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ARTICLE

Fine Particle Number Concentrations in Amman and Zarqa during Spring 2014

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Abstract: We measured the fine particle number concentrations at four sites in Amman and one site in Zarqa during March 6 – May 28, 2014. These were urban except for one, which was a sub-urban site. The highest number concentrations (24-hour median as high as 5.2×10^4 cm^{-3}) were observed at Hai Masoum; an urban site in Zarqa influenced by traffic and industrial activities. In Amman, the highest number concentrations were observed at the urban residential sites (Umm Summaq and Al-Hashmi Al-Shamali, 24-hour median as high as 4.6×10^4 cm^{-3}), whereas the lowest was at the sub-urban site (Shafa Badran, 24-hour median as high as 2.3×10^4 cm^{-3}). The daily pattern of the fine particle number concentrations was characterized by three peaks during the daytime. The first and last peaks are probably related to the morning and afternoon traffic rush hours, which are similar to those observed in the developed countries. The third peak was around midday, which is possibly related to increased traffic activities related to school buses. The lowest concentrations (~4600 cm^{-3}) at Shafa Badran were observed after midnight and before the morning rush hours. Different lowest values were observed at the five sites because of different population densities and nearby anthropogenic activities.

Keywords: Atmospheric aerosol particles, Spatial-temporal variation, Daily pattern, Background.

1. Introduction

Urban aerosols have a complex dynamic behavior, because they are a mixture of regionally transported aerosols and a wide range of locally emitted aerosols [1]. Besides being externally mixed, their composition can vary depending on the source type, geographical region, state of development and dynamic processes involved in their transformation.

While the urban aerosols impact the local air quality (e.g., loss of visibility), they also have a large spatial-scale effect, because they are not localized to the geographical location of the source area and are likely to be transported over large distances where they affect the air quality and the climate. Exposure to urban aerosols might lead to serious health effects [2–6]. As stated by the WHO, the health effects of urban aerosols are usually assessed by monitoring exposure to certain particulate matter classes (such as PM_{10} and $PM_{2.5}$), in addition to some gaseous pollutants (such as carbon oxides, nitrogen oxides, …etc.). Not long time ago, the WHO suggested that black carbon (BC, often

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measured as elemental carbon, EC) may operate as a carrier of a wide variety of combustion-derived chemical constituents of varying toxicity. While the health effects occur at relatively low particle mass concentrations, the toxicity of inhaled particles is believed to be linked to other concentration metrics, such as the particle number or surface area concentrations [7].

As will be presented herein, the aerosol research activities in the Middle East have been limited to PM concentrations, some gaseous pollutants, chemical and elemental analysis and very few about particle number concentration. It is worth to mention two studies that presented an Enhanced Particulate Matter Surveillance Program. This program aimed at providing scientifically founded information on the physical and chemical properties of dust collected during a period of approximately 1 year in Djibouti, Afghanistan, Qatar, United Arab Emirates, Iraq and Kuwait [8–9]. The region has been under considerable development and urbanization, leading to a change in land use and surface geology. For example, dried soils and diminished vegetation cover in the Fertile Crescent have caused greater dust generation and increased dust days in the past years [10]. As it is expected, the eastern Mediterranean region will suffer warming and drying during this century leading to higher dust emissions and thus, exposure to ambient aerosols.

In Egypt, aerosol research has been the most extensive in the Arab world. It is dated back to the late 70's and early 80's of the past century [11–12]. Tadros et al. [13] reported the difference in the aerosol size distribution, which was indirectly calculated by means of the Mie theory, between agricultural and industrial sites in Egypt. More recently, Moustafa et al. [14] determined the mass size distributions of seven elemental composition aerosols at an industrial site. More about elemental and chemical analysis of aerosols can be found in Boman et al. [15], Hassan et al. [16] and El-Araby et al. [17]. Mahmoud et al. [18] utilized a box model to derive the origin and amount of emissions of black carbon in Cairo. It was also shown that the air quality of the coastal regions in North Egypt is affected by the flow bringing long-range transported anthropogenic air pollution from Europe towards North Africa, as well as the flow of desert dust from North Africa towards Europe [19]. This phenomenon was explained by certain weather conditions prevailing in the Mediterranean Sea. In another study, El-Askary and Kafatos [20] examined the influence of dust storms, dense haze and a smog-like phenomenon known as the 'black cloud' on the aerosol optical properties. The effect of meteorological conditions on air pollution and the optical properties of aerosols were examined by Elminir [21] and by El-Metwally and Alfaro [22].

In Saudi Arabia, for instance, about eleven studies focused on PM concentrations and some chemical and elemental analysis [1, 23–30]. In the United Arab Emirates, there is a very few number of articles focused on aerosols with most of them dedicated to the aerosol optical depth and its relation to the dust episodes [31–33]. In fact, airborne dust affects the aerosol optical depth on a large scale [33–35].

In Kuwait, the main focus of aerosol research was dated to the oil fire plumes in 1991 [36–41] and very few focused on aerosol dust episodes [42]. In Iraq, Dobrzhinsky et al. [43] and Engelbrecht and Jayanty [44] focused on mineral and road dust events, whereas Hamad et al. [45] presented a source apportionment analysis for $PM_{2.5}$ carbonaceous aerosols in Baghdad.

Researchers in Lebanon have given extensive attention to analyze the chemical composition of fine and coarse aerosols and its relation to certain dust outbreaks, long-range transport and local emissions [46–52]. Waked et al. [53] modeled the evolution of some air pollution parameters (O_3, CO, NO_x and $PM_{2.5}$) at a sub-urban site in Beirut. In another study, they reported the composition and source apportionment of organic aerosols in Beirut during winter 2012 [54].

To our knowledge, there is less than ten articles published on PM, some gaseous pollutants and limited chemical analysis in Jordan. For instance, Al-Momani et al. [55] and Gharaibeh et al. [56] focused on heavy metals and elemental analysis of aerosol samples in Al-Hashimya and Irbid, respectively. Soleiman et al. [57] indicated that emissions from the highly populated and industrialized Israel-Gaza coast are transported inland and lead to elevated levels of ozone over Jordan. Hamasha and Arnott [58] reported black carbon concentrations at six sites in Irbid city. Abu Allaban et al. [59] focused on dust re-suspension from limestone quarries nearby a town located north east of Amman and reported PM_{10} concentrations as high as 600 μg/m^3 with most of the airborne PM being in the coarse fraction. Schneidemesser et al. [60] determined sources and seasonal variation of organic carbon as well as the contribution to fine particulate matter ($PM_{2.5}$) in Palestine, Jordan and Israel. They recently presented an extensive analysis on the $PM_{2.5}$ to report its major chemical components including metals, ions, as well as organic and elemental carbon [61]. According to their study, the $PM_{2.5}$ varied from 20.6 to 40.3 μg/m^3 and was higher in summer compared to winter. The $PM_{2.5}$ concentrations in the spring were greatly impacted by regional dust storms. There was only one study that focused on fine particle number concentrations in Jordan, specifically in Amman city [62].

However, the previous studies mainly focused on regional aerosols (i.e., dust) and did not present information on the spatial-temporal variations of particle number concentrations within cities in the Middle East. The main objective of this study is to investigate the number concentrations of sub-micron particles at four sites within Amman and compare them with another site located in Zarqa city. The measurement campaign took place during three months: March 6 – May 28, 2014. We specifically focused on: (1) temporal variation (hourly, daily and weekly) and (2) spatial variation that covered an area confined within an equilateral triangle (9 km side length) inside Amman and extended to the location in Zarqa (at a distance of about 20 km from Amman).

2. Materials and Methods

2.1. Sites Description: the Hashemite Kingdom of Jordan

The Hashemite Kingdom of Jordan (29º–33º North and 37º–39º East) is located about 100 km east of the Mediterranean Sea. To its south is the Arabian desert and to its north is the Fertile Crescent part of Syria (Fig. 1a). It comprises a wide variety of topography: desert area (eastern and southern parts), high mountains (northern and western parts), as well as the Dead Sea and the Jordan Valley (at about 400 m below the sea level).

The population of Jordan is about 9.5 million people (by the end of 2016). One third of the population live in the capital city, Amman, which covers an area of about 50×35 km^2. The capital city itself is located in the north-western part and is comprised of a complex terrain of several mountains that makes it challenging to evaluate the air quality in the city. About 30 km north-east of Amman is located the second largest city (Zarqa) in Jordan. The topography of Zarqa is rather flat. Besides being large in population density, Zarqa accommodates a vast range of industrial activities and waste management sites.

Following our 2009 measurement campaign [61], we performed a more extensive measurement campaign in the spring season of the year 2014 to measure sub-micron particle number concentrations at four sites in Amman and one site in Zarqa (Fig. 1b). Following is a detailed description of each site. Table 1 lists the measurement sites along with the aerosol measurement period and site abbreviations, which are to be used throughout the article.

Campus of the University of Jordan – Amman: *urban-background site*

The campus of the University of Jordan (JU @ [32.0129N,35.8738E]) is a mixture of pine tree forest and buildings (3–4 floors). It can be classified as an urban-background site. It is located at about 10 km from the city center. The surrounding of the campus is mainly a populated residential area. One of the main highways is parallel to the western side of the campus.

Umm Summaq – Amman: *urban-residential site with major traffic influence*

Umm Summaq (US @ [31.9880N,35.8387E]) is located in the north-western part of Amman at about 11 km from the city center. It can be classified as an urban-residential site. The surrounding area mainly contains residential buildings, schools, two big malls and business centers. The area has developed and most of the buildings have been built just few years ago.

Shafa Badran – Amman: *suburban-residential site with minor traffic influence*

Shafa Badran (SB @ [32.0527N,35.8960E]) is located in the north-eastern part of Amman at about 13 km from the city center. It can be classified as an urban-residential site. The nature of the area is rocky landscape intersected by one of the main highways (Al-Urdon street), which links the capital Amman with the northern cities (Jarash, Ajloun, Irbid, …etc.). The residential area has been under continuous development with many multi-floor buildings rising every year.

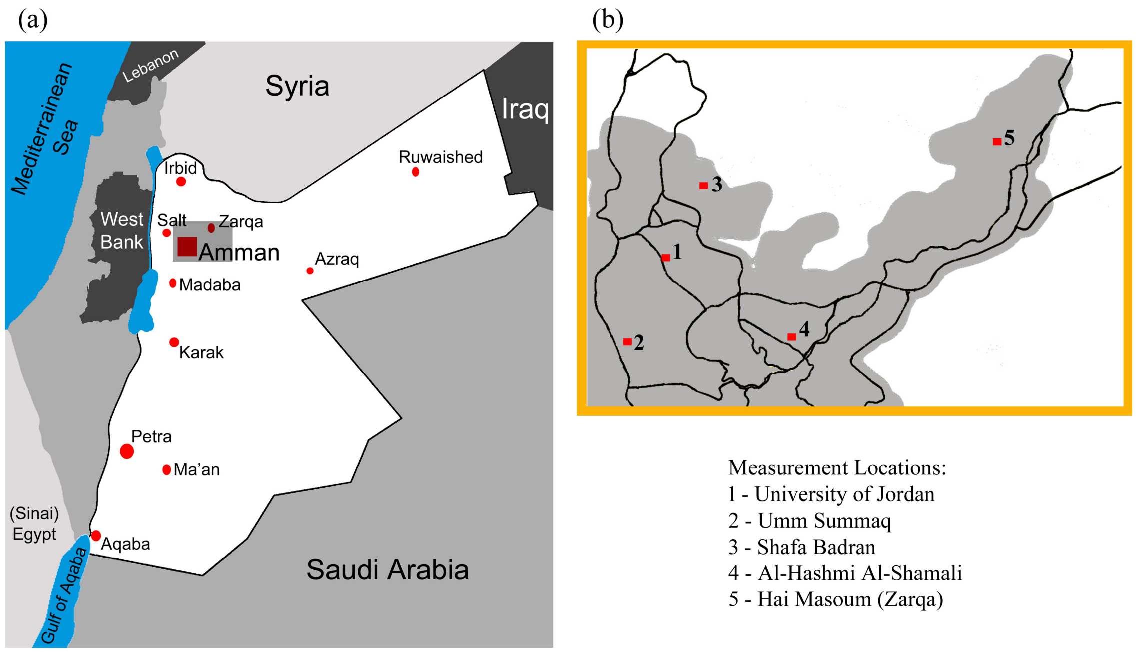


FIG. 1. (a) Map of Jordan showing the main cities and (b) A zoom in Amman and a part of Zarqa with a shade that indicates the land use. The numbers indicate the measurement site locations.

TABLE 1. Measurement sites.

Site Name	City	Classification			Period	Code
Campus of the University of Jordan	Amman	Urban	Background	--	March 6 – 18 April 14 – 30	JU1 JU2
Umm Summaq	Amman	Urban	Residential	Major traffic	March 18 – April 13	US
Shafa Badran	Amman	Sub-urban	Residential	Minor traffic	May 1 – 11	SB
Hai Masoum	Zarqa	Urban	Residential	Major traffic Minor industry	May 11 – 18	HM
Al-Hashmi Al-Shamali	Amman	Urban	Residential	Major traffic	May 19 – 26	HS

Al-Hashmi Al-Shamali – Amman: *urban-residential site with major traffic influence*

Al-Hashmi Al-Shamali (HS @ [31.9656N,35.9552E]) is located in the eastern part of Amman at about 2 km from the city center. It can be classified as an urban-residential site. The measurement location itself was situated on a slope of a mountain. Towards the south-west, there is a mountain on which the Royal Palaces are situated. Both mountains form a canyon, where one of the main roads (Al-Istiklal) connects the eastern parts to the western parts of the capital city.

Hai Ma'soum - Zarqa: *urban-residential site with major traffic and minor industry influence*

Zarqa is the second largest city in Jordan after Amman. It is located about 24 km northeast of Amman. The border between Amman and Zarqa is not well defined, because both cities have expanded toward each other over the past three decades. Zarqa accommodates densely packed residential areas mixed with military centers, small and large industrial facilities, waste management sites, as well as quarries and mines.

The measurement location at Hai Masoum (HM @ [32.0704N,36.0753E]) was chosen as close as possible to Amman, but still as far as possible from the potential sources other than local traffic. Therefore, this site can be classified as an urban-residential site with major traffic and minor industry influence.

2.2 Aerosol Measurement

The aerosol measurement was performed with a portable Condensation Particle Counter (CPC, TSI model 3007). This type of CPC is capable of recording the fine particle number concentration in the diameter range of 10 nm – 1 µm. We operated CPC with a 5-minute averaging time at each site. The sampling inlet was an about 1-meter copper tube (4–mm inner diameter). The use of a short sampling line would have minimal effects on the nominal flow rate, cut-off size and particle losses.

2.3 Weather Conditions

The Jordan Meteorological Department (JMD) provided the weather data during the measurement campaigns. The weather data used for this study was measured at the Amman Civil Airport, which is located in Marka. The airport itself is located at about 11.5 km south east of the central site in this study (the University of Jordan campus).

Records of the meteorological variables included hourly averages of the ambient temperature, relative humidity, wind direction and speed, precipitation and pressure.

According to this weather observation (Fig. 2), the wind speed was as high as 11.6 m/s, with a median of 2.7 m/s and an overall average of about 3 m/s. The overall average and median values of temperature were about 18.3 ºC, having a clear daily pattern with a maximum as high as 33 ºC (observed around midday) and a minimum as low as 4 ºC (registered around midnight). The relative humidity varied between 7% and 91% with an overall average value of about 40% (median 36%). The pressure varied between 917 mbar and 932 mbar with an average value around 925 mbar. During the whole measurement campaign, the prevailing wind direction was rarely from east; it was mainly (more than 65%) between -135^o and +45^o.

3. Results and Discussion

3.1 Spatial Variation

The fine particle number concentration showed a clear spatial variation within the capital city (Amman); see Tables 1–6 and Fig. 2. The lowest concentrations were observed at Shafa Badran (SB), which is a sub-urban residential site with minor traffic influence. As shown in Table 4, the daily median value varied between 1.0×10^4 and 2.3×10^4 cm^{-3} (average 1.1×10^4 – 2.4×10^4 cm^{-3}). The urban background site (the University of Jordan campus, JU) had slightly higher daily median concentrations than those observed at SB (Tables 2 and 4); the daily median value varied between 1.3×10^4 and 4.0×10^4 cm^{-3} (average 1.5×10^4 – 4.1×10^4 cm^{-3}).

The two urban sites (Umm Summaq and Al-Hashmi Al-Shamali) recorded somewhat higher daily median values of fine particle number concentrations (Tables 3–5). At Umm Summaq (US), the daily median value varied between 1.8×10^4 and 4.6×10^4 cm^{-3} (average 1.9×10^4 – 5.2×10^4 cm^{-3}), whereas at Al-Hashmi Al-Shamali (HS) it was 3.0×10^4 – 4.6×10^4 cm^{-3} (average 3.0×10^4 – 4.6×10^4 cm^{-3}). We attribute the higher concentrations at these two sites to the anthropogenic activities (mainly traffic emissions) nearby the measurement sites.

The site located in Zarqa city showed the highest concentrations with a daily median value between 2.0×10^4 and 5.2×10^4 cm^{-3} (average 2.2×10^4 – 5.3×10^4 cm^{-3}); Table 6. We expect the number concentrations to be even higher in areas nearby the center of Zarqa city, because this city has high population density with industrial activities distributed within and around the city.

As illustrated in the introduction section, fine particle number concentrations in the Middle East, especially in Jordan, have not been reported with an exception for the study by Hussein et al. [61], who reported the fine particle number concentrations at JU and HS during spring 2009; about one week measurement period at each site. The observed concentrations in this study for HS (average 3.0×10^4 – 4.6×10^4 cm^{-3}) agree with those previously reported by Hussein et al. [61] as 2.3×10^4 – 6.9×10^4 cm^{-3}. The same can be found for the JU site; in this study, the average concentrations are 1.5×10^4 – 4.1×10^4 cm^{-3}, whereas those reported by Hussein et al. [61] were 2.5×10^4 – 3.7×10^4 cm^{-3}.

In general, the observed number concentrations in Amman were higher than what is usually reported in some cities in the developed countries [63–73]. For example, Ruuskanen et al. [74] presented the number concentrations in three European cities; the average number concentrations were about 20300 cm^{-3}, 25900 cm^{-3} and 25800 cm^{-3} in Helsinki, Erfurt and Alkmaar, respectively. Recently, Reche et al. [75] reported the average particle number concentrations in the urban background of Barcelona (Spain), Lugano (Italy) and North Kensington (UK) as 16850 cm^{-3}, 14950 cm^{-3} and 12150 cm^{-3}, respectively. In the same study, the average number concentrations at road site in Bern (Switzerland) and Marylebone (UK) were 28000 and 22150 cm^{-3}, respectively. A sub-tropical urban site (Santa

Cruz Tenerife) influenced by shipping emissions had an average number concentration of about 12000 cm^{-3}, whereas at an industrial site at Huelva (Spain) it was 17900 cm^{-3}. Wehner and Wiedensohler [76] showed a seasonal trend in the particle number concentration at a moderately polluted site in Leipzig (Germany) with average concentration as 21400 cm^{-3} in winter and 11600 cm^{-3} in summer. Puustinen et al. [77] compared fine particle number concentrations between central and residential locations in four EU cities. At the central locations of Helsinki, Athens, Amsterdam and Birmingham, they were about 12500 cm^{-3}, 20300 cm^{-3}, 18100 cm^{-3} and 18800 cm^{-3}, respectively. At the residential sites, they were 4500 cm^{-3}, 15250 cm^{-3}, 26350 cm^{-3} and 16100 cm^{-3}, respectively. We, therefore, expect that the number concentrations in some locations in Amman are in line with the previous results obtained in various locations in Europe.

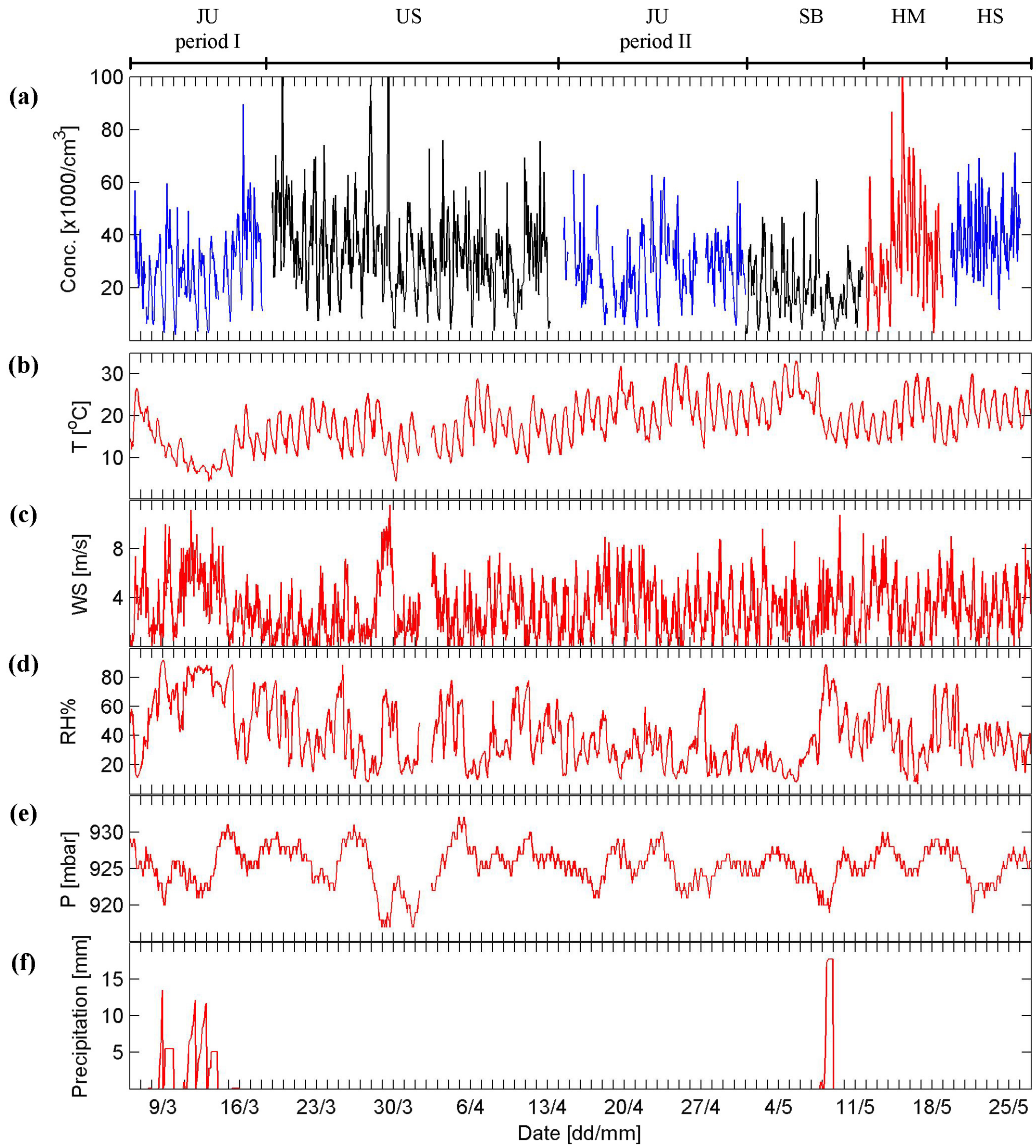


FIG. 2. Hourly average (a) fine particle number concentration, (b) ambient temperature, (c) wind speed, (d) relative humidity, (e) pressure and (f) precipitation during the whole measurement campaigns March 6 – May 28, 2015. *The abbreviations on top of the figure refer to the name of the site location as the campus of the University of Jordan (JU), Umm Summaq (US), Shafa Badran (SB) and Hai Masoum (HM).*

TABLE 2. 24-hour statistics of fine particle number concentrations at the University of Jordan campus (JU), which is an urban background site in Amman.

Date	Day	Mean	STD	25%	Median	75%
6 March	Thursday	32376	10449	23839	28829	39754
7 March	Friday	19090	8654	12031	19486	26082
8 March	Saturday	22133	10229	14226	24457	29056
9 March	Sunday	27721	16098	11395	31335	41351
10 March	Monday	22672	12489	10766	25193	28524
11 March	Tuesday	22112	7774	16937	19491	25990
12 March	Wednesday	20300	10891	10244	23877	29839
13 March	Thursday	21705	12292	8668	24050	32867
14 March	Friday	26632	7411	19027	25618	32205
15 March	Saturday	30911	13003	18057	34855	38462
16 March	Sunday	41123	16892	30147	39591	51179
17 March	Monday	34554	12896	24964	37533	43024
14 April	Monday	31852	7692	25021	31072	38339
15 April	Tuesday	33805	11829	26050	28603	43649
16 April	Wednesday	24104	10661	15661	22846	29543
17 April	Thursday	30874	10238	21398	30031	38091
18 April	Friday	14957	7619	9340	12768	21843
19 April	Saturday	15657	4866	12793	14383	19643
20 April	Sunday	25180	8901	15564	27597	29602
21 April	Monday	25839	14373	11077	25301	39698
22 April	Tuesday	34100	13901	22767	33069	42835
23 April	Wednesday	34635	17081	19900	32596	50521
24 April	Thursday	34059	9166	26932	32037	40572
25 April	Friday	20195	6232	15842	19843	23196
26 April	Saturday	25401	9551	17463	26061	33738
27 April	Sunday	31604	5468	27148	31697	36253
28 April	Monday	29938	8491	22208	29749	38027
29 April	Tuesday	27115	9566	17339	26700	36485
30 April	Wednesday	25839	14287	9798	24919	33908

TABLE 3. 24-hour statistics of fine particle number concentrations at Umm Summaq (US), which is an urban residential site with major traffic influence in Amman.

Date	Day	Mean	STD	25%	Median	75%
19 March	Wednesday	51613	27651	34945	46306	57965
20 March	Thursday	43544	11062	36168	42667	51589
21 March	Friday	35651	11749	26784	31529	41669
22 March	Saturday	36992	17475	22659	36693	50152
23 March	Sunday	32713	16335	20331	35175	40029
24 March	Monday	30540	13633	16333	31469	42103
25 March	Tuesday	32673	14250	22008	31788	45623
26 March	Wednesday	36193	11312	28673	34214	41279
27 March	Thursday	44989	24696	26289	41473	62581
28 March	Friday	37193	9874	31086	37822	43705
29 March	Saturday	36626	45626	16448	19343	35825
30 March	Sunday	19362	9924	11178	20308	24818
31 March	Monday	33176	12704	18995	34411	45214
1 April	Tuesday	26876	9703	19300	28034	35451
2 April	Wednesday	26913	12562	19857	25107	30858
3 April	Thursday	31968	17961	18163	28672	47663
4 April	Friday	28710	15392	12797	27596	40215
5 April	Saturday	33281	9393	27083	32256	37061
6 April	Sunday	27740	15216	15932	28210	38656
7 April	Monday	28586	11843	22286	26181	30932
8 April	Tuesday	27509	11934	23905	29167	37409
9 April	Wednesday	25067	10929	17040	25201	31788
10 April	Thursday	20083	15696	10818	18040	21926
11 April	Friday	36014	10427	27059	35239	43974
12 April	Saturday	37162	13033	28514	36032	41461
13 April	Sunday	6594	1626	5167	6413	7912

TABLE 4. 24-hour statistics of the particle number concentrations at Shafa Badran (SB), which is a sub-urban residential site with minor traffic influence in Amman.

Date	Day	Mean	STD	25%	Median	75%
1 May	Thursday	20840	11362	9615	23198	30409
2 May	Friday	21274	13781	7844	18677	32991
3 May	Saturday	19713	9964	13746	19976	23883
4 May	Sunday	20430	11436	12576	15994	27873
5 May	Monday	18151	8422	13520	16216	23561
6 May	Tuesday	19008	11753	10243	17829	23335
7 May	Wednesday	23834	16305	12299	17449	32216
8 May	Thursday	14415	6516	8973	14963	19052
9 May	Friday	11281	4914	7210	9990	14569
10 May	Saturday	20390	7537	14699	20170	25910
11 May	Sunday	16806	8242	7090	16700	24771

TABLE 5. 24-hour statistics of fine particle number concentrations at Al-Hashmi Al-Shamali (HS), which is an urban residential site with major traffic influence in Amman.

Date	Day	Mean	STD	25%	Median	75%
20 May	Tuesday	35609	12418	27490	34259	45474
21 May	Wednesday	37872	12934	26747	33198	48763
22 May	Thursday	38316	13242	28838	36061	45751
23 May	Friday	38717	10554	30934	36366	47197
24 May	Saturday	33688	13219	25684	30050	40669
25 May	Sunday	45317	11281	35877	45640	50898

TABLE 6. 24-hour statistics of fine particle number concentrations at Hai Masoum (HM), which is an urban residential site with major traffic and minor industry influence in Zarqa.

Date	Day	Mean	STD	25%	Median	75%
12 May	Monday	25639	15262	17718	21179	32314
13 May	Tuesday	22303	10466	15692	22173	30731
14 May	Wednesday	35103	19556	23141	36046	49287
15 May	Thursday	52847	27866	27846	48184	69366
16 May	Friday	41546	16820	29903	41084	51440
17 May	Saturday	33090	13889	18411	34342	42643
18 May	Sunday	26706	14501	15624	26259	36079

3.2 Temporal Variation – Daily Pattern

The temporal variation of fine particle number concentrations showed a clear daily pattern at each measurement site (Fig. 3). The average daily pattern of fine particle number concentrations at the urban background site (JU) was characterized by high concentrations during daytime (07:00–18:00) on all days. Dividing the dataset into workdays and weekends, we observed that on workdays, the daytime concentration was higher than 30000 cm^{-3}, while it was in the range of 20000–30000 cm^{-3} on weekends. The workdays had the highest concentrations (as high as 45000 cm^{-3}) during the morning traffic rush hours (between 06:00 and 09:00). The lowest concentrations (as low as 10000 cm^{-3}) were observed after midnight and before 06:00.

The sub-urban site (SB) showed rather a similar daily pattern to that of the urban background site (JU), but the concentrations were lower at the sub-urban site (Fig. 4). On both workdays and weekends, the average fine particle number concentrations were in the range of 20000–35000 cm^{-3} (Fig. 4a) on workdays and in the range of 20000–25000 cm^{-3} on weekends (Fig. 4b). On workdays, the effect of the morning traffic rush hours was also visible with the highest concentrations recorded at this site. Another peak in fine particle number concentrations was recorded around noon on workdays; that is most likely linked to increased traffic activities related to school buses, which are mainly operated by diesel engines. The lowest concentrations (as low as 4000 cm^{-3}) were observed after midnight and before 06:00.

The urban residential sites (Figs. 5 and 6), which were influenced by major traffic activities, showed similar daily patters, but the concentration values were higher at HS than at US. This is due to the fact that HS is a more populated area than US. Both workdays and weekends showed two main peaks during the daytime and a late evening peak. The first daytime peak was between 06:00 and 09:00 and represented the morning traffic rush hours, while the second daytime peak was around noon and represented the traffic activity of school buses, and the late evening peak was most likely due to late shopping activities. The workdays' daytime average concentration was 25000–55000 cm^{-3} at HS and 30000–42000 cm^{-3} at US. The late night peak observed on both workdays and weekends was as high as 45000 cm^{-3} at HS and as high as 42000 cm^{-3} at US. The lowest concentrations at both sites were recorded after midnight and before 06:00; at HS, the lowest concentration was as low as 20000 cm^{-3} and at US it was as low as 12000 cm^{-3}.

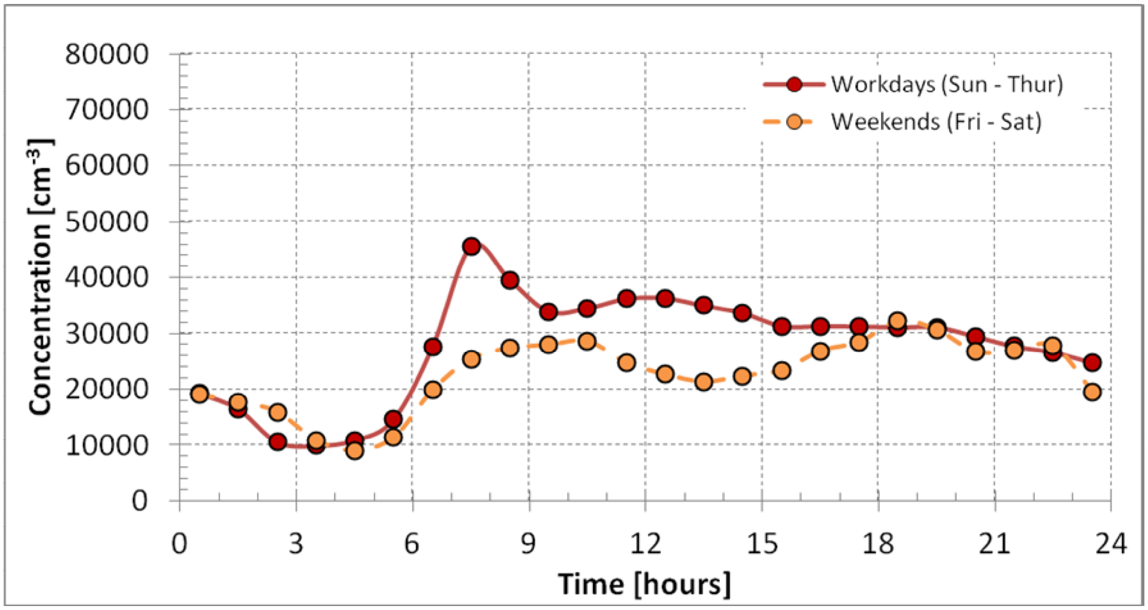


FIG. 3. Average daily patterns of fine particle number concentrations at the campus of the University of Jordan (JU, urban background) during March 6–18 and during April 14–30, 2014.

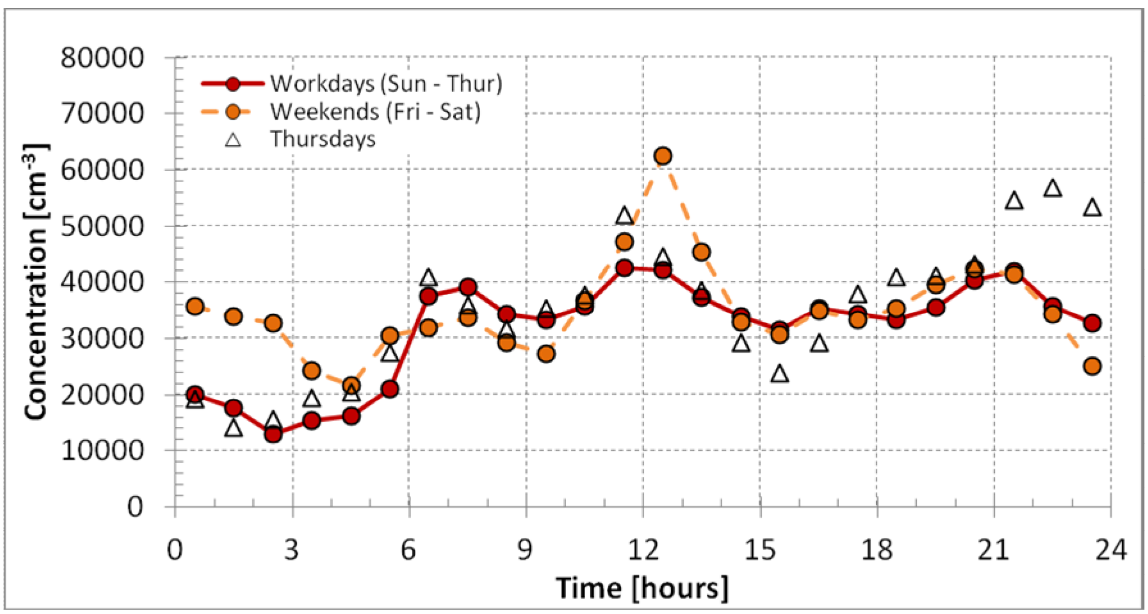
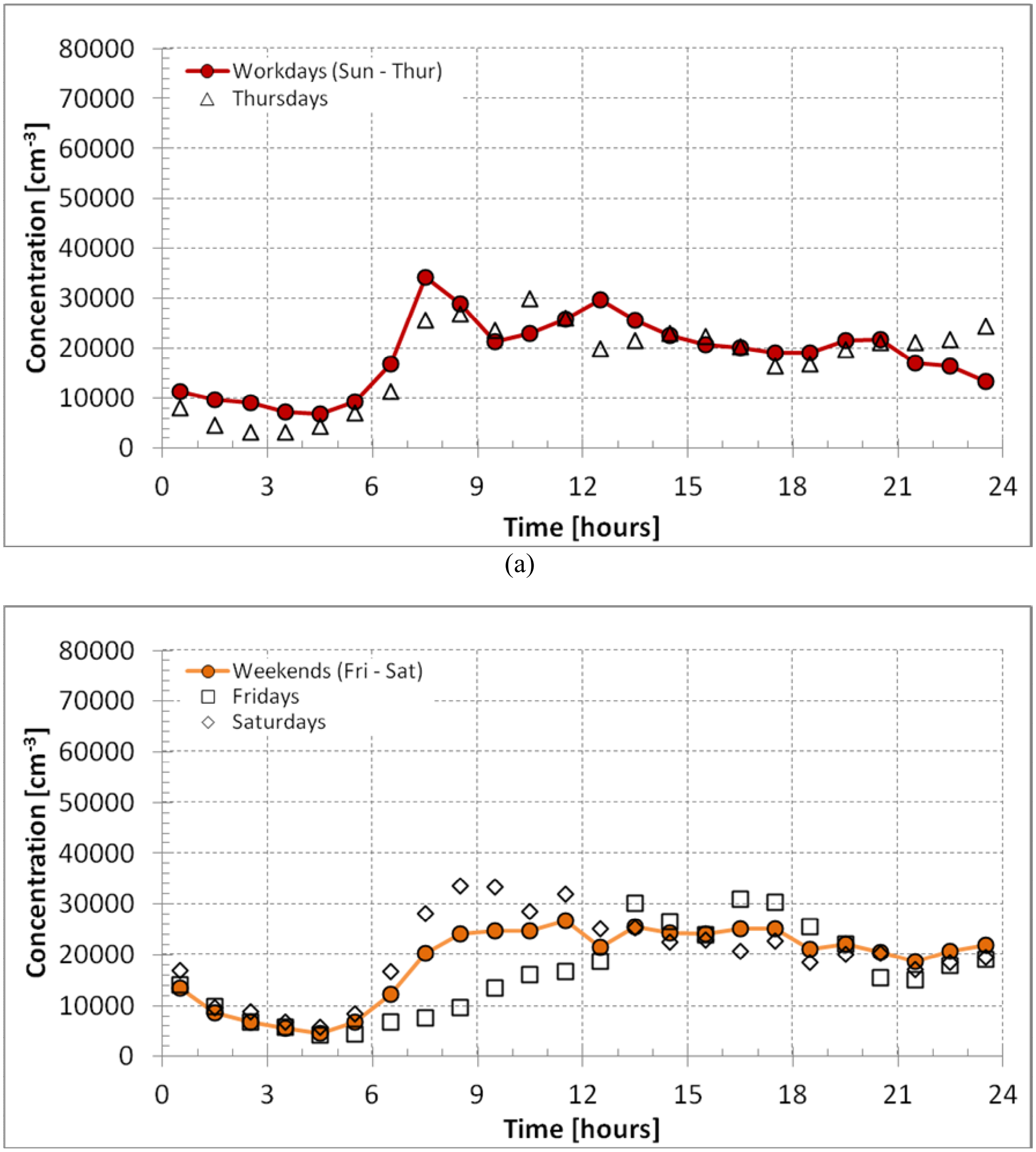


FIG. 4. Average daily patterns of fine particle number concentrations at Umm Summaq (US, urban residential with major traffic influence) during March 18 – April 13, 2014.



(a)

(b)

FIG. 5. Average daily patterns of fine particle number concentrations at Shafa Badran (SB, suburban residential with minor traffic influence) during May 1–11, 2014: (a) during workdays (Sunday - Thursday) and also showing Thursday separately and (b) on the weekend (Friday – Saturday) and also showing Friday and Saturday separately.

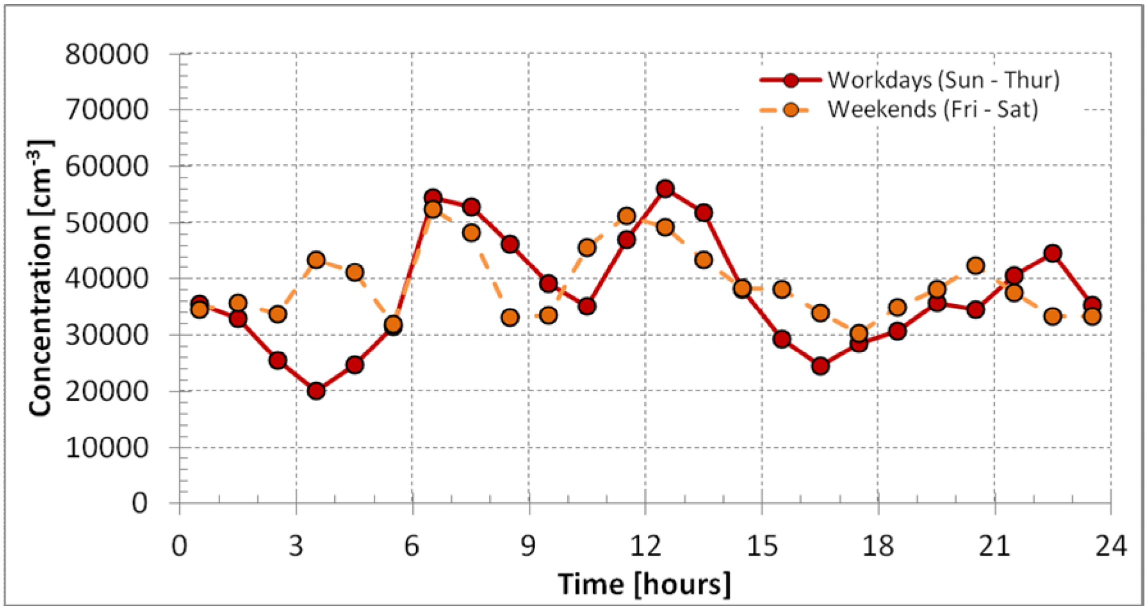


FIG. 6. Average daily patterns of fine particle number concentrations at Al-Hashmi Al-Shamali (HS, urban residential with major traffic influence) during May 26 – 29, 2014.

The urban site (HM) in Zarqa city also showed a similar daily pattern as those observed at HS and US (Fig. 7). The common thing between the three sites is that they are all urban residential with major traffic influences. However, the HM site had a minor influence of industrial activities. What is also interesting is that this site had a dominant morning peak in fine particle number concentrations that started around 05:00 and lasted until noon with a maximum concentration (higher than 60000 cm^{-3} around 07:00). Similar to the sites in Amman, the lowest concentration was recorded after midnight and before 06:00 and it was as low as 10000 cm^{-3}.

To sum up the findings about the daily patterns, all the urban residential sites showed a daily pattern for fine particle number concentrations that is characterized by three peaks (two during the daytime 06:00–18:00 and a late night peak); this daily pattern was similar for both workdays and weekends. The absolute value of the concentration was related to the population density and other anthropogenic activities. For example, HM and HS were more populated than US; and additionally, HM was influenced by industrial activities.

In the urban areas, the daily pattern of fine particle number concentrations is closely related to emissions from traffic and industry. For example, traffic activity on workdays is usually characterized by two main rush hours (morning and afternoon) that represent the times when people go to work and return back home [69]. Such daily patterns were reported in most cities in the developed countries [76, 78–79].

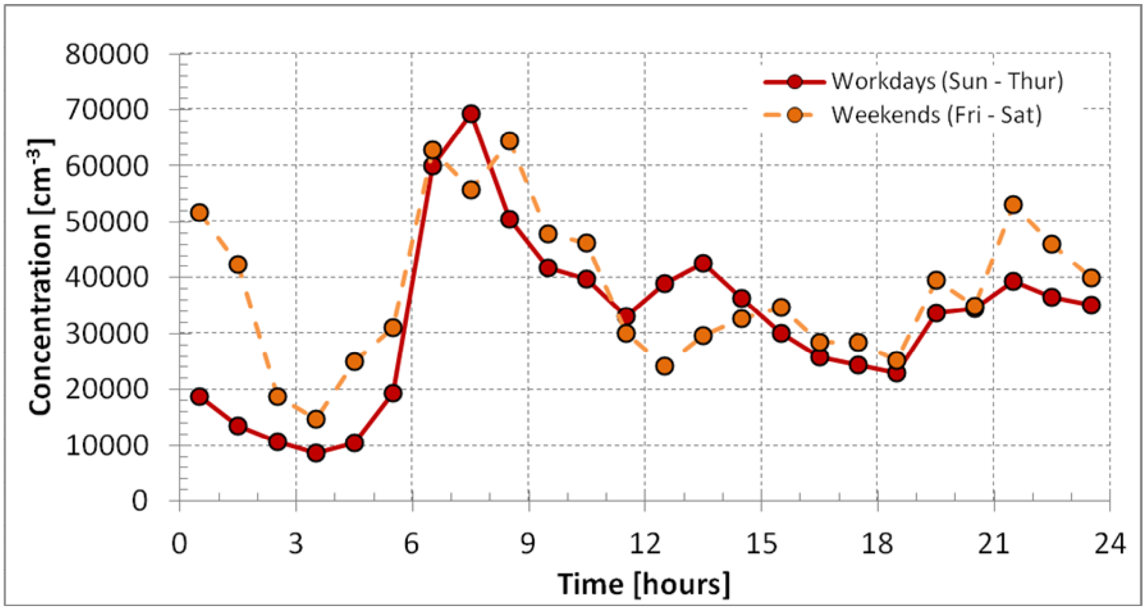


FIG. 7. Average daily patterns of fine particle number concentrations at Hai Masoum in Zarqa city (HM, urban residential with major traffic and minor industrial influence) during May 11–18, 2014.

4. Conclusions

We measured fine particle number concentrations in Jordan at four locations within the capital city, Amman. We additionally performed similar measurements at a single site in the second largest city in Jordan, Zarqa. The measurement campaign took place during March 6 – May 28, 2014. We specifically focused on the temporal-spatial variation (hourly, daily and weekly) of fine particle number concentrations. The measurement sites in Amman included an urban-background site (the University of Jordan campus), two urban-residential sites (Umm Summaq and Al-Hashmi Al-Shamali) and suburban-residential site (Shafa Badran). The site in Zarqa was an urban-residential site with minor industrial influence. All sites were influenced by traffic emissions.

There was a clear spatial and temporal variation of fine particle number concentrations within Amman. The highest concentrations were observed at the urban residential sites (Shafa Badran and Al-Hashmi Al-Shamali, 24-hour median value as high as 34.6×10^{4} cm^{-3}) and the lowest were at the sub-urban site (Shafa Badran, 24-hour median value as high as 2.3×10^{4} cm^{-3}). The highest concentrations among all sites were recorded at the urban-residential site in Zarqa (Hai Masoum); 24-hour median value being as high as 5.2×10^{4} cm^{-3}.

The daily pattern at the residential sites was characterized by three peaks during the daytime. The first peak and last peak are related to the morning and afternoon traffic rush hours, which are similar to those observed in the developed countries. The third peak was around midday, which is possibly related to increased traffic activities related to school buses. During the day, the lowest fine particle number concentrations (~4600 cm^{-3}) were observed at the sub-urban residential site (Shafa Badran) after midnight and before the morning rush hours. This lowest value was different among the sites, and it was most likely related to population density. For example, at the urban sites, it was higher than that at the sub-urban site.

The spatial variation found in fine particle number concentrations agrees well with one of our studies about polycyclic aromatic hydrocarbons (PAHs) in collected floor dust within Amman city [80]. PAHs are usually accompanied with combustion processes and we presume that the main sources of fine particulate matter is also related to the same processes in Amman; hence, high fine particulate matter concentrations are expected to be in the same locations with high PAHs concentrations found in floor dust.

The limitations of this study are as follows: (1) It did not consider the particle number size distribution that can reveal the modal structure of aerosol particles and (2) The measurement campaign at some of the sites was very short that it might not be enough to make a strong conclusion about the fine particle characteristics. These features would require more comprehensive observations in Jordan.

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