



# Investigations on PM<sub>10</sub>, PM<sub>2.5</sub>, and Their Ratio over the Emirate of Abu Dhabi, United Arab Emirates

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## Abstract

Worldwide monitoring of ambient outdoor air quality is critical for planning mitigation measures and controls for public safety. Several airborne pollutants are measured and continuously monitored by multiple government environmental agencies. Such pollutants include particulate matter (PM) levels, both PM<sub>10</sub> and PM<sub>2.5</sub>, ozone, nitrogen dioxide, sulfur dioxide, carbon monoxide, lead, and volatile organic compounds. However, scientific studies related to air pollution and the temporal variability of PM levels in the United Arab Emirates are limited. This study comprehensively analyzes the spatiotemporal variations in PM<sub>10</sub>, PM<sub>2.5</sub>, and the PM<sub>2.5</sub>/PM<sub>10</sub> ratio over the Emirate of Abu Dhabi in the United Arab Emirates during 2017–2018. The PM levels are high during April–September, peaking in July each year, likely because of intense dust and sandstorms; the same levels are low during October–March. Industrial areas have higher annual average PM<sub>10</sub> levels (162 µg/m<sup>3</sup>) compared to urban core areas (132 µg/m<sup>3</sup>) and suburban areas (131 µg/m<sup>3</sup>). In general, the values of the PM<sub>2.5</sub>/PM<sub>10</sub> ratio are low ranging between annual averages of 0.29 and 0.49 across the industrial, urban core, and desert/suburban areas. This is a characteristic particular to arid and semi-arid environments owing to the prevalence of high quantities of PM<sub>10</sub> leading to a low PM<sub>2.5</sub>/PM<sub>10</sub> ratio. In addition, this low ratio indicates that, within the Emirate of Abu Dhabi, air pollution is primarily driven by natural processes related to sand particle uplift, movement, and deposition rather than by human activities.

**Keywords** Particulate matter · Atmospheric aerosols · United Arab Emirates · PM ratio

## 1 Introduction

Air pollutants, especially particulate matter (PM), has been actively researched over the past few decades (Basahi et al. 2017; Bell et al. 2004). Airborne PM is generally calculated as the total sum of all solid and liquid particles suspended in the air. Such PM is regarded as a complex mixture of both organic and inorganic particles arising from smoke, dust, soot, or liquid droplets. PM considerably varies in size (typically measured via the aerodynamic diameter) and is traditionally classified into coarse and fine particles. Coarse

particles usually vary in size between 2.5 and 10 µm and are referred to as PM<sub>10</sub>. Conversely, fine particles are usually those that have an aerodynamic diameter of less than 2.5 µm, called PM<sub>2.5</sub>, and are largely formed from gases.

Many of these air-suspended particles are hazardous to humans and can cause serious health problems (Khalil et al. 2016; Kim et al. 2015). Exposure to common air contaminants such as PM<sub>2.5</sub> is associated with increased hospital admissions due to cardiorespiratory conditions, increased emergency room visits and work/school absenteeism, increased respiratory symptoms, and decreased lung function (Dominici 2014; Langrish et al. 2012; Leitte et al. 2011). Common air pollutants include aerosols, ozone (O<sub>3</sub>), nitrogen dioxide (NO<sub>2</sub>), carbon monoxide (CO), and sulfur dioxide (SO<sub>2</sub>). The health effects of exposure to CO, SO<sub>2</sub>, and NO<sub>2</sub> include a reduced ability to perform simple physical tasks and the aggravation of respiratory and cardiovascular diseases (Anderson 2009; Bernard et al. 2001; Krewski et al. 2000; Li et al. 2010; Pope et al. 2011).

The formation of such pollutants depends on the sources of their precursors—whether the sources are natural or

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anthropogenic (Alobaidi et al. 2017; Lopez et al. 2011; Mazzei et al. 2008; Omari et al. 2019). The challenges of meeting air quality standards in any region are impacted by the identification of the sources and the transborder transport of these pollutants. Because air pollutants originate from diverse sources, the ratio of  $PM_{2.5}$  to  $PM_{10}$  ( $PM_{2.5}/PM_{10}$ ) can be used to provide important information concerning the origin of such pollutants and their formation processes (Blanco-Becerra et al. 2015; Speranza et al. 2014; Tiwari et al. 2012). This dimensionless ratio, obtained by dividing the  $PM_{2.5}$  levels by the  $PM_{10}$  levels at any location, has been deemed a good indicator of the type of dominant pollutant. A higher  $PM_{2.5}/PM_{10}$  ratio indicates a major contribution from finer anthropogenic particles, and a lower ratio signifies a significant contribution from natural airborne particles through natural processes (Xu et al. 2017). Furthermore, the  $PM_{2.5}/PM_{10}$  ratio has been shown to provide useful information concerning local atmospheric dust processes and the types of PM pollution in a particular region (Khodeir et al. 2012; Munir 2017; Sugimoto et al. 2016; Xu et al. 2016). Because various factors contribute to the formation of airborne pollutants, the spatiotemporal variability of such pollutants is expected to considerably vary depending on the pollutants' formation processes and local meteorological conditions, such as wind speed, wind direction, and temperature (Almazroui et al. 2017).

Identifying the spatiotemporal distribution of PM and the  $PM_{2.5}/PM_{10}$  ratio levels is important for assessing the population levels of exposure; in addition, such identification significantly aids in identifying the sources and formation of air pollutants (Abuelgasim and Farahat 2020). The primary objectives of this study are to identify the spatiotemporal variations in  $PM_{10}$ ,  $PM_{2.5}$ , and  $PM_{2.5}/PM_{10}$  over the Emirate of Abu Dhabi in the United Arab Emirates (UAE). PM data collected from different stations in the emirate are analyzed to quantify the PM levels and their variabilities during 2017–2018. This is expected to provide insight into the factors affecting the measured ambient particulate levels and provide decision makers with useful information regarding the air quality levels at large spatial scales.

## 2 Materials and Methods

### 2.1 Study Area

The UAE is located on the Arabian Peninsula at  $22^{\circ} 50'–26^{\circ} 4' N$  latitude and  $51^{\circ} 5'–56^{\circ} 25' E$  longitude (Fig. 1), with a total area of approximately  $83,600 \text{ km}^2$ . The UAE is bordered by the Arabian Gulf to the north, Saudi Arabia to the west, and Oman to the east and south. The country is a union of seven states, called emirates, with the Emirate of Abu Dhabi being the largest in terms of population and

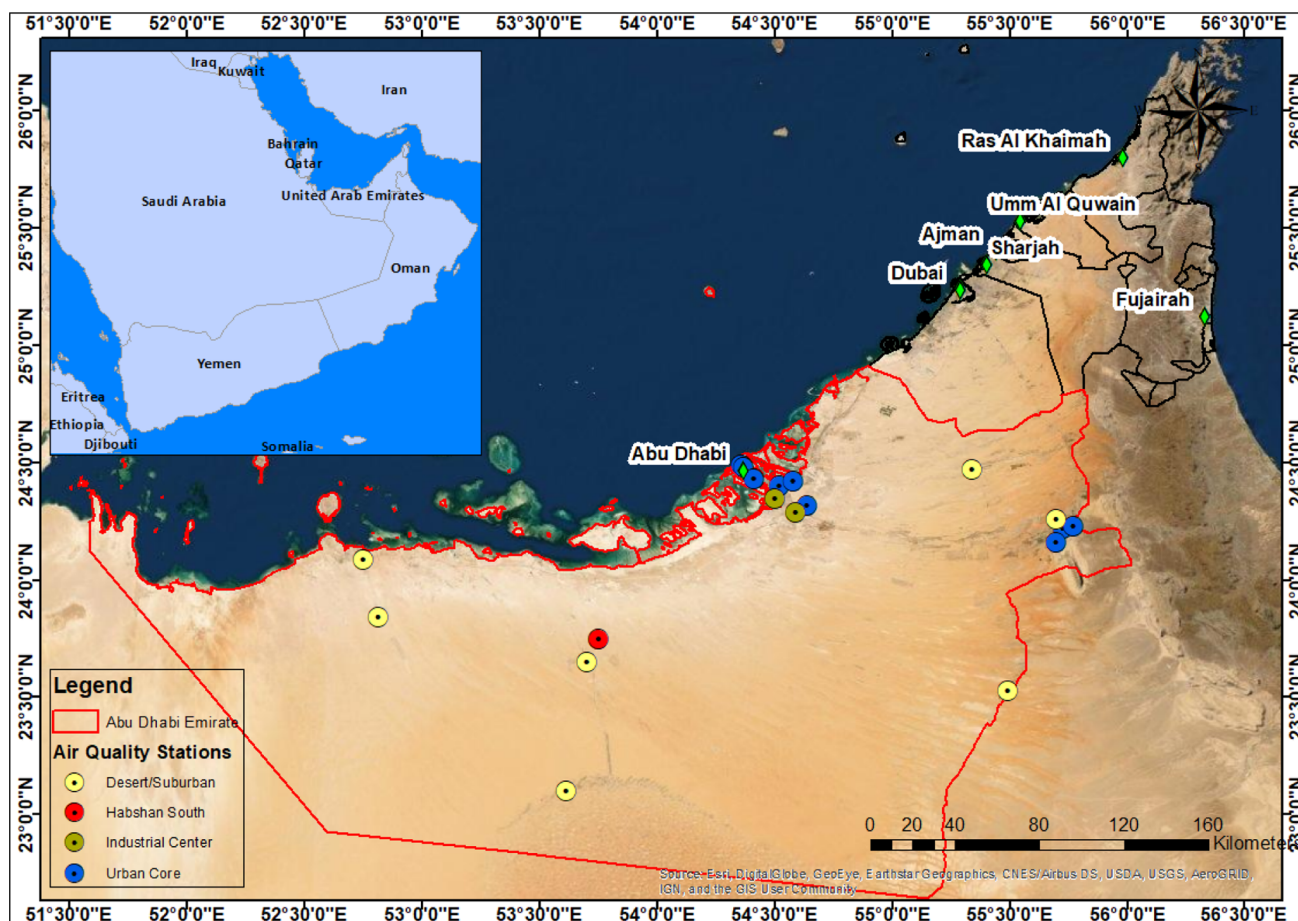
land area. It is located in the western part of the country and covers an area of  $\sim 67,340 \text{ km}^2$ , constituting slightly more than 75% of the country's total land area (Fig. 1). It is also where the capital city of Abu Dhabi ( $24^{\circ} 28' 0.0012'' N$ ,  $54^{\circ} 22' 0.0084'' E$ ) is located along with major federal government institutions. Despite the small size of the country and the dominance of desert landscapes, the UAE has a very diverse landscape and climate (Böer 1997). The different landscapes include coastal areas, mountains, and desert arid areas. The dominant desert landscape comprises different types of sand dunes extending from the west along the border with Saudi Arabia to the south and east along the border with Oman. Precipitation is scarce therein and mostly occurs in the winter season with relatively more sporadic rainfall in the mountains (Böer 1997).

The dominant climate system in the UAE is desert with hot and sunny days and extremely high temperatures in the summer. The two hottest months are July and August with temperatures occasionally reaching  $50^{\circ} C$ . The months of January and February usually experience the area's minimum temperatures ranging between  $10^{\circ} C$  and  $14^{\circ} C$  (UAE University 1993). Desert surfaces during winter can be much colder. Humidity is generally high throughout the year, exhibiting higher levels along the main water bodies of the Arabian Gulf and the Sea of Oman (Böer 1997). As previously stated, precipitation is scarce in the UAE with an average annual rainfall of 120 mm; however, mountainous areas can receive twice this annual average (Böer 1997; Embabi 1993; IAL 1991). Similar to most arid and desert lands, the country is prone to dust storms, which, at certain times, can severely impair visibility.

The study area includes the largest emirate, the Emirate of Abu Dhabi. It is bordered by Saudi Arabia to the south and west and Oman to the east. Sand dunes and salt flats along the coastal areas are dominant features in the landscape, and isolated mountains occur along the border with Oman. The emirate includes major urban cities such as the capital city of Abu Dhabi, Madinat Zayed in the west, and Al Ain in the southeast. The emirate is also a major onshore oil hub for the country's production of oil and gas. The predominance of sand and sand dunes in the emirate renders it frequently exposed to major dust outbreaks that help transport aerosols (Abuelgasim and Farahat 2020). Dust storms can significantly affect air quality by transporting airborne particles and heavy metals, such as Pb, As, V, and Se, from industrial to residential areas or even across international borders (Farahat et al. 2016; Tawabini et al. 2017).

### 2.2 Air Quality Data

The air quality measurements of  $PM_{10}$  and  $PM_{2.5}$  used in this study were obtained from the Environment Agency—Abu Dhabi (EAD) (<https://www.adairquality.ae/>), measured



**Fig. 1** Map of the United Arab Emirates and air quality stations

through its extensive network of air monitoring stations. The network includes 19 measuring stations spread throughout the Emirate of Abu Dhabi, covering major urban population centers and cities with low population, in addition to stations in close proximity to major hydrocarbon industries (Table 1). PM<sub>10</sub> and PM<sub>2.5</sub> were measured using advanced OPSIS SM200 PM monitors. These devices meet the international standards of the US Environmental Protection Agency and the British Environment Agency's Monitoring Certification Scheme (MCERTS). The data obtained from EAD comprise hourly measurements of PM<sub>10</sub> and PM<sub>2.5</sub> from the air quality monitoring stations over a period of 2 years: January 1, 2017–December 31, 2018. The measurements were recorded hourly, providing a full 24-h view of the air pollutants' temporal variability. Figure 1 shows the locations and spatial distribution of the air quality monitoring stations within the study area.

### 2.3 Methods

Local PM<sub>10</sub> and PM<sub>2.5</sub> concentrations are highly influenced by the local land cover and land use within close proximity

to the measuring air quality stations. While air quality station measurements are likely influenced by regional or cross-boundary PM and dust transport, this study assumes that the measurements reflect the prevailing local air quality and are primarily influenced by local land cover and land use. This study divides the PM measuring stations into three major groups based on the underlying land use and land cover of the station locations (Fig. 3). This classification of the station locations differs from that followed by the EAD.

Because both PM<sub>10</sub> and PM<sub>2.5</sub> are strongly influenced by the local land cover and land use, the distribution of each is expected to show some level of difference between the different groups. In addition to the three main station groups, Station 19 "Habshan South" was the only station within a rural industrial area and within reasonable proximity to the major hydrocarbon industries in the country.

The first group comprises stations located within major urban population centers (Stations 1–9) and areas within new urban developments. This group represents core urban centers with little to no industrial activity, and predominantly includes residential neighborhoods, business centers, transportation facilities, and other components of metropolitan

**Table 1** PM<sub>10</sub> and PM<sub>2.5</sub> measuring stations locations

Station ID	Station Name	Latitude	Longitude	Station location/land use
1	Hamdan Street	24.49	54.36	Urban core
2	Khadejah School	24.48	54.37	Urban core
3	Khalifa School	24.43	54.41	Urban core
4	Baniyas School	24.32	54.64	Urban core
5	Al Ain Islamic Institute	24.22	55.73	Urban core
6	Al Ain Street	24.23	55.77	Urban core
7	Bain Al Jessrain	24.40	54.52	Urban core
8	Khalifa City A	24.42	54.58	Urban core
9	Zakher	24.16	55.70	Urban core
10	Sweiham	24.47	55.34	Desert/suburban
11	Al Tawia	24.26	55.70	Desert/suburban
12	Al Qua'a	23.53	55.49	Desert/suburban
13	Liwa Oasis	23.10	53.61	Desert/suburban
14	Ruwais	24.09	52.75	Desert/suburban
15	Bida Zayed	23.65	53.70	Desert/suburban
16	Gayathi School	23.84	52.81	Desert/suburban
17	Mussafah	24.35	54.50	Industrial center
18	Al Mafraq	24.29	54.59	Industrial center
19	Habshan South	23.75	53.75	Rural industry/hydrocarbon

areas. This group of stations is referred to as the urban core. The second group comprises seven stations (Stations 10–16) located in small towns with low populations surrounded by major concentrations of open desert and sand dune fields. These small towns contain major residential areas, business centers, and transportation networks. Some of these towns are surrounded by scattered agricultural palm and vegetable plantations, primarily owned and operated by local town residents. This group is referred to as the desert/suburban group to describe the land cover and land use in the area. Station 19 is the only station that cannot be grouped with the other major groups; thus, no meaningful group statistics can be generated for this station. As such, its statistics will be reported separately as those for an individual station.

The third group comprises two stations (Stations 17 and 18) located within major industrial areas. These stations are located among various types of industries, such as aluminum product, electronic device, ceramic, and cement industries. One notable industrial complex is the Industrial City of Abu Dhabi (ICAD) (<https://www.zonescorp.com/en/zones/industrial-zones/industrial-city-of-abu-dhabi>). It includes a mix of heavy and light industries that range from steel and metals to construction materials, logistics, food, and oil and gas. This group of stations is referred to as industrial centers to highlight the different industrial activities in the area. This area is also surrounded by major open desert and sand dune fields. Stations 19 and 20 were excluded from the study because of a lack of data and the inconsistency in the available data.

The air quality stations measured the levels of the air pollutants on an hourly basis. These hourly measurements

of both PM<sub>10</sub> and PM<sub>2.5</sub> were averaged to produce daily measurements for all days during the study period. The daily averages were later averaged to produce monthly average concentration levels for the 24 months spanning the study period. Furthermore, for each station group, average monthly levels of PM<sub>10</sub>, PM<sub>2.5</sub>, and the PM ratio were calculated for each month. The data analyses involved generating descriptive statistical analyses of the average monthly data to investigate the monthly, seasonal, and annual patterns of the PM levels in the emirate. Time series graphs portraying the average monthly variations of PM<sub>10</sub> and PM<sub>2.5</sub> were generated from the average monthly data for each station group. In addition to the analysis of the time series graphs of the station pollution levels, a trend analysis using the Mann–Kendall test was performed (Kendall 1975; Mann 1945).

## 3 Results and Discussion

### 3.1 Data Analysis

#### 3.1.1 Descriptive Statistics of the Station Groups

The monthly PM<sub>10</sub> and PM<sub>2.5</sub> concentration levels were grouped according to the prevailing land cover and land use in the station areas. Table 2 lists the descriptive statistics for the various station groups' monthly and annual means for 2017 and 2018, aiming to summarize the statistics to describe the basic features of the data. In 2017, the annual mean concentrations of the different groups ranged between

**Table 2** Average monthly PM levels in 2017 and 2018

	Urban Core 2017			Urban Core 2018			Desert/Suburban 2017			Desert/Suburban 2018			Industrial Centers 2017			Industrial Centers 2018		
	PM10	PM2.5	PM Ratio	PM10	PM2.5	PM Ratio	PM10	PM2.5	PM Ratio	PM10	PM2.5	PM Ratio	PM10	PM2.5	PM Ratio	PM10	PM2.5	PM Ratio
January	76.30	27.52	0.36	112.79	33.57	0.30	72.23	26.98	0.37	105.37	30.34	0.29	117.53	42.34	0.36	157.20	35.19	0.22
February	123.07	37.25	0.30	110.58	39.29	0.36	146.59	51.84	0.35	98.79	35.99	0.36	170.23	58.74	0.35	146.97	39.97	0.27
March	123.91	42.13	0.34	93.95	36.91	0.39	150.23	48.83	0.33	90.61	33.96	0.37	187.28	58.28	0.31	135.56	39.34	0.29
April	126.36	43.05	0.34	146.37	50.15	0.34	124.02	39.97	0.32	146.19	49.95	0.34	172.28	57.09	0.33	181.18	42.42	0.23
May	132.37	47.50	0.36	151.24	65.81	0.44	131.25	45.62	0.35	155.26	69.39	0.45	203.26	62.75	0.31	169.49	46.99	0.28
June	129.37	50.55	0.39	163.43	68.67	0.42	127.42	51.19	0.40	186.97	80.75	0.43	161.48	63.81	0.40	188.84	63.37	0.34
July	196.56	69.17	0.35	268.81	114.27	0.43	201.28	82.40	0.41	292.19	137.19	0.47	258.89	71.00	0.27	279.91	79.70	0.28
August	152.70	52.71	0.35	165.19	64.02	0.39	134.97	48.89	0.36	154.23	59.63	0.39	198.30	46.33	0.23	188.27	56.23	0.30
September	113.37	50.09	0.44	137.75	50.55	0.37	104.89	51.64	0.49	120.54	47.06	0.39	148.46	50.33	0.34	181.69	51.00	0.28
October	88.87	35.93	0.40	88.64	38.37	0.43	80.71	34.66	0.43	84.56	34.52	0.41	121.99	38.61	0.32	117.10	41.48	0.35
November	68.22	26.77	0.39	89.11	30.17	0.34	62.09	24.88	0.40	84.05	24.61	0.29	106.70	29.74	0.28	121.89	31.87	0.26
December	76.14	29.92	0.39	54.37	23.56	0.43	77.46	27.34	0.35	47.21	21.47	0.45	110.70	32.67	0.30	85.03	27.44	0.32
Average	117.27	42.71	0.37	131.85	51.28	0.39	117.76	44.52	0.38	130.50	52.07	0.39	163.09	50.97	0.32	162.76	46.25	0.29
Std. Dev	34.97	11.77	0.04	52.79	23.61	0.04	38.52	15.08	0.05	61.43	30.97	0.06	43.45	12.55	0.04	47.09	13.97	0.04
Minimum	68.22	26.77	0.30	54.37	23.56	0.30	62.09	24.88	0.32	47.21	21.47	0.29	106.70	29.74	0.23	85.03	27.44	0.22
Maximum	196.56	69.17	0.44	268.81	114.27	0.44	201.28	82.40	0.49	292.19	137.19	0.47	258.89	71.00	0.40	279.91	79.70	0.35



117.27 and 163.09  $\mu\text{g}/\text{m}^3$  for  $\text{PM}_{10}$  and between 42.71  $\mu\text{g}/\text{m}^3$  and 50.97  $\mu\text{g}/\text{m}^3$  for  $\text{PM}_{2.5}$ . The major industrial center stations show the highest levels of both  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$ . Initially, higher levels of both  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  and heavier pollutants were expected within the industrial areas, with the coarser  $\text{PM}_{10}$  mostly originating from cement and ceramic factories in addition to the nearby open desert and sand dunes.

The industrial areas exhibited the highest levels of average annual  $\text{PM}_{2.5}$ . The second highest levels occurred in the desert/suburban areas. Initially, the urban core stations were expected to have higher  $\text{PM}_{2.5}$  levels owing to the major contribution of fine pollutants from transportation facilities and the heavy use of air conditioning. However, the urban core stations had an average  $\text{PM}_{2.5}$  level of 42.71  $\mu\text{g}/\text{m}^3$ , whereas the desert/suburban stations had an average  $\text{PM}_{2.5}$  level of 44.52  $\mu\text{g}/\text{m}^3$ . While the difference in their magnitudes is not large, the elevated levels of  $\text{PM}_{2.5}$  are likely due to pollution from the hydrocarbon industry within the Emirate of Abu Dhabi. This is highly probable as three of the air quality stations (Ruweis, Gayathi School, and Bida Zayed) are not far from major hydrocarbon industrial areas.

The annual average PM ratios of the different groups ranged between 0.32 and 0.38, with the industrial centers reporting the lowest ratios. This is due to the significantly high  $\text{PM}_{10}$  value at the industrial sites, which produces low overall ratio values. The variability of the PM ratio among the different groups is not significant, with an average of 0.36 for all station groups. This value is low, suggesting that most of the airborne pollutants are produced via natural processes, such as dust emissions or dust storms, rather than anthropogenic factors. Sand storm records of Abu Dhabi show wind speeds of 15 km/h and higher during February, March, and August in 2017 and during July 2017 in Al Ain, suggesting that dust storms and rising dust significantly reduced visibility during these periods. Similarly, toward the extreme west of the Emirate of Abu Dhabi, in Al Ruweis and Al Gheweifat, higher wind speeds exceeding 16 km/h led to rising dust and dust storms during February–June in 2017. This is a major characteristic of desert areas, which generally have lower PM ratios because of their high  $\text{PM}_{10}$  levels.

Table 2 lists the descriptive statistics for the monthly and annual means of  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$ , and the PM ratio for the different station groups in 2018. The year 2018 was very active in terms of dust storms and sand movement. This is apparent in the high values associated with both  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  for that year. The annual mean  $\text{PM}_{10}$  for all station groups ranged between 130.50 and 162.76  $\mu\text{g}/\text{m}^3$ . Similar to the pattern in 2017, the industrial station group had the highest  $\text{PM}_{10}$  levels, suggesting that the major driving factor of the  $\text{PM}_{10}$  level was predominantly coarse airborne particles generated by industrial facilities, such as cement and ceramic factories as well as nearby desert and sand dune surfaces.

In contrast,  $\text{PM}_{2.5}$  showed a completely reversed pattern in comparison to its 2017 levels. Significantly, high levels of  $\text{PM}_{2.5}$  were reported for both the urban core and desert/suburban groups. To further investigate this observation, actual individual station measurements were analyzed. Two stations from the urban core station group (Al Ain Islamic Institute and Al Ain Street, Stations 4 and 5, respectively, in Table 1) reported extremely high levels of both  $\text{PM}_{10}$  (350.44 and 302.15  $\mu\text{g}/\text{m}^3$ , respectively) and  $\text{PM}_{2.5}$  (235.33 and 152.58  $\mu\text{g}/\text{m}^3$ , respectively). These stations are in close proximity to a massive construction project for a grand mosque. Consequently, most of the airborne pollutants, both  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$ , originated from the onset of sand movement, cement construction work, and heavy vehicle movement in the area. Figures 2a, b show the differences in the reported pollutant levels for the 2 years of the study period.

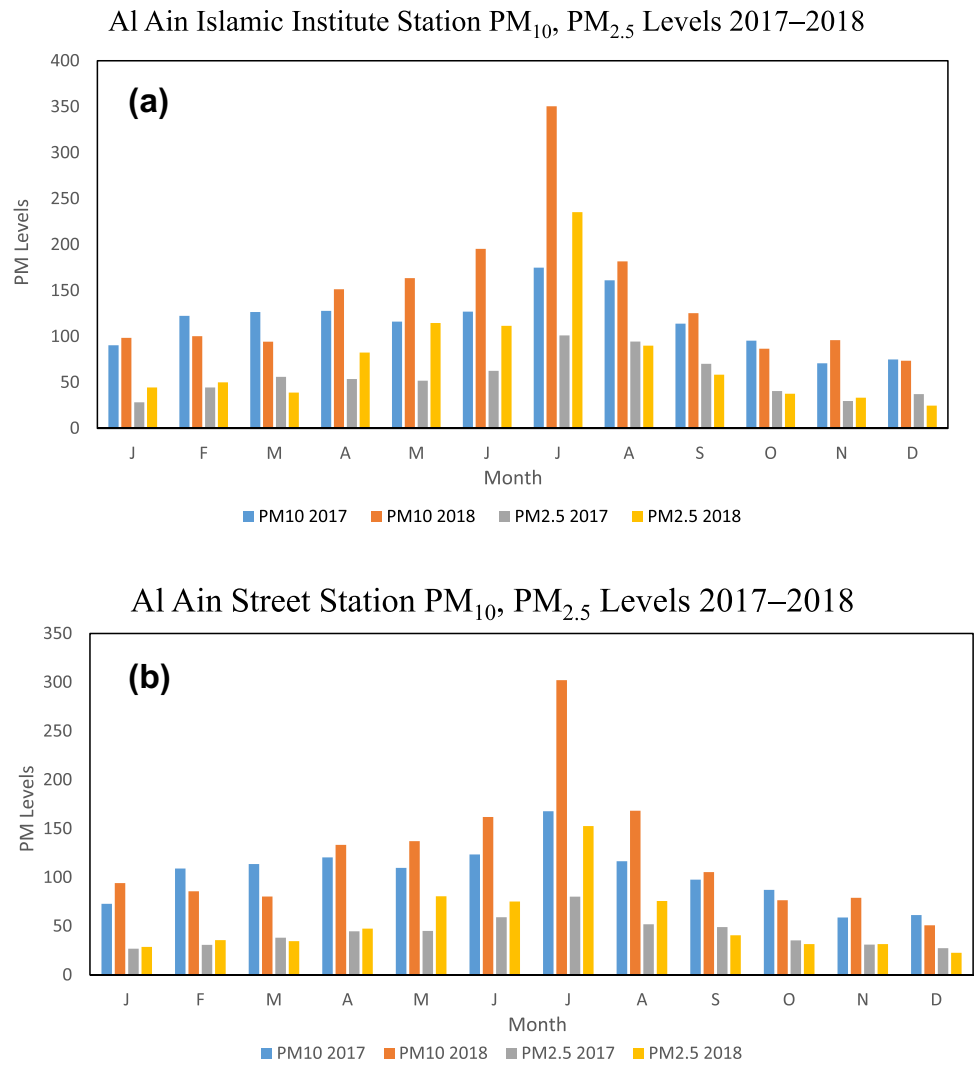
In 2018, the  $\text{PM}_{2.5}$  levels ranged between 46.25 and 52.07  $\mu\text{g}/\text{m}^3$  with the desert/suburban and urban core areas exhibiting the highest  $\text{PM}_{2.5}$  levels. This is likely due to the burning of ground biomass (usually occurring in late spring and late fall in preparation for the growing season) resulting in the significant presence of fine particles, which increases the overall annual mean  $\text{PM}_{2.5}$  levels. The variability of the PM ratio among the different groups is insignificant and ranged between 0.29 and 0.39 with an annual mean of 0.35.

The Habshan south air quality station demonstrated a similar pattern in terms of the monthly variability of PM levels, as shown in Table 3. The  $\text{PM}_{10}$  levels ranged between 54.54 and 197.10  $\mu\text{g}/\text{m}^3$  in 2017 and between 41.77 and 231.57  $\mu\text{g}/\text{m}^3$  in 2018. In both years, the levels peaked during summer and spring. This pattern has been observed for both  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  levels.  $\text{PM}_{2.5}$  level ranged from 0.26 to 0.51  $\mu\text{g}/\text{m}^3$  in 2017. Interestingly, the large PM ratio of 0.51 that occurred in the winter month of January in the UAE is associated with lower levels of  $\text{PM}_{10}$ . Apparently, in that particular month of January, fine-sized particle concentrations dominated the atmosphere likely owing to industrial pollution from nearby hydrocarbon industrial complexes.

### 3.1.2 Temporal Analysis of Station Groups

Figures 3, 4, 5, 6, 7 and 8 show the average monthly levels of  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$ , and the PM ratio for all station groups. The concentrations of the PM levels show significant average monthly variations at most of the air quality measuring stations. The concentration levels are usually low at the beginning of the year and increase by April in each year. Across all station groups, the period representing the months of June–August has elevated PM levels. This is likely due to the persistent temperature increase in this area during this particular period and is associated with sporadic dust and sandstorms as well as the excessive use of domestic cooling, which constitutes a significant additional source of PM. The

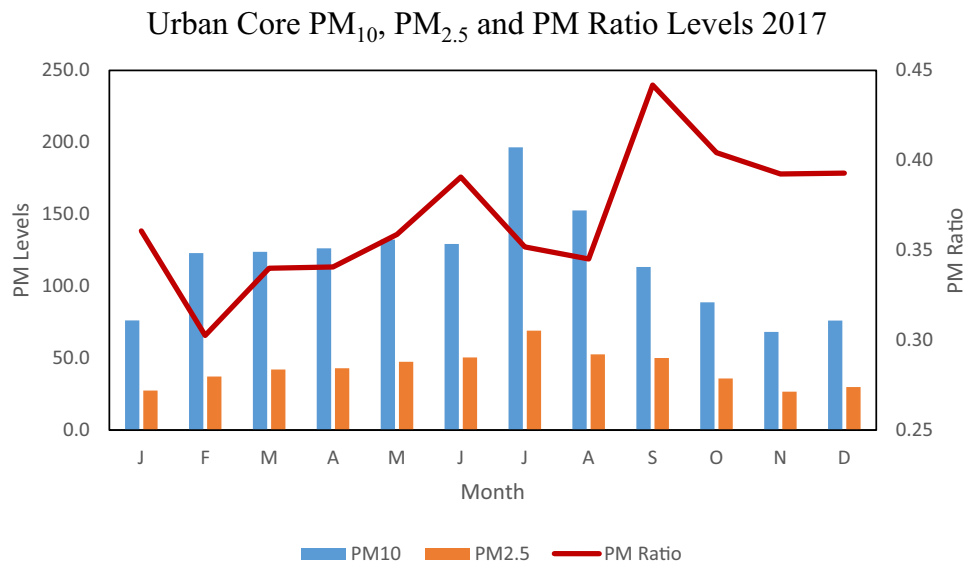
**Fig. 2 a** Al Ain Islamic Institute PM Levels 2017–2018. **b** Al Ain Street PM Levels 2017–2018



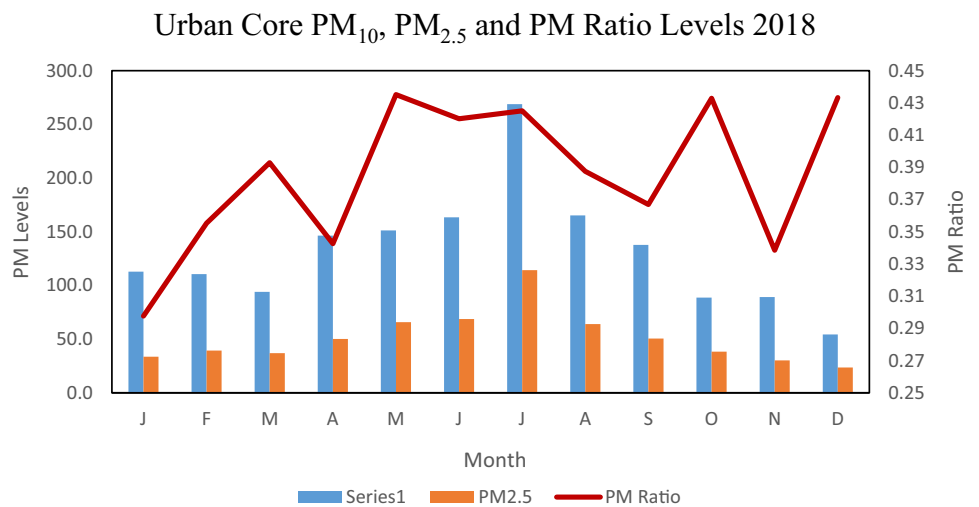
**Table 3** Average monthly PM levels for Habshan South Station

Month	2017			2018		
	PM10	PM2.5	PM ratio	PM10	PM2.5	PM ratio
January	58.65	29.91	0.51	105.51	27.70	0.26
February	153.23	39.45	0.26	108.00	35.56	0.33
March	197.10	67.07	0.34	84.77	32.35	0.38
April	121.16	46.76	0.39	148.00	42.98	0.29
May	136.48	41.63	0.31	158.82	65.02	0.41
June	127.72	49.55	0.39	165.38	57.28	0.35
July	194.79	82.11	0.42	231.57	83.80	0.36
August	136.39	47.06	0.35	140.77	51.89	0.37
September	138.68	40.75	0.29	126.90	43.04	0.34
October	79.50	28.58	0.36	85.55	35.97	0.42
November	54.83	22.99	0.42	89.39	24.81	0.28
December	72.98	22.54	0.31	41.77	19.76	0.47
Average	122.28	43.20	0.36	123.87	43.35	0.36
Std. Dev	46.47	16.83	0.07	47.38	17.69	0.06
Minimum	54.54	22.54	0.26	41.77	19.76	0.26
Maximum	197.10	82.11	0.55	231.57	83.80	0.47

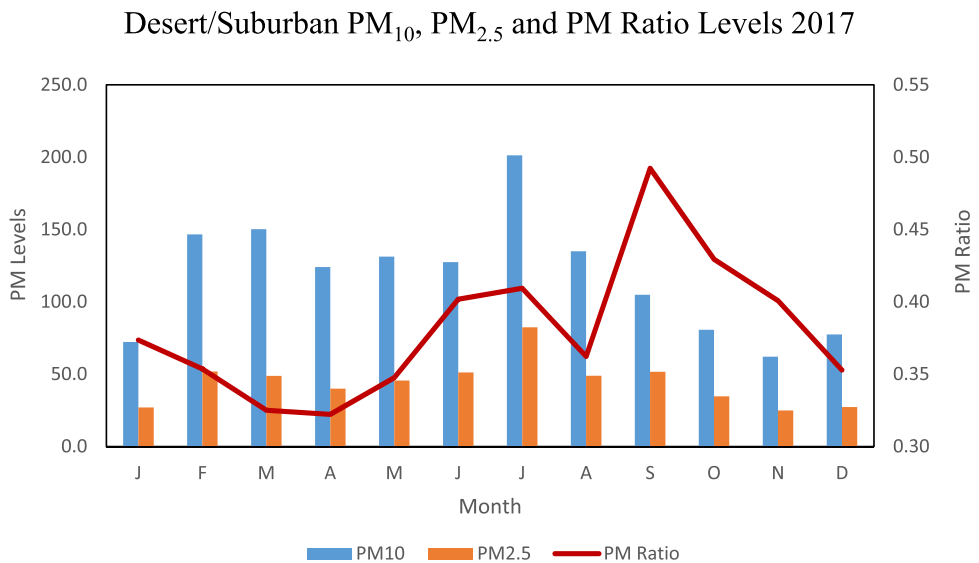
**Fig. 3** Urban core PM levels 2017



**Fig. 4** Urban core PM levels 2018

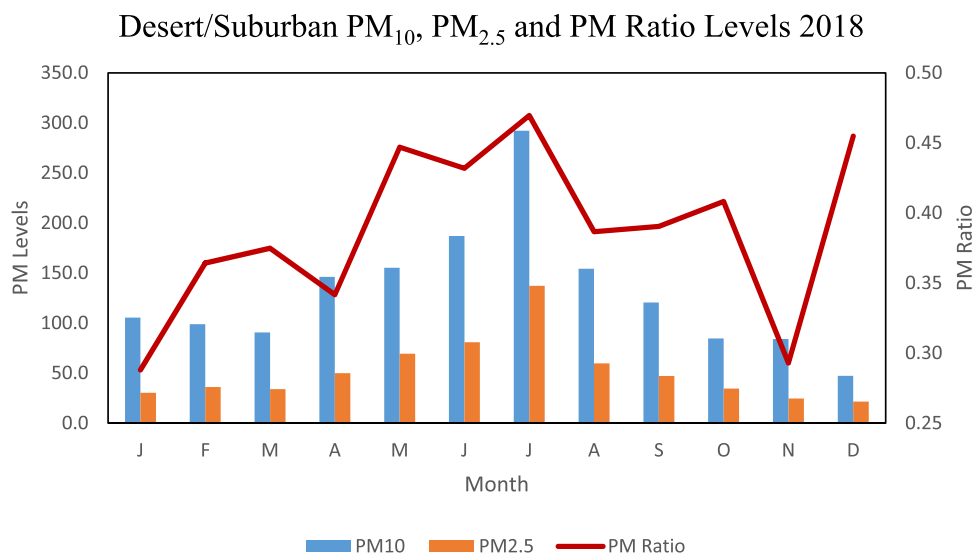


**Fig. 5** Desert/Suburban PM levels 2017

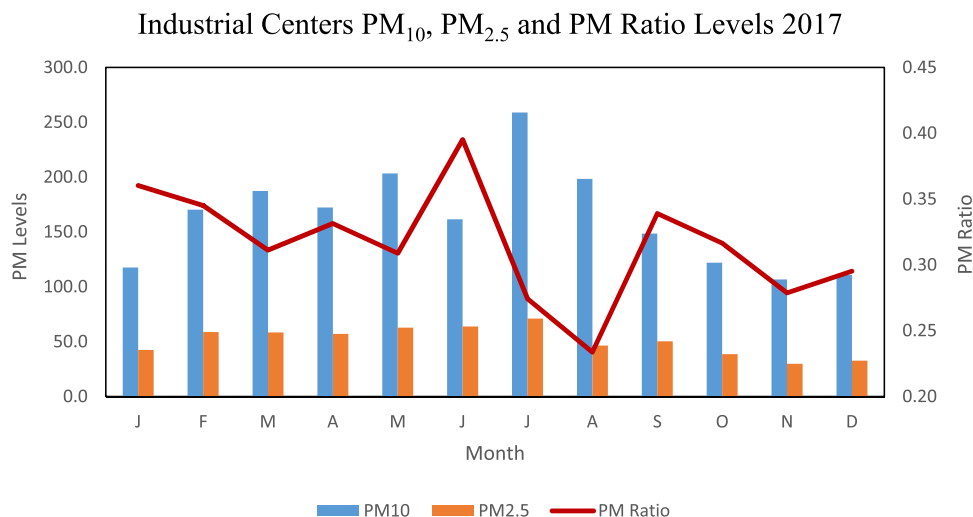




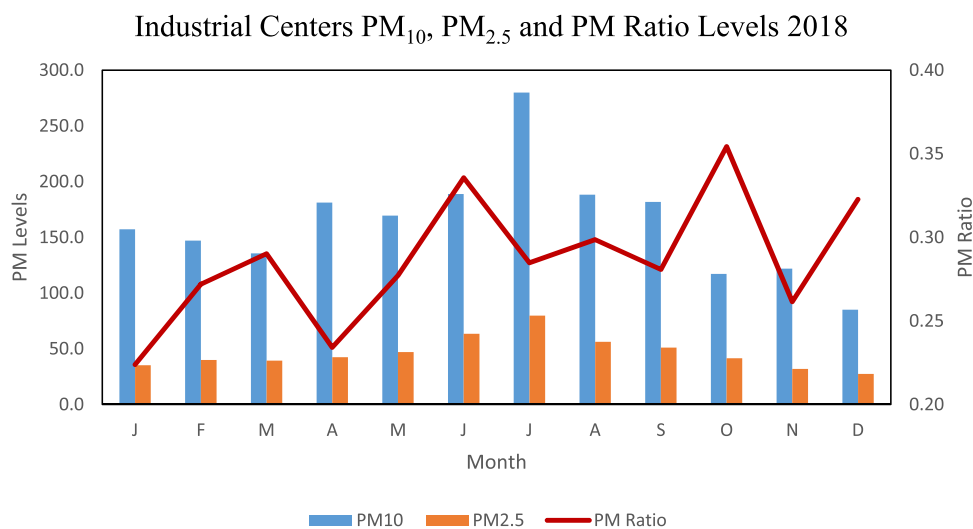
**Fig. 6** Desert/suburban PM levels 2018



**Fig. 7** Industrial centers' PM levels 2017



**Fig. 8** Industrial centers' PM levels 2018



PM levels begin to decrease by late September and usually reach their lowest levels by December in each year. This pattern of monthly variability is apparent for all station groups. The major industrial group stations consistently exhibit the highest levels of pollutant concentrations.

### 3.1.3 Pollution Level Trend Analysis

To analyze trends in the air pollution levels of the different station groups, the research implemented the Mann–Kendall trend analysis test (Kendall 1975; Mann 1945). This test is usually used to determine whether a particular time series dataset exhibits any specific monotonic trend, i.e., an upward positive trend or a downward negative trend, over time. One interesting fact about this test is that the underlying time series data do not need to have any particular distribution; therefore, this test works well with nonparametric datasets. The Mann–Kendall test involves the application of statistical hypothesis testing, wherein the null hypothesis is that the data do not exhibit any particular trend and the alternate hypothesis is that the data exhibit a trend. The trend direction can be either downward or upward.

Trend analysis was performed on the combined  $PM_{10}$  and  $PM_{2.5}$  data (2017 and 2018) for the three station groups. Hypothesis testing was performed using a two-tailed test with an alpha significance level of 0.05. Table 4 lists the results of the test, which indicate that, for both  $PM_{10}$  and  $PM_{2.5}$ , the combined data for 2017 and 2018 exhibit no apparent trend. Only the results for the  $PM_{10}$  are shown for brevity. Note that a trend analysis using only 2 years of data with only 24 observations may not be optimal. The results should therefore be treated with caution.

### 3.1.4 Temporal Analysis of the PM Ratio

Figures 9, 10 show the monthly variations in the PM ratio during the study period for each station group. The variation

pattern for the urban core station group starts lower with low variability; however, it drops during July–August because of the significant increase in the  $PM_{10}$  levels. The desert/suburban station group exhibits a similar pattern albeit with a slightly elevated overall average PM ratio. This pattern can be observed in the data of both 2017 and 2018. The industrial center stations show a slightly different pattern and trend for the study period under investigation. In 2017, the PM ratio dropped, reaching its lowest value during July and August, before increasing again. Notably, the months of July and August are active months with wind and dust storms in this region resulting in low PM ratio values. This pattern of a drop in the PM ratio during the summer months of July and August can also be observed in 2018. There is a drop in the PM ratio in 2018 compared to 2017 resulting from the higher  $PM_{10}$  levels in November and higher  $PM_{2.5}$  levels in December. These variations are caused by differences in the wind patterns and speed.

In 2017, the PM ratio in the urban core areas appears to slightly increase starting in winter, when it is the lowest, and subsequently rising to a peak in autumn. There is also an obvious tendency for the PM ratio in the desert/suburban areas to increase in a similar fashion. Overall, the desert/suburban areas have a higher PM ratio than the urban core areas in all seasons. The spatial disparity between the three groups is most obvious during the summer season, with an approximate difference of 11% between the urban core and desert/suburban areas; additionally, the PM ratio in the desert/suburban areas is ~50% larger than that in the industrial centers. Notably, fine airborne pollutant particles and coarse particles are typically emitted and produced through human activities in urban core areas; however, fine particles can travel much farther than coarse particles, resulting in higher PM ratios in suburban areas (Khuzestani et al. 2017; Parkhurst et al. 1999; Wang et al. 2017; Xu et al. 2017).

The summer disparity is also obvious in 2018 with the desert/suburban PM ratio peaking in comparison to the

**Table 4** Mann–Kendall trend analysis

Industry PM10	Desert PM10		Urban PM10		
Kendall's tau	– 0.18577	Kendall's tau	– 0.16206	Kendall's tau	– 0.05138
S	– 47	S	– 41	S	– 13
Var(S)	1433.667	Var(S)	1433.667	Var(S)	1433.667
<i>p</i> -value (Two-tailed)	0.224411	<i>p</i> -value (Two-tailed)	0.290777	<i>p</i> -value (Two-tailed)	0.7513
alpha	0.05	alpha	0.05	alpha	0.05
Test interpretation:		Test interpretation:		Test interpretation:	
$H_0$ : There is no trend in the series		$H_0$ : There is no trend in the series		$H_0$ : There is no trend in the series	
$H_a$ : There is a trend in the series		$H_a$ : There is a trend in the series		$H_a$ : There is a trend in the series	
As the computed <i>p</i> -value is greater than the significance level $\alpha=0.05$ , one cannot reject the null hypothesis $H_0$		As the computed <i>p</i> -value is greater than the significance level $\alpha=0.05$ , one cannot reject the null hypothesis $H_0$		As the computed <i>p</i> -value is greater than the significance level $\alpha=0.05$ , one cannot reject the null hypothesis $H_0$	

## PM Ratio Seasonal Variations 2017

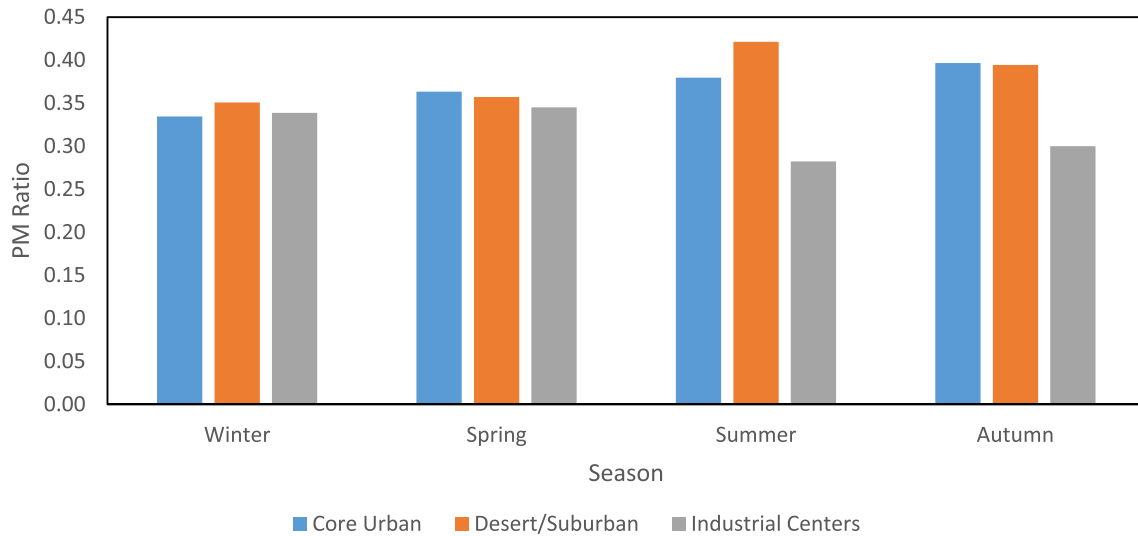


Fig. 9 PM ratio seasonal variations 2017

## PM Ratio Seasonal Variations 2018

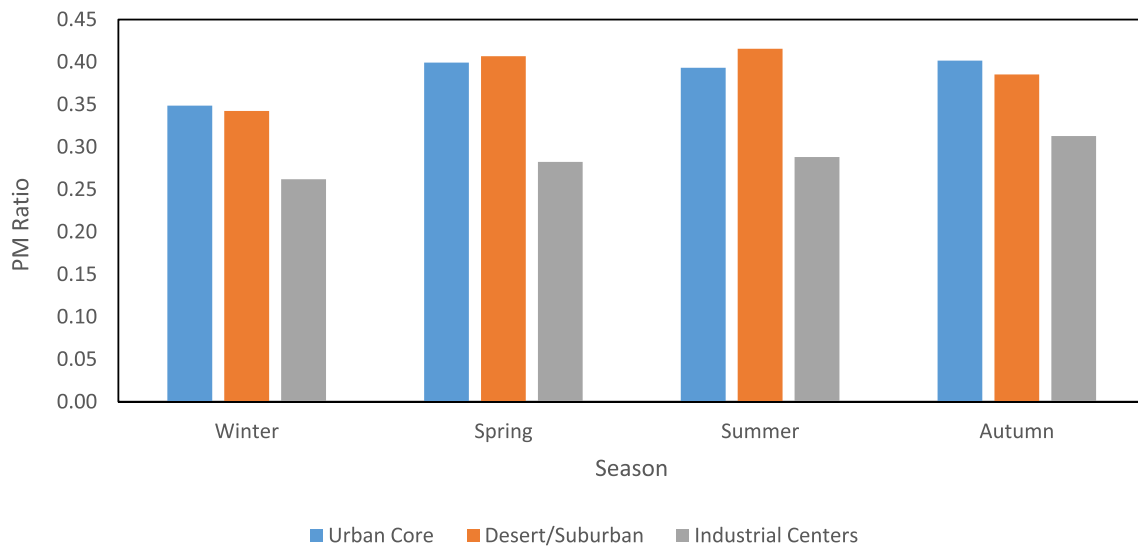


Fig. 10 PM ratio seasonal variations 2018

other two groups and being significantly higher than that in the industrial centers. One noticeable difference in 2018 is the significantly lower PM ratios in the industrial centers in comparison to the other groups. The seasonal trend levels of the PM ratio indicate a large variation in this ratio across time and space. In the UAE, summer and spring correspond to significant increases in the PM levels, resulting in high PM ratios.

The results of our analysis of the PM<sub>10</sub> and PM<sub>2.5</sub> levels indicate significant variability in the measured

concentrations throughout the year across all land cover and land use areas. This demonstrates seasonality in the particle pollution over the study area. PM levels are usually lower during the months of January–March. By April, PM levels begin to increase, reaching a peak during July and August, before starting to drop by late September to early October. This variability is thought to be strongly related to the variability in the area's meteorological conditions. The peak in July and August is primarily driven by wide sporadic dust storm events that result in suspended dust particles in the air.

Stations located within industrial areas report the highest  $PM_{10}$  concentrations; these levels are primarily driven by dust and industrial smoke, with annual averages of  $\sim 163 \mu\text{g}/\text{m}^3$  in 2017 and 2018. In comparison, stations located in urban core and suburban/desert areas had annual average  $PM_{10}$  levels of 117–132 and 117–130  $\mu\text{g}/\text{m}^3$ , respectively, in 2017 and 2018 (Figs. 3, 4, 5, 6, 7 and 8).

The PM ratio has been reported to vary from one geographic region to another based on various factors, such as land use, emission sources, and meteorology (Khodeir et al. 2012). Herein, the urban core and desert/suburban areas had higher PM ratio levels compared with the industrial areas. This is due to the dominance of higher  $PM_{10}$  levels within industrial areas, which is most likely related to dust and smoke (Table 2). The seasonal trend in the PM ratio results from the seasonal fluctuations in the PM levels across all stations. Thus, the variability of the PM ratio is related to the seasonality of the emissions and pollutants. The overall average PM ratio for the Emirate during 2017 and 2018 was 0.36. This magnitude is significantly low in comparison to similar ratio values reported in other parts of the world, such as the value of 0.6 reported for North America (Dockery and Pope 1994) and the value of slightly less than 0.5 that was reported for Asia (Hopke et al. 2011). In addition to the difference in the PM ratio magnitudes in different parts of the world, a difference exists in the timing of the PM ratio's peak. In the Emirate of Abu Dhabi, the peak of the PM ratio is usually attained during the summer months of July and August, whereas in urban Chinese cities (Xu et al. 2017) and in Birmingham in the UK (Harrison et al. 1997), it is usually attained in the winter.

Related future studies will address the major limitations of this study. One major limitation is the exclusion of the impact of the cross-boundary transport of air pollutants. PMs, particularly light pollutants, can be carried by the wind over long distances (Gupta and Mohan 2013). Local meteorological conditions need to be integrated to assess their impacts on the magnitude of the PM ratio, its variability, and its spatial distribution.

## 4 Conclusions

This study highlights the temporal variability of air pollution PM levels ( $PM_{10}$  and  $PM_{2.5}$ ) along with the  $PM_{2.5}/PM_{10}$  ratio in the Emirate of Abu Dhabi. Herein, air quality-measuring stations were grouped according to their prevailing land cover and land use within the regions surrounding the stations. Air quality station groups reported high PM levels during April–September and low levels during October–March. Stations located within industrial centers reported the highest levels of annual average  $PM_{10}$  and  $PM_{2.5}$  pollution. The PM levels exhibited obvious spatiotemporal

variability. Similarly, the  $PM_{2.5}/PM_{10}$  ratio considerably varied in space and time. In general, the absolute value of the  $PM_{2.5}/PM_{10}$  ratio was low, ranging between annual averages of 0.29 and 0.49 for the different station groups. This characteristic is inherent to arid and semi-arid environments because of the prevalence of high quantities of  $PM_{10}$  resulting in a low  $PM_{2.5}/PM_{10}$  ratio. The seasonal PM ratio exhibited higher levels in summer ( $> 0.40$ ) compared with other seasons. There was also an apparent gradient in the ratio in 2017, increasing from industrial centers (0.28), to urban core areas (0.38), to the highest levels in desert/suburban areas (0.42). The absolute magnitude level of the PM ratio indicated that, within the Emirate of Abu Dhabi, air pollution is primarily driven by natural processes related to local and cross-boundary dust storms that cause sand particle uplift, movement, and deposition, rather than by human activity.

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## Compliance with ethical standards

**Conflict of interest** The authors have no conflicts of interest to declare that are relevant to the content of this article.

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