Investigations on the Patterns of Air Pollution in the Emirate of Abu Dhabi, United Arab Emirates (UAE)

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Abstract

Understanding the formation and spatiotemporal distribution of particulate matter (PM) is crucial in atmospheric science and air quality assessment (Omari et al., 2019). PM comprises a mix of organic and inorganic particles suspended in the air, categorized by aerodynamic diameter into PM_{10} (2.5–10 µm) and $PM_{2.5}$ (<2.5 µm), with the latter largely derived from gaseous precursors (Abuelgasim and Farahat, 2020; Abuelgasim et al., 2021). This study analyses the distribution of air pollutants in the Emirate of Abu Dhabi using hourly data from air quality stations to assess concentrations of PM_{10}, $PM_{2.5}$, and other gases such as NO_2 , CO, SO_2 , and O_3 . Spatial maps and statistical analyses reveal that PM concentrations follow a seasonal cycle, peaking in summer due to natural dust events and declining in winter. Maximum PM_{10} and $PM_{2.5}$ values reached 218 µg/m³ and 60 µg/m³ in summer, and 169 µg/m³ and 34 µg/m³ in winter, respectively. The $PM_{2.5}$ / PM_{10} ratio was generally below 0.5, indicative of dominant natural sources typical of arid environments (Abuelgasim and Farahat, 2020). Results suggest that the primary drivers of pollution are desert dust and transboundary transport, with limited influence from local anthropogenic sources. While this study focuses on inland areas, future research will address coastal zones where sea salt aerosols and human activities, including marine transport and urbanization, may contribute significantly to air pollution.

1. Introduction

Air pollution is a significant environmental challenge in urban areas, with particulate matter (PM) being one of the primary pollutants affecting air quality. These airborne particulates originate from both natural sources—such as wildfires, desert storms, and volcanic eruptions—and anthropogenic activities, including industrial emissions, vehicle exhaust, and dust resuspension (Al Suwaidi et al., 2024; Abuelgasim & Farahat, 2020). PM consists of a mixture of solid and liquid particles released into the atmosphere through processes such as diesel combustion, road and agricultural dust, and industrial operations (Thangavel et al., 2022).

Particulate matter is typically classified based on its aerodynamic diameter: PM_{10} refers to particles with diameters of 10 micrometers or less, while $PM_{2.5}$ refers to finer particles with diameters of 2.5 micrometers or less (Abuelgasim & Farahat, 2020). $PM_{2.5}$ poses a particularly serious threat to human health, as these fine particles can be inhaled into the respiratory system, penetrate deep into the alveoli of the lungs, and enter the bloodstream (Ramadan, Abuelgasim, & Al Hosani, 2024; Thangavel et al., 2022). Consequently, prolonged exposure to high levels of PM has been linked to an increased risk of respiratory diseases such as asthma, as well as chronic conditions like lung cancer (Al Suwaidi et al., 2024). Additionally, high infant mortality rates in some developing countries, particularly in parts of Africa, have been associated with poor air quality and elevated pollution levels (Ghorani-Azam et al., 2016).

The United Arab Emirates (UAE) experiences frequent dust storms throughout the year, contributing to degraded air quality and elevated concentrations of suspended particulate matter. The UAE's geographic location in an arid and semi-arid climate zone significantly influences the frequency and intensity of sand and dust storms, which in turn impact air quality on both seasonal and annual timescales. Given these conditions, assessing air quality by monitoring $PM_{2.5}$ and PM_{10} concentrations is essential for understanding pollution trends and formulating effective mitigation strategies.

Abu Dhabi, the capital of the UAE, is located at 24°24′49″N, 54°25′59″E. It shares international borders with Saudi Arabia to the south and the Sultanate of Oman to the east (Figure 1). Covering the largest land area of any emirate, Abu Dhabi includes extensive desert regions that serve as a major natural source of PM_{10} due to wind-blown dust and recurring sandstorms.

This study aims to assess air quality in the Emirate of Abu Dhabi by analyzing $PM_{2.5}$ and PM_{10} concentrations across 20 monitoring locations distributed across the emirate's three main regions: Abu Dhabi, Al Ain, and Al Dhafra. Table 1 provides a list of these monitoring locations and their respective classifications by site type.

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Name	Type
Hamdan Street	Urban Traffic
Khadejah School	Urban Background
Khalifa School	Suburban Background
Mussafah	Suburban Industrial
Baniyas School	Suburban Background
Al Ain Islamic Institute	Suburban Background
Al Ain Street	Urban Traffic
Bida Zayed	Suburban Background
Gayathi School	Suburban Background
Liwa	Rural Background
Ruwais	Suburban Industrial
Habshan South	Rural Industrial
E11 Road	Rural Traffic
Bain Al Jessrain	Suburban Background
Khalifa City A	Suburban Background
Al Mafraq	Suburban Industrial
Sweihan	Suburban Background
Al Tawia	Suburban Background
Zakher	Urban Background
Al Qua'a	Rural Background

Table1. Land Use of 20 Locations Distributed in Abu Dhabi

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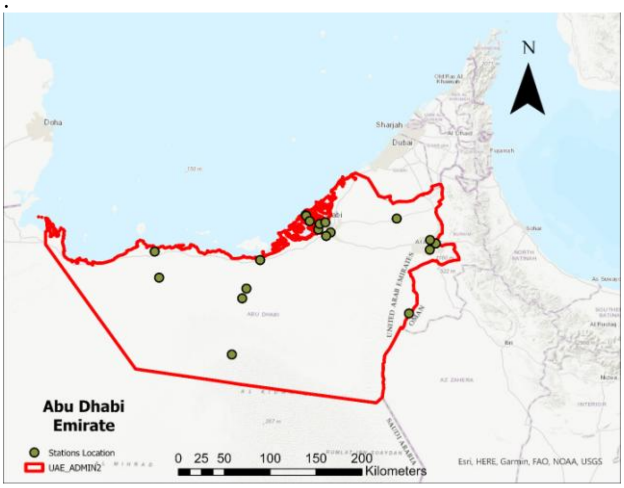

Figure 1. The Study Area and the Location of 20 stations in Abu Dhabi

By measuring PM levels on a monthly basis, this study aims to identify trends and variations in air pollution across different environments. Understanding these patterns is essential for determining the primary sources of particulate matter pollution and assessing how various background types influence air quality. This analysis is critical for the development of targeted mitigation strategies, the enhancement of air quality regulations, and the reduction of health risks associated with prolonged exposure to airborne particulates.

2. Data and Methods

The data for this study were obtained from the Abu Dhabi Government and are based on 20 monitoring locations distributed across the three main regions of the emirate: Abu Dhabi, Al Ain, and Al Dhafra. The study utilized daily and monthly average concentrations of PM_{10} and $PM_{2.5}$ from these locations for the year 2022 (Figure 1). These datasets provided essential insights into particulate matter concentrations across the study area.

2.1 Interpolation Method: Inverse Distance Weighting (IDW)

The Inverse Distance Weighting (IDW) interpolation method was applied using ArcMap to generate monthly spatial distribution maps of PM_{10} and $PM_{2.5}$ for the year 2022. IDW was selected for its ability to estimate values based on nearby observations while effectively preserving local spatial variations (Shepard, 1968). The IDW interpolation equation is expressed as follows:

$$Z(x) = \frac{\sum_{i=1}^{N} \frac{z_i}{d_i^p}}{\sum_{i=1}^{N} \frac{1}{d_i^p}} \quad (1)$$

In the IDW interpolation formula, Z(x)Z(x)Z(x) represents the estimated value at the interpolation point xxx, ZiZ_iZi is the known value at sample point iii, did_idi denotes the distance between the interpolation point xxx and the known point iii, ppp is the power parameter that controls the influence of distance, and NNN is the total number of sample points used in the interpolation. The flowchart illustrating the interpolation process is provided in Figure 2.

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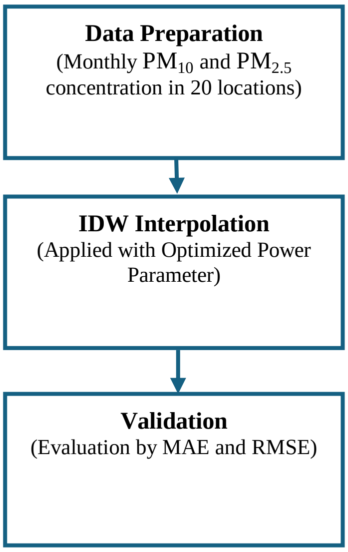

Figure 2. The flowchart for Interpolation for 2022

2.2 Land Use-Based Comparison

To evaluate the impact of land use on PM distribution, the study classified the area into six distinct land use categories: Urban Traffic, Urban Background, Suburban Background, Suburban Industrial, Rural Background, and Rural Industrial. Trends in PM_{10} and $PM_{2.5}$ concentrations were analyzed for each land use type based on the provided monthly particulate matter data. Temporal variations were examined to identify seasonal patterns and understand the dynamics of air pollution (Huang et al., 2014).

2.3 PM Ratio Analysis for Source Identification

To investigate potential sources of particulate matter (PM), the PM ratio was calculated for each location and land use category. This ratio provides insight into the dominant sources of PM. Specifically, higher ratios indicate a stronger influence from combustion sources, such as traffic emissions and industrial activities (human sources), while lower ratios suggest a greater contribution from coarse or larger particles, such as dust resuspension and natural sources (Zhang et al., 2015; Al-Dabbous & Kumar, 2015). Additionally, the ratio analysis was further complemented by seasonal assessments to identify potential shifts in pollution sources throughout the year. The equation for the PM ratio is as follows:

$$PM\ ratio = \frac{PM_{2.5}}{PM_{10}} \qquad (2)$$

Where $PM_{2.5}$ is the concentration of fine particles equal or smaller than 2.5 (≤2.5) and PM10 is the concentration of coarse particles equal or smaller than 10 (≤10).

3. Results and Discussions

This section will display the major findings of the study which are divided into three main sections.

3.1 $PM_{2.5}$ Interpolation Maps based on 20 Monitoring Points in Abu Dhabi (PM2.5)

The interpolated maps above depict the spatial distribution of $PM_{2.5}$ concentrations across the Abu Dhabi Emirate for the year 2022, based on the Inverse Distance Weighting (IDW) method. $PM_{2.5}$ concentrations began to rise in May, reaching a peak value of approximately 60 µg/m³ in August (summer season), followed by elevated levels in September and October. In contrast, the lowest concentration was recorded in January, at around 21.15 µg/m³, during the winter season.

A study by Al-Jallad et al. (2017) reported a similar seasonal pattern, attributing higher $PM_{2.5}$ levels in summer to frequent dust storms, while lower concentrations in winter were associated with increased rainfall events, which help in settling particulate matter.

The best air quality, as indicated by the maps, was observed in the eastern part of the emirate specifically in the Al Ain region—between January and April, with concentrations below 21 µg/m³. Conversely, the poorest air quality was recorded from August to October across most of Abu Dhabi, except in the eastern region. In November and December, $PM_{2.5}$ concentrations above 60 µg/m³ were observed in the northwestern areas of the emirate, while the remaining regions experienced moderate levels ranging between 34–47 µg/m³.

This spatial pattern can be attributed to the dominance of desert and sandy terrain in the northwestern and inland areas of Abu Dhabi, which influences local weather conditions and contributes to higher $PM_{2.5}$ levels. A similar distribution pattern was reported by Wei et al. (2023) in a study on $PM_{2.5}$ concentrations in China, where elevated values in the northwestern region were linked to frequent sand and dust processes that persist throughout much of the year.

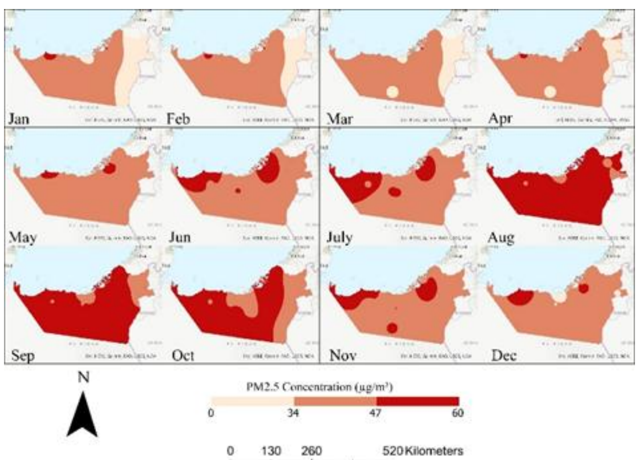

Figure3. Interpolation Monthly Maps of $PM_{2.5}$ for 2022

3.2 Interpolation Maps based on 20 points in Abu Dhabi (PM_{10})

Figure 4 presents interpolated maps illustrating the average monthly concentrations of PM_{10}, showing a gradual increase from January to December. From January to April, PM_{10} concentrations are classified as low, with minimum recorded values of approximately 74.2 µg/m³, 78.7 µg/m³, 72.9 µg/m³, and 75.2 µg/m³, respectively. However, concentrations begin to rise from May to July, with monthly averages ranging between 120–169 µg/m³. The highest PM_{10} concentration is observed in August, reaching approximately 218 µg/m³—particularly in the central Abu Dhabi region, parts of the eastern region (Al Ain), and the western region (Al Dhafra).

The primary source of PM_{10} in these regions is natural, stemming from sand and dust storms associated with the UAE part of Al Rub' al Khali desert. These storms frequently occur between April and September, significantly increasing PM_{10} levels (Abuelgasim & Farahat, 2020). Furthermore, transboundary transport from the deserts in neighbouring Saudi Arabia adds further to the dust concentrations in western Abu Dhabi as evident in Figure 4.

The seasonal variability of PM_{10} in desert regions like the UAE is strongly influenced by the frequency of dust storms and heat waves, both of which are intensified by high summer temperatures (Saqer et al., 2024). A related study on PM_{10} in Abu Dhabi confirmed this trend, indicating that the lowest concentrations occur during the winter months, while the highest are recorded during the summer (Saqer et al., 2024).

For example, Habshan, located in the Al Dhafra region of Abu Dhabi, is a rural industrial area known for significant emissions of PM_{10} and $PM_{2.5.}$ The presence of major oil and gas processing facilities, combined with natural desert dust, contributes to elevated levels of air pollution in the region (Abuelgasim & Farahat, 2020).

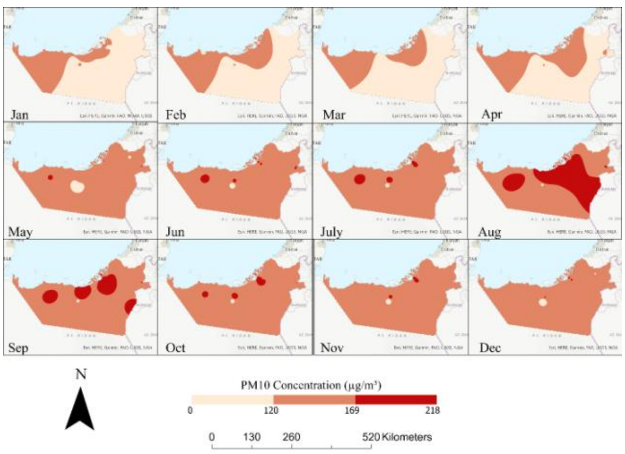

Figure 4. Interpolation Monthly Maps of PM_{10} for 2022

3.3 $PM_{2.5}$ and PM_{10} Trend in the 6 different locations in Abu Dhabi

In this section, Figure 5 illustrates the monthly average trends of PM_{10} and $PM_{2.5}$ concentrations throughout the year 2022. Only six stations were chosen from the dominant land use in the emirate for brevity. Overall, the data show an increase in particulate matter levels beginning in April (spring season), reaching a peak during the summer months of July and August. The autumn season exhibited elevated PM concentrations until the end of September for both PM_{10} and $PM_{2.5}$, followed by a decline leading into the winter season (December to February).

Similarly, previous studies on PM concentrations in Abu Dhabi have reported comparable trends for $PM_{2.5}$ and PM_{10}. A decrease in PM levels was observed during the early months of the year (winter), followed by a significant increase from June to August (summer). This seasonal rise is primarily attributed to elevated air temperatures, accompanied by gusts of sandstorms and dust particles typical of the summer months in the region (Abuelgasim & Farahat, 2020). In general, this pattern is observed in mostly all studied land-use categories, suggesting that natural pollution sources are the dominant sources of air pollution.

However, variations in the magnitude of PM levels were evident across different locations and land-use types. Industrial areas exhibited the highest concentrations of PM_{10}, with recorded values of approximately 217.63 µg/m³ in Habshan South, 214.87 µg/m³ in Al Mafraq, and 191.89 µg/m³ in Mussafah. These were followed by the rural area of Al Qua'a, with an average of 180.39 µg/m³, and the suburban background area, with 161.91 µg/m³. The lowest concentration was observed in the urban traffic site of Hamdan Street, at 123.86 µg/m³.

According to Saqer et al. (2024), industrial activities are the leading contributors to particulate emissions in the Abu Dhabi Emirate, accounting for 45% of PM_{10} emissions (4,427 tons/year), followed by the oil and gas sector at 28% (2,793 tons/year), and road transportation at 15% (1,464 tons/year).

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Figure 5. Comparison between PM_{10} and $PM_{2.5}$ in six different land uses.

3.4 $PM_{2.5}/PM_{10}$ Ratio for 2022 in Six Different Locations

Figure 6 presents the $PM_{2.5}$ / PM_{10} ratio results for six different locations in the UAE, based on the monthly values of PM_{10} and $PM_{2.5}$. Overall, the PM ratios are below 0.5, indicating again that the dominant sources of particulate matter are natural rather than anthropogenic—primarily dust storms and agricultural activities. The graphs display monthly fluctuations in the PM ratio, with lower values observed during the summer months (June to August) and higher values during winter. This seasonal pattern aligns with previous studies, which found higher PM ratios in winter and lower ratios in summer due to elevated temperatures and increased atmospheric instability in the summer, leading to enhanced pollutant dispersion (Munir et al., 2017). Conversely, during the winter, the atmosphere tends to be more stable and cooler, allowing for higher PM concentrations.

For instance, in Hamdan Street, an urban location—the PM ratio exhibits a gradual increase from January through December, remaining below 0.5. This trend can be attributed to vehicle emissions and elevated PM concentrations in winter, which are facilitated by the more stable atmospheric conditions (Abuelgasim & Farahat, 2020; Munir et al., 2017). In industrial areas such as Mussafah, Al Mafraq, and Habshan South, the PM ratio generally rises at the beginning of the year and declines during the summer months (June to August). This pattern is linked to industrial activities, including manufacturing, busy ports, and regional transportation (Tariq et al., 2022). Additionally, sand and dust storms in the spring and summer contribute to elevated PM concentrations. In Habshan South, oil and gas processing further increases PM concentrations in winter, while winds in summer help disperse pollutants (Abuelgasim & Farahat, 2020).

A similar trend is observed in Al Qua'a, categorized as a rural/desert area, where the PM ratio is higher in the early months and decreases between May and August. This decline is associated with rising temperatures and strong wind gusts during spring and summer, along with frequent dust events near desert regions such as the Empty Quarter (Abuelgasim & Farahat, 2020; Hamdan et al., 2021). Finally, in Al Tawia a suburban area—the PM ratio remains relatively stable, with slight reductions during the summer. This stability is likely due to the lower presence of anthropogenic pollution sources and the regular occurrence of dust events that influence atmospheric conditions.

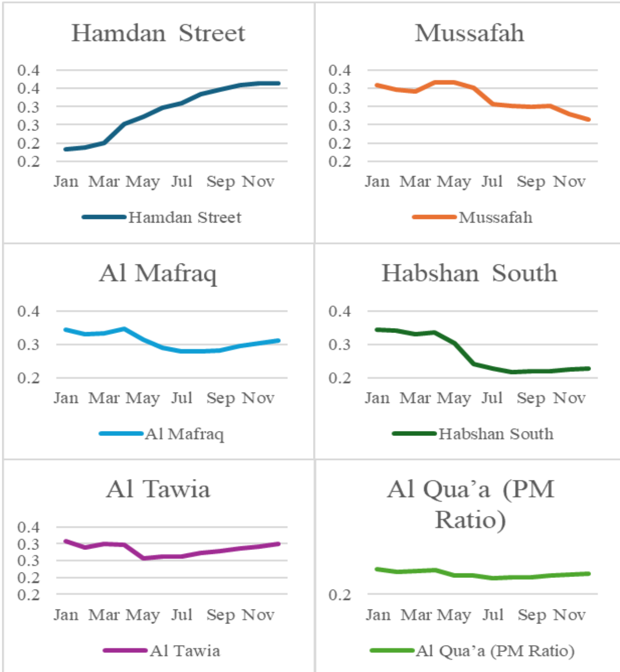

Figure 6. PM ratio in six different land uses.

4. Conclusion

This study has provided an in-depth analysis of air pollution patterns in the Emirate of Abu Dhabi, UAE, during the year 2022. The analysis focused on the daily, monthly, and seasonal concentrations and trends of particulate matter (PM_{10} and $PM_{2.5}$). The major findings show that air pollution in Abu Dhabi generally follows a seasonal trend, with higher levels during the summer months—primarily due to frequent and intense dust storms. During this period, maximum concentrations reached 218 µg/m³ for PM_{10} and 60 µg/m³ for $PM_{2.5}$. In contrast, PM levels decreased in the winter, with maximum values of 169 µg/m³ and 34 µg/m³ for PM_{10} and $PM_{2.5}$, respectively.

Based on PM concentrations, the prevailing air quality category can be classified as "Unhealthy for Sensitive Groups," during the summer due to the high concentration of PM value found. According to the United States Environmental Protection Agency (EPA) Air Quality Index (AQI) standards, PM_{10} levels between 155–254 µg/m³ and $PM_{2.5}$ levels between 35.5–55.4 µg/m³ fall within the "Unhealthy for Sensitive Groups" range. Thus, $PM_{2.5}$ values above 55.5 µg/m³ are considered "Unhealthy". As a result, Abu Dhabi's summer air quality periodically fell into the "Unhealthy" category, mostly as a result of high dust levels. $PM_{2.5}$ and PM_{10} levels, however, dropped to levels that fall within the "Moderate" to "Unhealthy for Sensitive Groups" categories throughout the winter. These results imply that the region's seasonal air pollution trends, which correspond with the predominant wind, are significantly shaped by natural resources, particularly dust and sand.

Additionally, the $PM_{2.5}$ / PM_{10} ratio at selected locations was mostly below 0.5, further indicating the dominance of natural sources of particulate pollution, such as dust storms. This study primarily focused on inland areas of Abu Dhabi. However, coastal regions—where a large portion of the population reside were not specifically analyzed. These areas are expected to experience elevated air pollution levels due to both natural and anthropogenic sources. Natural contributors include sea salt aerosols, while human activities such as maritime transport and urbanization add further pressure. These coastal dynamics will be the subject of a forthcoming study.

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