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Seasonal impact to air qualities in industrial areas of the Arabian Gulf region

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ABSTRACT

Air quality conditions and pollution status have been evaluated in the industrial area between Sharjah and Ajman border in UAE. Daily concentrations of O_3, CO, NO_2, SO_2, $PM_{2.5}$, PM_{10}, Total Volatile Organic Compounds (TVOC) and Total Suspended Particulate (TSP) have been monitored from Sept. 2015 to April 2016. The monthly average concentrations of O_3, CO, NO_2, SO_2, TVOC were within the UAE ambient air quality standards during the survey period. However, PM_{10} and TSP levels exceeded the recommended limits in Sept. 2015, Oct. 2015 and March 2016. Temporal variations in air quality parameters showed highest levels in March 2016 for $PM_{2.5}$, PM_{10}, NO_2, TVOC and TSP, whereas O_3, SO_2 and CO showed relatively low values in this month. $PM_{2.5}$ levels in ambient air were above the EPA guideline of 35 $\mu g/m^3$ in all months. $PM_{2.5}$ was the critical ambient air pollutant with Index for Pollutant (I_p) values varying from 103-209, indicating Air Quality Index categories of unhealthy for sensitive groups (62.5%) to unhealthy (25%) to very unhealthy (12.5%). The I_p average values of $PM_{2.5}$ decreased from Sept. 2015 to reach lowest value in Dec. 2015 before increasing gradually, peaking in March 2016. These results suggest the potential health risks associated with $PM_{2.5}$ is low in winter, where the prevailing meteorological conditions of lower temperatures, higher humidity, higher wind speed reduced particulate matter. The results revealed the industrial area is impacted by anthropogenic and natural sources of particulate matter.

Keywords: Aerosol sources, Air pollution, Particulate matter, UAE

1. Introduction

Short- and long-term exposure to ambient air pollution has been associated with several adverse health effects, particularly among sensitive groups [1-10]. Air pollution has also become a leading cause of death in the world and has imposed a heavy burden on government's health care budgets [11].

Atmospheric pollutants can directly or indirectly affect ecosystems, reduce visibility, cause property damage and harm to the human. They may undergo changes in their compositions between their emission and their detection. In addition to its local effects, the impacts of air pollution are extended to a global scale, where climate change and global warming are likely to aggravate food shortages, alter water resources and damage the infrastructure in certain countries (rising sea-levels and extreme weather).

Thousands of chemicals emitted into the air are considered air pollutants. The WHO has identified particulate matter (PM), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2) and ozone (O_3) as the pollutants with greatest public health importance. The United States National Ambient Air Quality Standard designates all of the above plus airborne lead as criteria pollutants.

CO, NO_x, and part of Volatile Organic Compounds (VOCs) are largely traffic-related emissions, whereas O_3 and NO_2 are secondary pollutants photochemically formed from precursors [12, 13]. SO_2 is primarily originated from power plants and heavy industry. The ground-level O_3 formation also depends the concentrations of NO_x, VOCs, and their VOCs:NO_x ratios [14]. The NO_2, a major O_3 precursor [15, 16] is related to anthropogenic combustion emissions. It is subject to atmospheric oxidation to form nitrate aerosol, which effects PM10 levels [17]. VOCs are oxidized to form CO [18]. The SO_2 may contribute to photoformation of O_3 with the NO_x and VOCs under the intense insulation [19, 20]. Therefore, the photochemistry of the NO–NO_2–O_3 system in ambient air is locally controlled by the reactions

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with CO and many VOCs and even SO_2 [13, 20].

United Arab Emirates (UAE) is one of the fastest growing countries. The recent economic and industrial development in UAE has substantially impacted the air quality and increased the severity of air pollution. This requires frequent inspection and monitoring program of the levels of pollutants in ambient air to reduce emissions and define environmentally friendly economic growth plans.

The industrial area between Sharjah and Ajman, is becoming one of the cornerstones of the UAE industrial development. In response to the growing public concern and to communicate the health significance of air pollution to the public, the authority is developing an air quality monitoring and control center. The measurements are used to determine the human exposure to pollutants and assess trends of atmospheric pollution. In addition, this air quality monitoring network provides data to decision makers in a timely manner to determine whether these industrial facilities maintain compliance with national ambient air quality requirements.

This work is intended to characterize the ambient levels of air pollution in the industrial area between Sharjah and Ajman, UAE. This is likely to provide best available evidence in supporting public health policy decision making and support emission strategy development and to activate emergency control procedures that prevent or alleviate air pollution episodes.

2. Materials and Methods

2.1. Description of Study Area

The industrial area between Sharjah and Ajman in UAE (Fig. 1), has a unique geographic location with a multi-access to neighboring and global countries through land, sea and air. It is fast becoming one of the cornerstones of the UAE industrial development. The management body of the industrial area has published the "Engineering, Environmental, Health and Safety Regulations" which specifies its Engineering Policy and Health, Safety & Environment (HSE) Policy and expects its investors to partner with them in their objective of promoting good HSE performance which will ensure long term success of the businesses. These regulations urge the investors to accord prime significance to HSE performance with business performance. To provide air pollution data to its decision makers and investors in a timely manner, it has developed an air quality monitoring network that has both mobile and fixed monitoring stations, as well as the state of art sensors technology. The recorded measurements are used to determine the human exposure to pollutants and can be combined with trace/background monitoring as well as stack monitoring to assess an organization's contribution to pollution, and the effect is usually compared to natural levels.

The UAE Federal Environment Agency and several international regulatory bodies (ex.: EPA, WHO, etc.) identified six major air pollutants called "criteria pollutants" (Table 2). These air pollutants are particulate matter (PM_{10}), SO_2, NO_2, O_3, CO and lead (Pb). Fine particulate matter ($PM_{2.5}$) was later added as an additional criteria pollutant. In addition, VOCs are regulated as a criteria pollutant because they are precursors to O_3.

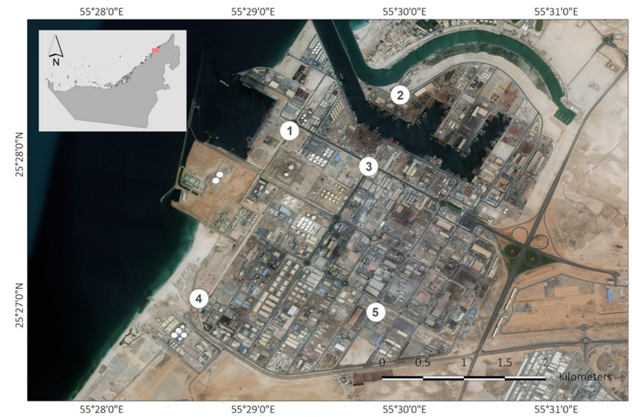

Fig. 1. Location map of the industrial area between Sharjah and Ajman border, UAE, and the locations of air quality monitoring stations.

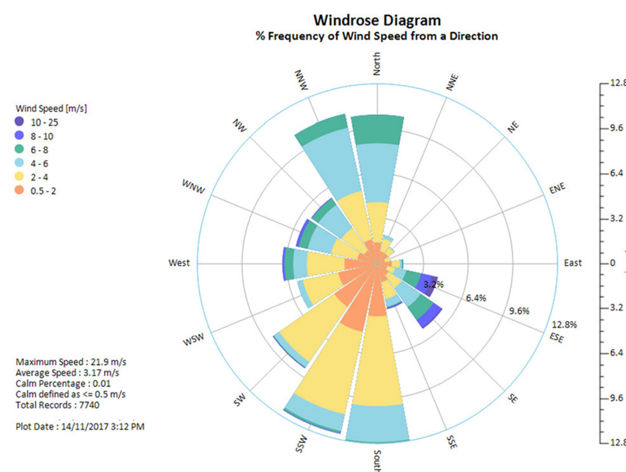

Fig. 2. Wind rose diagram showing the prevailing wind directions and speed at the industrial area during the study period.

UAE is part of prevailing arid climate, with mild winter season that lasts from November through March. The hot and humid summer season extends from April through September. In the industrial area the strong winds are generally from the N-NNW to S-SSE direction, wind rose diagram is presented in Fig. 2. The average daily temperatures varied between 17.0℃ (occurring mainly in winter) and 31.8℃ during 2015 with a maximum temperature of around 40℃ (in summertime). The average maximum relative humidity is around 87%. The highest rainfall during winter seasons can reach up to 79 mm.

2.2. Air Quality Monitoring Stations

Five monitoring stations were used to measure the ambient air quality in the industrial area (Fig. 1). The airpointer and ecotech air quality sensors were used to monitor airborne pollutants. Ecotech sensors were configured and fixed to be stationary and airpointers as mobile stations (model numbers and manufacturing countries are tabulated in Table 1). The daily baseline ambient air quality was investigated through monitoring concentrations

Table 1. Model Numbers and Manufacturing Countries of Ecotech Sensor and Analyzers Used for Ambient Air Quality Monitoring

S. No.	Parameter	Model offered	Make
1	SO_2	Serinus 50	Ecotech, Australia
2	O_3	Serinus 10	Ecotech, Australia
3	NO_x	Serinus 40	Ecotech, Australia
4	CO	Serinus 30	Ecotech, Australia
5	BTEX(Benzene, Toluene, Ethylbenzene & xylene)	Airmo VOC BTEX GC866	Chromatotec, France
6	PM_{10}	BAM 1000 (PM_{10})	Metone, USA
7	$PM_{2.5}$	BAM 1100 ($PM_{2.5}$)	Metone, USA
8	TSP	BAM 1000 (PM_{10})	Metone, USA

of $PM_{2.5}$, PM_{10}, Total Suspended Particulate (TSP), SO_2, NO_2, CO, Total VOCs and O_3. Those parameters were measured daily from Sept. 2015 to April 2016.

A 24-h sample was taken from midnight to midnight, at frequency interval, to ensure full coverage for 7 d a week using airpointers and for 30 (or 31) d using ecotech analyzers. Data required for comparison to the National Center of Meteorology & Seismology have specific completeness requirements. These completeness requirements generally start from completeness at hourly and 24-h concentration values. The VOC was collected using MiniRAE 3000. Its Photoionization Detector's (PID) extended range of 0 to 15,000 ppm makes it an ideal instrument for applications from industrial hygiene, for leak and HazMat detection.

2.3. Air Quality Index (AQI)

The EPA has a standardized AQI calculation methodology for the key air pollutants. The following equation represents the model using linear interpolation for single pollutants. Using the Eq. (1) with the aid of the EPA values of breakpoints [21] and the pollutant concentration data, the Index for Pollutant (I_p) is calculated. The highest I_p value represents the daily AQI.

$$I_P = [(I_H - I_L)/(C_H - C_L)] \times (C_p - C_L) + I_L \qquad (1)$$

where I_p is the index for pollutant, p; C_p is the concentration of pollutant, p; C_H is the breakpoint that is greater than or equal to C_p; C_L is the breakpoint that is less than or equal to C_p; I_H is AQI value corresponding to C_H; and I_L is AQI value corresponding to C_L.

3. Results and Discussion

3.1. Air Quality Conditions

The statistical analysis of the monthly average concentrations of O_3, CO, NO_2, SO_2, $PM_{2.5}$, PM_{10}, TSP and TVOC are tabulated in Table 3. The concentrations of O_3, CO, NO_2, SO_2 comply with the maximum allowable limits of the national air quality standards (Table 2 and Table 3). The monthly average concentrations of PM_{10} exceeded the recommended standard limit of 150 μg/m³ in Sept. 2015, Oct. of 2015 and in March 2016, with highest values were observed in the latter month. Exceptionally high concentrations of PM_{10} during the episode of dust storm were due to transport from local and regional deserts.

Table 2. The UAE Ambient Air Quality Standards

Substance	Max allowable limits (μg/m³)	Average time
SO_2	350	1 h
	150	24 h
	60	1 y
CO	30 (mg/m³)	1 h
	10 (mg/m³)	8 h
NO_2	400	1 h
	150	24 h
O_3	200	1 h
	120	8 h
TSP	230	24 h
	90	1 y
PM_{10}	150	24 h
Pb	1	1 y

The ambient air levels of $PM_{2.5}$ were above the EPA (2015) [21] guidelines of 35 μg/m³ in all months, with slightly above the limit values observed in Nov. and Dec. of 2015 (Table 2 and Table 3). The TSP showed monthly average values that exceeded the maximum allowable limit in Sept. 2015, Oct. 2015 and March 2016, though there have been some events with elevated daily levels exceeding the allowable standards, in the remaining months.

TVOC showed lower monthly average levels compared with the national standards limit of 20 mg/m³. Relatively higher levels of TVOC were measured from Feb. 2016 through April 2016 and lowest values observed in Dec. 2015 (corresponding to periods of lower use of fossil fuel and industrial activities).

The VOCs are precursors of O_3. Under appropriate ambient conditions, VOCs and NO_x are photochemically reacted to form smog. Smog is composed of O_3 and particles, among others. Therefore, the VOCs levels are decreased as they are converted to O_3, during which higher O_3 values are observed. However, when the weather conditions are not favorable, ambient air VOCs show higher values whereas O_3 levels remain at lower levels.

Table 3. Summary Statistics of Ambient Air Quality from Sept. 2015 to April 2016

	O_3	CO	NO_2	SO_2	$PM_{2.5}$	PM_{10}	TSP	TVOC
	$\mu g/m^3$	mg/m^3	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	mg/m^3
Sept. 2015								
Mean	17.89	0.38	24.44	2.03	74.07	185.7	270.18	0.15
SD	7.03	0.13	6.81	0.2	86.79	100.99	112.37	0.12
Min	0.53	0.18	6.98	1.7	33.96	79.8	96.55	0
Max	33.55	0.65	38.85	2.46	524.15	585.58	550.59	0.44
Count	30	30	30	30	30	30	30	30
Oct. 2015								
Mean	18.33	0.4	24.55	0	57.82	159.09	240.84	0.12
SD	4.99	0.08	5.79	0	46.01	44.63	161.8	0.05
Min	10.16	0.25	12.53	0	20.24	63.56	75.8	0
Max	31.66	0.58	36.68	0	277.69	238.89	856	0.14
Count	31	31	31	31	31	31	31	31
Nov. 2015								
Mean	24.67	0.43	17.88	1.09	36.94	139.35	191.84	0.19
SD	9.02	0.13	14.54	0.68	12.36	62.46	84.31	0.083
Min	10.49	0.21	0.35	0.07	12.479	71.57	100.17	0.10
Max	40.7	0.70	42.57	2.04	64.47	378.97	501.05	0.50
Count	30	30	30	30	30	30	30	30
Dec. 2015								
Mean	19.56	0.49	28.33	1.62	36.29	117.90	157.53	0.003
SD	7.64	0.17	9.21	0.92	11.70	38.61	52.67	0.01
Min	9.44	0.23	8.30	0.65	5.3	26.31	71.37	0
Max	37.98	0.978	40.46	3.33	65.22	202.52	303.98	0.08
Count	31	31	31	31	31	31	31	31
Jan. 2016								
Mean	22.18	0.77	28.00	3.13	44.06	151.94	174.54	0.12
SD	8.11	1.12	10.75	1.19	16.98	48.04	57.63	0.13
Min	9.66	0.218	4.62	1.07	13.35	48.87	61.71	0
Max	45.79	6.66	44.10	5.83	77.38	256.45	292.48	0.29
Count	31	31	31	31	31	31	31	31
Feb. 2016								
Mean	17.69	0.54	35.21	3.06	50.98	108.83	186.05	2.06
SD	12.05	0.12	9.00	0.92	15.11	35.22	79.66	1.18
Min	0.638	0.32	7.83	1.742	24.66	26.31	74.53	0
Max	48.14	0.78	51.48	5.02	86.60	201.72	417.46	2.77
Count	28	28	28	28	28	28	28	28
March 2016								
Mean	4.62	0.45	47.08	2.56	158.49	831.7	283.46	3.74
SD	5.47	0.1	8.61	1.19	297.18	320.73	248.65	0.78
Min	0.72	0.28	21.13	-0.77	21.1	72.58	83.32	2.16
Max	20.1	0.66	62.22	5.35	985	985	985	5.14
Count	31	31	31	31	31	31	31	31
April 2016								
Mean	27.48	0.66	-	-	50.98	108.83	186.05	2.88
SD	11.25	0.27	-	-	15.12	35.22	79.66	0.94
Min	8.66	0.06	-	-	24.66	26.31	74.53	2.06
Max	49.48	1.03	-	-	86.6	201.72	417.46	7.25
Count	30	30	-	-	30	30	30	30

Unlike other place, for example [17], which showed peak in O_3 levels in springtime (March, April and May) compared to the summer (June, July and August) due to the summertime monsoon and clouds. In addition, [17] found that the lowest O_3 level was observed in the winter due to the low photolysis.

The kinetics associated with VOC → CO → CO_2 reaction during combustion, is explained by a composite behavior [22]. At early stage of combustion, VOCs produce CO (VOCs levels are reduced whereas CO increases). As the reaction continues, both are reduced while CO_2 consistently increases [22, 23]. In addition, CO can form from atmospheric oxidation of VOCs [18], where the concentrations of VOCs decreased as they were converted to CO.

As mentioned earlier, the CO, NO_x, and part of VOCs are largely traffic-related emissions, whereas O_3 and NO_2 are secondary pollutants photochemically formed from precursors [12, 13]. SO_2 is primarily originated from power plants and heavy industry.

It is noteworthy to mention that due to the prevailing arid to hyper-arid climate of the UAE, it experiences high temperatures throughout the year, except in winter, where the average temperature drops to about 17°C (and rarely deceases below to 6°C). Air-conditioning is required almost year-round except in winter. Electricity consumption for air-conditioning is high (reaching, for examples, over 51% of the annual electricity consumption in residential area). In addition, industries in UAE require no heating considering the arid climate (hot temperatures with high relative humidity). The industrial demand of energy for cooling is at low levels during winter. Therefore, the overall energy consumption decreases considerably in wintertime, with reduced levels of TVOCs emissions.

3.2. Critical Ambient Air Pollutants

The critical pollutant is identified as the pollutant with the highest I_p value of the six ambient air pollutant, which also represents the daily AQI category [21]. The I_p and AQI values were calculated based on a 24-h average for SO_2, PM_{10}, and $PM_{2.5}$, and they were calculated based on peak 8-h running average for O_3 and CO. The I_p and AQI values for NO_2 were calculated based on one-hour average as per standard procedure [24].

Air quality monitoring data were collected for each of the five monitoring stations for 30 (or 31) d (NO_2 and SO_2 data were unavailable for April 2016). These data were used to identify the dominant AQI values in the industrial area. The calculated I_p values for CO ranged from 3-8 with a mean value of 5.29 representing good to moderate AQI category. However, O_3 showed I_p values varying between 4 and 25 with an average of 17.25 corresponding to good AQI class. Similarly, the I_p values for NO_2 and SO_2 ranged from 16-44 (with a men value of 27.29) and from 1-4 (with a men value of 2.67), respectively, corresponding to good AQI category.

Except for March 2016, the monthly average of I_p values for $PM_{2.5}$ were consistently higher than that for PM_{10} (from 77-116). This indicates that $PM_{2.5}$ was the critical ambient air pollutant that can cause potential health impacts during the study period and that the air quality categories were determined by AQI values for $PM_{2.5}$ parameters.

$PM_{2.5}$ showed I_p values varying from 103-209 with an average of 141. These values indicate AQI categories of unhealthy for sensi

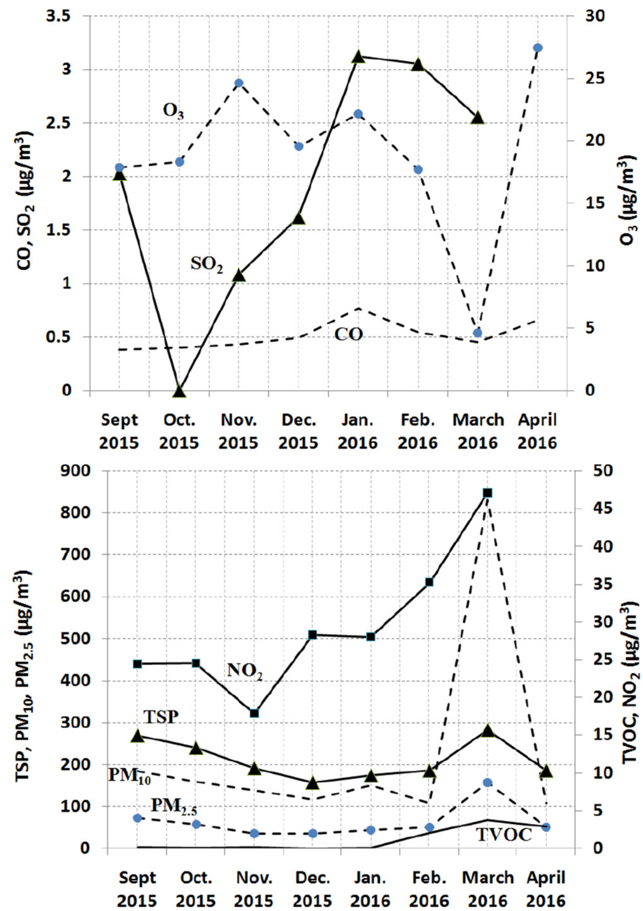

Fig. 3. Ambient air quality parameter from Sept. 2015 to April 2016.

tive groups (62.5%) to unhealthy (25%) to very unhealthy (12.5%). The I_p average values of $PM_{2.5}$ tended to decrease from Sept. 2015 to reach lowest value in Dec. 2015 before increasing back gradually, peaking in March 2016. These results suggest that the potential health risks related to $PM_{2.5}$ concentrations is low in winter. This is probably attributed to the prevailing meteorological conditions of lower temperatures, higher humidity and higher wind speed, and more rainy days helped the dissipation of PM and provided relatively better and homogenous ambient air quality [25].

The temporal variations in ambient air quality parameters are presented in Fig. 3 with highest levels were observed in March 2016 for $PM_{2.5}$, PM_{10}, NO_2, TVOC and TSP. In contrast, O_3, SO_2 and CO tended to show relatively low values in March 2016.

These higher values of particulate matter represent the end of winter and beginning of spring season with frequent dust events. In addition, these are likely related to increased rate of industrial activities following the winter season with subsequent increased use of fossil fuel.

3.3. $PM_{2.5}/PM_{10}$ Ratio

The $PM_{2.5}/PM_{10}$ ratio, presented in Fig. 4, has been used to assess the aerosol sources and types [26]. The high ratios generally indicate the dominance of anthropogenic aerosols whereas the low ratios indicate prevailing dust aerosols. Anthropogenic sources produce more fine particles (traffic emissions or burning activities), whereas natural sources (windblown or road dust) contribute higher quantities of coarse particles resulting in a lower ration [27-31].

The relative high average ratios of $PM_{2.5}/PM_{10}$ observed during the study period suggest significance contribution of fine particles and that the atmospheric particles are related to anthropogenic sources (industrial activities and heavy traffic). The highest $PM_{2.5}/PM_{10}$ ratio coincided with the high concentrations of CO and O_3 (Fig. 3 and Fig. 4) indicating predominant emissions from anthropogenic sources.

[27] reported lower ratio in residential area compared to urban area. Also, [32] indicated that $PM_{2.5}$ is dominant within immediate proximity to industrial area.

Combustion sources (traffic, biomass burning and industrial processes) emit more fine particles, whereas mechanical processes (crushing, gridding and construction activities) contribute to coarse fraction of PM [33].

Monthly variations in $PM_{2.5}/PM_{10}$ ratio were also apparent. There has been generally a slight decrease in the ratio from Sept. 2015 through Jan 2016, before relatively an abrupt increase in $PM_{2.5}/PM_{10}$ ratio was observed in the following months (except for March 2016).

The lowest average ratio observed for March 2016 (Fig. 4) compared to other months suggests that during this month the area has experienced dust storms and that they were potentially the dominant source of particulate matter. [27] reported that coarse particles from dust storm contribute significantly to PM_{10}. However, higher levels of TVOC recorded during March 2016 (Fig. 3) indicate that anthropogenic sources, from burning fossil fuel, were common. These results suggest that industrial area was impacted by both sources of aerosols, with prevailing anthropogenic sources from Nov. 2015 through Jan. 2016 and in March 2016.

In addition to combustion sources (traffic, fossil fuel burning and industrial processes) which emit more fine particles and increase the ratio, the increasing trend after Jan. 2016 (except for March 2016) may be attributed to the meteorological conditions. High wind velocity, rainfall and relative humidity during this period (winter season) reduce large particle emissions leading to increase in the $PM_{2.5}/PM_{10}$.

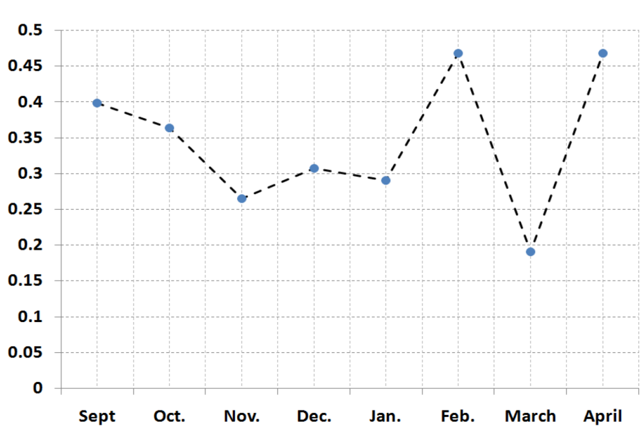

Fig. 4. Monthly average $PM_{2.5}/PM_{10}$ ratios.

4. Conclusions

Five monitoring stations (fixed and stationary) were used to measure the daily baseline ambient air quality in the industrial area between Sharjah and Ajman border in UAE. $PM_{2.5}$, PM_{10}, TSP, SO_2, NO_2, CO, TVOCs and O_3 were measured from Sept. 2015 to April 2016. The monthly average concentrations of air parameters were within the UAE ambient air quality standards during the survey period, except for PM_{10} and TSP in Sept. 2015, Oct. 2015 and March 2016. $PM_{2.5}$ was the critical pollutant with index values indicating AQI categories of unhealthy for sensitive groups (62.5%) to unhealthy (25%) to very unhealthy (12.5%). The results revealed the industrial area is impacted by anthropogenic and natural sources of PM. However, in such a fast growing industrial area surrounded by desert region, it is likely that PM exceeds the acceptable limits due to frequent dust events. These monitoring data can help the management authority to communicate information to investors and public about the current status of ambient air quality and advise for further precautionary measures to maintain healthy air quality conditions.

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