfall and $PM_{2.5}$ concentrations (Li et al., 2017; Ntziachristos et al., 2007).

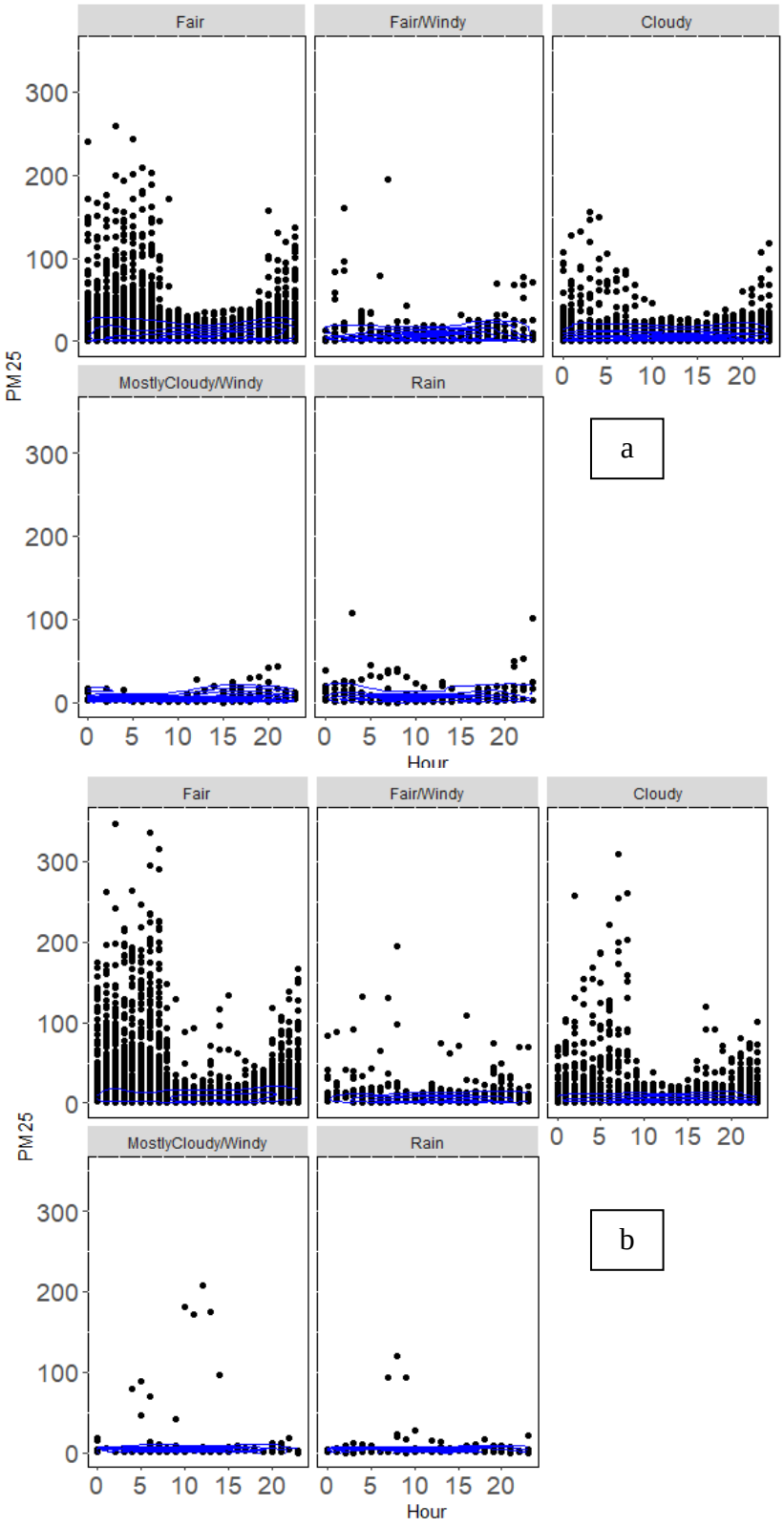

Figure: (14). Diurnal variation of $PM_{2.5}$ concentrations under different weather conditions. Each subplot represents a distinct weather category (fair, fair/windy, cloudy, mostly cloudy/windy, and rainy), with the x-axis showing hour of the day and the y-axis showing $PM_{2.5}$ concentration ($\mu g/m^3$). Notably, $PM_{2.5}$ levels are substantially lower during rainy conditions compared to other weather types, consistent with the removal of airborne particles by precipitation: (a) the 2023 data and (b) the 2024 data.

Ramadan is a month-long religious observance in the region where this study was conducted. During this period, work and school typically begin at 9:30 a.m., later than on regular days. Daily traffic patterns also shift: traffic increases around 5 p.m., drops sharply just after sunset, and rises again at night due to shopping and other activities. These changes in traffic behavior provide an opportunity to examine its impact on $PM_{2.5}$ concentrations by comparing diurnal $PM_{2.5}$ trends during Ramadan with those from the rest of the year. Figure 15 shows this comparison for 2023 and 2024. The results indicate no notable differences, suggesting that traffic has only a limited influence on $PM_{2.5}$ concentrations (Khalil et al., 2016).

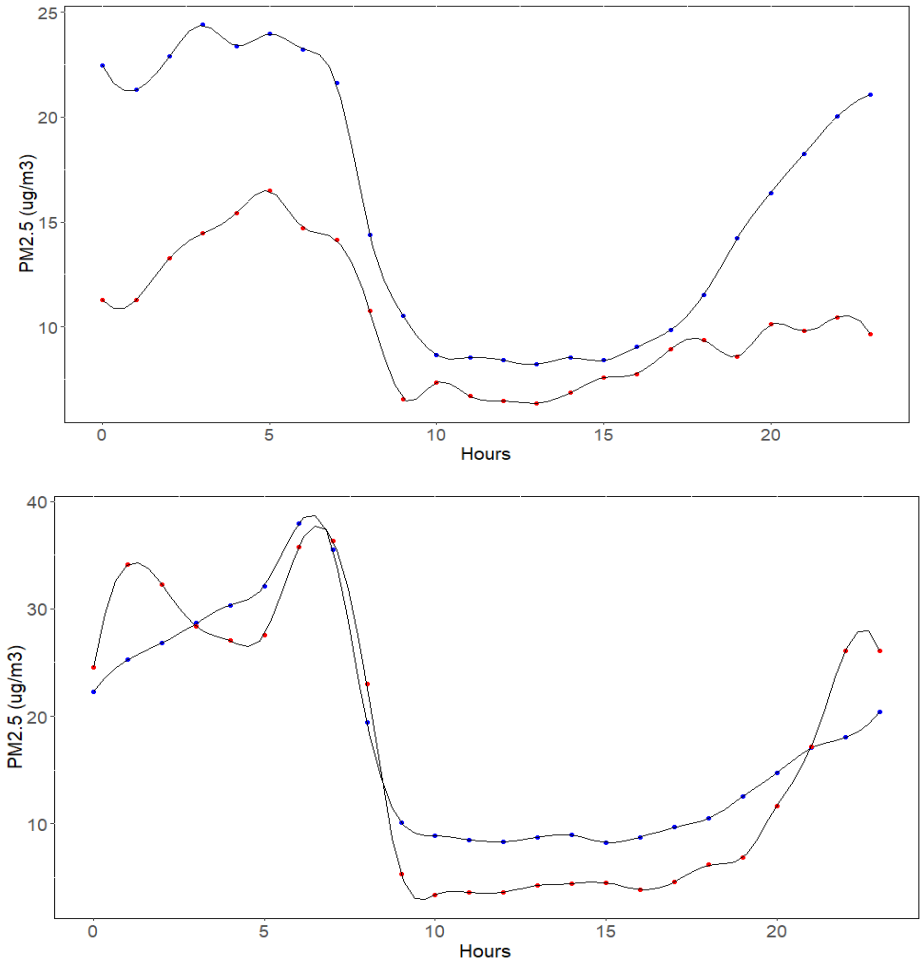

Figure: (15). Diurnal variation of $PM_{2.5}$ concentrations during the month of Ramadan compared to the rest of the year (a) for 2023 and (b) for 2024. Despite Ramadan's distinct traffic patterns, the two curves exhibit nearly identical behavior, suggesting that traffic may not be the dominant factor influencing $PM_{2.5}$ levels in the study area. The slightly lower values observed during Ramadan may be attributed to limited data availability.

CONCLUSION

$PM_{2.5}$ concentrations were monitored in Al Bayda, Libya, over a two-year period (2023–2024) to improve understanding of air quality in this source-limited region. The analyses showed that both WHO and US-EPA standards were exceeded, with annual averages surpassing the limits in both years and daily averages frequently exceeding the guidelines and standards. These findings underscore the need for additional efforts to improve air quality in the region.

Temporal analyses indicated that weekdays do not exhibit a distinctive pattern in $PM_{2.5}$ concentrations. Similarly, diurnal trends during Ramadan were comparable to those observed

during the rest of the year. Taken together, the weekday boxplots and diurnal trends do not provide strong evidence that traffic is a dominant contributor to $PM_{2.5}$ concentrations in the study area.

Diurnal trends of $PM_{2.5}$ concentrations and wind speed, however, indicate that $PM_{2.5}$ levels are strongly influenced by meteorological conditions. Specifically, higher wind speeds during the daytime appear to reduce $PM_{2.5}$ concentrations, while calmer nighttime winds allow particles to accumulate, leading to increased concentrations. Rainy weather also has a negative impact on $PM_{2.5}$ concentrations.

Monthly $PM_{2.5}$ concentration graphs, together with weekday boxplots, suggest that the timing of elevated concentrations does not follow a consistent or systematic pattern. Based on the above analyses, the observed nighttime increases are consistent with intermittent local emission activities, including open waste burning, which are known to occur irregularly and predominantly at night, but source-specific measurements are needed to confirm their contribution.

To further investigate the source of $PM_{2.5}$ concentrations, chemical composition analyses are recommended. Additionally, a community-engaged follow-up study in which residents use technology to report poor air quality events could help identify emission sources and provide a more detailed spatial understanding of $PM_{2.5}$ concentrations.

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Author contributions: M.E., H.B., G.A., and S.L.M. contributed to the initial conceptualization of the study, including defining the research objectives, methodology, and analysis framework. F.A. was primarily responsible for data collection, sensor operation, routine maintenance, and troubleshooting to ensure continuous sensor performance. Data downloads were performed by H.B. and F.A. M.E. conducted the data analysis, developed and ran the analysis codes, and prepared the original manuscript draft. Statistical methods were developed and refined by M.E., G.A., and H.B. S.L.M. provided scientific advice and guidance throughout the study and reviewed and edited the manuscript drafts. All authors reviewed the final manuscript and approved the submitted version.

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