



Temporal and spatial pattern of dust storms, their polycyclic aromatic hydrocarbons, and human health risk assessment in the dustiest region of the world

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Abstract This study evaluated the concentration and health risks of polycyclic aromatic hydrocarbons (PAHs) in Abadan City under 4 different climatic conditions: normal days, dusty days, dust with northwesterly winds, and dust with southeasterly winds. It also determined the sources of aromatics and discussed the relationship between meteorological parameters and PAH concentrations. The spatiotemporal distribution of dust in the area was determined using the HYSPLIT (hybrid single-particle Lagrangian integrated trajectory) back trajectory model, moderate resolution imaging spectroradiometer (MODIS) images. For this purpose, sampling was performed for 70 days using an Omni device. The concentrations of 16 PAHs (USEPA) ranged from 46.22 to 90.96 ng/m³. The highest concentration of high molecular weight (HMW) PAHs was 4–6 rings, of which 4 rings were predominant in all samples. PAH sources were identified using diagnostic ratios and principal component analysis (PCA), and it was shown that PAHs mainly originate from a mixture of sources, including vehicular emissions, petrol emissions, and traffic. Wind speed was negatively correlated with dust, except on dusty days. This result indicates a decrease in PAH

concentrations when wind speed increases. On the other hand, the dust correlation with PAH was positive on normal days, but a negative correlation was observed on dusty days. This result was due to the lower concentration of PAHs from natural resources (such as dust source areas) vs. human resources (such as traffic and industry). PAH health risk assessment in Abadan City showed that the risk of carcinogenesis was higher on normal days and through skin contact. The probability of incremental lifetime cancer risk (ILCR) in all sampling conditions was potential in terms of carcinogenic risk (10^{-4} – 10^{-6}). As a critical risk factor, relevant authorities should prevent, control, and reduce it.

Keywords Dust · Polycyclic aromatic hydrocarbons · Remote sensing · HYSPLIT model · Health risk assessment

Introduction

Dust storms are an important source of air mineral particles. This phenomenon often occurs in arid and semi-arid countries and is considered the most crucial environmental hazard (Tajiki et al., 2021). Dust is one of the most important pollution indicators in the urban environment. These particles carry pollutants such as polycyclic aromatic hydrocarbons (PAHs) and have adverse environmental effects and consequences on the life and health of city dwellers (Shi et al.,

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2011). Atmospheric aerosols, including black carbon (BC) aerosol and PAHs, can pose a serious risk to human health (Ambade et al., 2021b). Human activities adversely influence air quality. Interesting results were obtained during the COVID-19 pandemic by Ambade et al. (2021b), confirming the improvement in air quality and a significant reduction in concentrations of BC, PAHs, and particulate matter (PM_{2.5}) were extracted before and during the COVID-19 pandemic. Also, emission sources changed before and during the COVID-19 pandemic.

Investigating dust particles in the environment is an essential step in determining pollution and assessing potential hazards (Sorkheh et al., 2022). Dust can threaten human health through ingestion, inhalation, and dermal contact (Gope et al., 2018). However, inhalation has a lower cancer risk than the other 2 exposure routes (Wang et al., 2011; Yu et al., 2014).

PAHs are semi-volatile persistent hydrocarbons whose ubiquitous presence, recalcitrance, bioaccumulation potential, and carcinogenic, mutagenic, and endocrine disrupting effects raised serious concerns (Mitra et al., 2019). Although 16 individual PAH compounds were identified as important pollutants (as reported by the US Environmental Protection Agency [US EPA]), 7 of them were reported as potential human carcinogenic pollutants by the International Agency for Research on Cancer (Zheng et al., 2016). PAHs have 2 or more aromatic rings, which can be classified as high and low molecular weight (HMW/LMW) PAHs according to their molecular weight (Abdollahi et al., 2013). HMW PAHs (4 or higher ring PAHs) have been reported as more lipophilic, less unstable, and less water dissolved than LMW PAHs (3 or lesser ring PAHs). HMW PAHs have been identified as more carcinogenic than LMW PAHs (Tavakoly Sany et al., 2014).

Nowadays, remote sensing is increasingly used to monitor dust by considering the temporal-spatial changes affecting it according to the land and climatic conditions of the region (Chen et al., 2021; Sowden et al., 2018; Wu et al., 2016). The advantages of remote sensing include monitoring a large area simultaneously, tracking the paths of dust pollutants, identifying endangered populations, and eliminating the need for a dense monitoring network (Chen et al., 2021; Sowden et al., 2018).

Abadan City was selected as a developing city for this research because environmental pollution has

grown due to rapid urbanization, population growth, petrochemical and refinery activities, public incineration of municipal waste, increased use of vehicles, and traffic load. Globally, Abadan City is one of the dustiest cities in terms of the frequency of dust. The lack of rainfall and improper management of water resources have created domestic and foreign dust sources in countries such as Iraq, Syria, Saudi Arabia, and Kuwait, from which a large amount of dust comes to Iran and Abadan City every year.

To our knowledge, no study comprehensively investigated the relationship between mineral dust storms and PAHs in Iran. Accordingly, this research aimed to compare the concentration and PAH health risk assessment in the 2 categories of dusty and normal days in Abadan City. Dusty days were examined as 2 groups of dusty days with northeasterly winds and dusty days with southeasterly winds. Researchers have studied dust-associated aromatics in relation to meteorological parameters but so far have not reviewed these dust-related compounds in terms of wind direction and dust source. In this study, in addition to wind direction, spatial distribution and temporal variations of dust masses were also investigated using satellite data. The findings of this research are helpful in implementing effective environmental management and pollution control strategies, according to the source. The main purposes of this study are the following:

- investigate temporal and spatial differences of dust in the study area,
- evaluate 16 PAH concentrations from samples and assessment of their health risk,
- determine the sources of PAHs in the study area,
- compare PAH concentrations on dusty and normal days, and,
- investigate which source and in what direction has the most PAHs bound to dust particles.

Materials and methods

Study area

Abadan is a city in Khuzestan Province in the southwest of Iran (Fig. 1). It is one of the most important cities in the Middle East and Iran due to its strategic

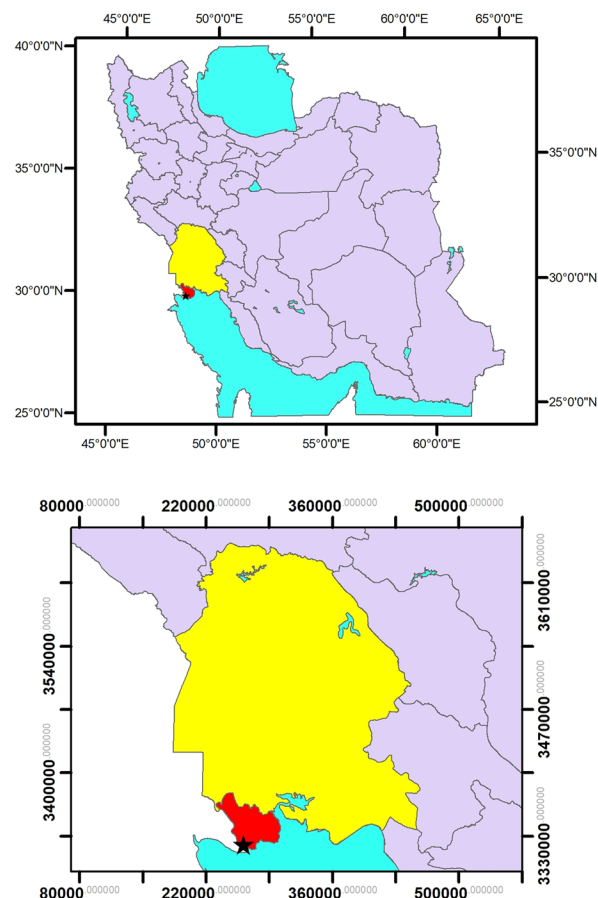
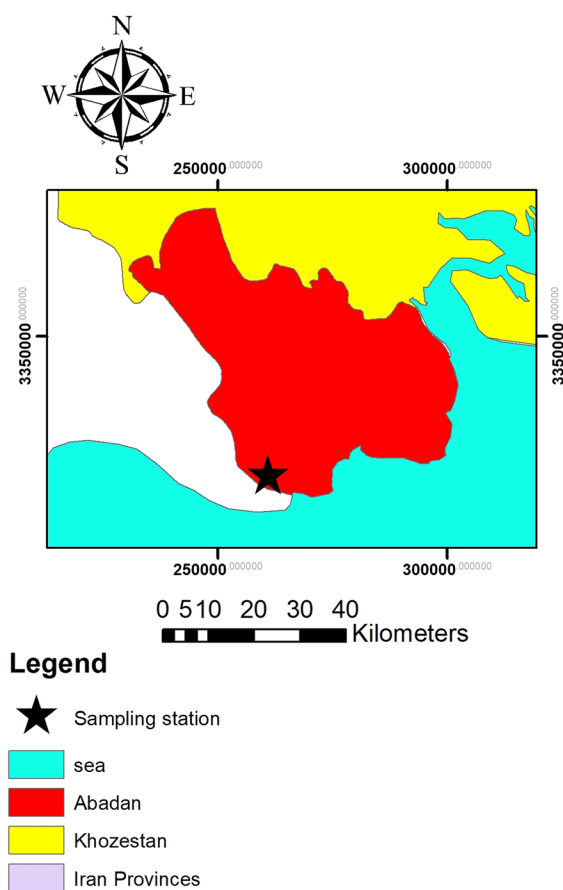


Fig. 1 Study area

oil and petrochemical refinery and the border with Iraq. One of the largest oil refineries in the world (Abadan Oil Refinery) is located in this city. Oil reaches this city through most parts of Khuzestan by pipeline, and after refining, it is exported to the whole world. In recent years, dust storms have become a critical environmental concern in Khuzestan Province, especially in cities such as Abadan. The population of Abadan City is equal to 217,988 people. The geographical location of this city is $48^{\circ} 17'$ (W) longitude and $30^{\circ} 20'$ (N) latitude, with a height of 3 m above sea level and an area of 2796 km^2 . In general, this city has a warm desert climate, and northwesterly and southeasterly winds are frequent wind directions in this city. The annual surveys during the 22 years of the statistical period (1995–2016) show that the Abadan region, with an average frequency of 16 days per year, has the highest number of dusty days in the

whole western and southwestern parts of Iran (Arami et al., 2018).

Sample collection and analysis

This study was carried out in the summer of 2018 in Abadan, southwest Iran. Sampling was performed in 4 climatic conditions: normal days, dusty days, dust with northwesterly winds, and dust with southeasterly winds. The dust samples were collected using an active sampling system. Polytetrafluoroethylene (PTFE) filters were used along with the Omni sampler. After sampling, each PTFE filter was placed in a Teflon container separately and kept at 4°C until the analysis. According to NIOSH 5515, the target PAHs were extracted and purified from the collected samples using a florisil column that was conditioned using a mixture of nitric acid 5%, distilled water,

5 mL methanol (ratio 1–1 V%), and 5 mL dichloromethane (ratio 1–1 V%) were added. The resulting extracts were stored in clean and sterilized glass bottles at 4 °C. Finally; the extracted samples were analyzed for PAH determination using an Agilent gas chromatograph (7890 N) equipped with a mass spectrometer (5975c). A capillary column (HP5-MS 30 m×0.25 mm×0.25 µm) was used for separation. Helium (99.9999%) was used as the carrier gas at a rate of 1 mL/min. The volume of the injected sample or standard was 2 µL. The injector temperature was set at 230 °C. The initial oven temperature was 80 °C for 2 min, and next, it was raised to 285 °C at 10 °C/min and held at this temperature for 4 min.

Quality control

The external standard method was used to measure the concentration of PAHs. A series of PAH standard solutions with different concentration levels were used for calibration. To quantify PAH concentrations and minimize analytical errors, all the instrument and method parameters including the linear working ranges, extraction recoveries, limits of detection, and limits of quantification were calculated.

Linear range

To evaluate data performance, calibration was done with predetermined PAH concentration levels ranging from 100 to 1000 pg/L. The correlation coefficients for all PAHs were above 0.995, which reveals good linearity in these ranges of concentration.

Extraction recoveries

The blank samples were spiked with a standard mixture of PAHs at concentration levels of 100 and 1000 ng/m³, separately. The extraction recoveries of the spiked standards were obtained in triplicate at different times. Table 1 presents the extraction recoveries and the relative standard deviations (RSD %, $n=3$) of the blank samples.

Limits of detection and quantification

The instrument and method detection limits were obtained to evaluate the sensitivity of the extraction method. The instrumental detection limit (IDL) was obtained based on the response at a signal-to-noise ratio (S/N) of 3. Under the present extraction protocol, the method detection limits (MDL) were

Table 1 Recovery efficiency using blank sand samples spiked with standard solutions of PAH mixture at 100 and 1000 (ng/m³) levels

	Recovery ± RSD (%) $N=3$ Concentration 1000 (ng/m ³)	Recovery ± RSD (%) $N=3$ Concentration 100 (ng/m ³)
Naphthalene (Nap)	89 ± 2.91	80 ± 2.44
Acenaphthylene (Acy)	88 ± 3.97	78 ± 2.65
Acenaphthene (Ace)	95 ± 2.88	78 ± 1.08
Fluorene (Fl)	84 ± 4.78	92 ± 2.56
Phenanthrene (Phe)	91 ± 4.21	92 ± 2.42
Anthracene (Ant)	91 ± 4.15	79 ± 5.41
Fluoranthrene (Flu)	91 ± 3.52	86 ± 4.35
Pyrene (Pyr)	82 ± 3.26	78 ± 3.32
Benzo(a)anthracene (BaA)	86 ± 2.18	84 ± 4.21
Chrysene (Chr)	98 ± 1.23	91 ± 2.24
Benzo(b)fluoranthene (BbF)	89 ± 4.56	85 ± 5.81
Benzo(k)fluoranthene (BkF)	71 ± 2.17	79 ± 1.29
Benzo(a)pyrene (BaP)	84 ± 1.09	91 ± 6.01
Dibenzo(a,h)anthracene (DBA)	88 ± 3.92	79 ± 2.39
Dibenzo(g,h,i)perylene (BghiP)	90 ± 2.89	80 ± 1.91
Indeno(1,2,3cd)pyrene (IND)	87 ± 2.29	81 ± 2.28

calculated using the IDLs, the volume of extracts, and the sample weights (Wang et al., 2014). Accordingly, the instrumental limit of quantification (ILOQ) and the method limits of quantifications (MLOQ) were calculated based on the signal-to-noise ratio (S/N) of 10. Some PAH concentrations, especially on dusty days with the north wind, were lower than LOD, which was considered not detected and excluded from the calculation. Table 2 indicates the LOD and LOQ of methods and instrument.

Dust and air mass monitoring using remote sensing and HYSPLIT model

Moderate resolution imaging spectroradiometer (MODIS) images have always been used to identify dust sources and their properties by many researchers. A large number of spectral bands and high spatial-temporal resolution are unique characteristics of MODIS images (Kandakji et al., 2020). Thus, MODIS images are the best tool for dust monitoring and are used to assess the spatial-temporal dust distribution in the region. Dust time series were extracted from Google Earth Engine and aerosol optical depth (AOD) product of MODIS images. The dust mask was obtained by applying the

brightness temperature difference (BTD) algorithm for bands 31 and 32 from MODIS images. Furthermore, to assess the areas with more dust exposure in Khuzestan Province, the dust event frequency map was extracted using MODIS AOD products in Google Earth Engine. The origins and pathways of air masses arrived in the study area were studied with the HYSPLIT (hybrid single-particle Lagrangian integrated trajectory) back trajectory model (Draxler & Hess, 1998).

Statistical analysis

Parametric statistical methods were used to determine the results. A Pearson correlation test was conducted among wind speed, temperature, dew point pressure, PM₁₀, PM_{2.5}, ΣPAHs, HMW, and LMW. Meteorological parameters, including wind speed, temperature, dew point, and pressure, play a significant role in airborne PAHs, PM₁₀, and PM_{2.5}. A significant correlation coefficient was considered at the level of 0.05. Also, a one-way analysis of variance (ANOVA) and least significant difference (LSD) test were used to assess the significant difference among the mean PAHs in all climate conditions.

Table 2 Instrumental detection limit (IDL), instrumental limit of quantification (ILOQ), method detection limits (MDL), and method limits of quantifications (MLOQ)

	Instrument		Method	
	IDL (ng/m3)	ILOQ (ng/m3)	MDL (ng/m3)	MLOQ (ng/m3)
Naphthalene (Nap)	0.018	0.058	0.020	0.067
Acenaphthylene (Acy)	0.007	0.022	0.009	0.030
Acenaphthene (Ace)	0.059	0.195	0.061	0.203
Fluorene (Fl)	0.048	0.160	0.080	0.267
Phenanthrene (Phe)	0.076	0.252	0.057	0.190
Anthracene (Ant)	0.027	0.088	0.028	0.093
Fluoranthrene (Flu)	0.027	0.088	0.028	0.093
Pyrene (Pyr)	0.081	0.268	0.084	0.280
Benzo(a)anthracene (BaA)	0.069	0.228	0.070	0.233
Chrysene (Chr)	0.099	0.330	0.050	0.167
Benzo(b)fluoranthene (BbF)	0.099	0.330	0.050	0.167
Benzo(k)fluoranthene (BkF)	0.099	0.330	0.010	0.033
Benzo(a)pyrene (BaP)	0.090	0.300	0.099	0.330
Dibenzo(a,h)anthracene (DBA)	0.012	0.040	0.018	0.058
Dibenzo(g,h,i)perylene (BghiP)	0.060	0.200	0.070	0.232
Indeno(1,2,3cd)pyrene (IND)	0.033	0.11	0.059	0.195

PAH source identification

Two methods were widely used in previous studies to identify PAH sources, including diagnostic ratios and principal component analysis (PCA). To identify PAH sources, a few ratios of PAH species are used. These ratios are widely used to determine PAH sources. These ratios can show the possible sources of PAH emissions. Some of these diagnostic ratios are Phe/(Phe + Ant), Flu/(Flu + Pyr), BaA/(BaA + Chr), and BaP/BghiP. PCA reduces PAHs into 2 or 3 PCs. The varimax method was used to rotate the PC matrix and analyze the relationship between measured PAHs (Chen et al., 2016).

Health risk assessment

To calculate the equivalent of the toxicity factor among all PAHs, benzopyren (Ferreira-Baptista & De Miguel, 2005), due to high carcinogenicity and toxicity, is identified as an indicator and reference and used for the line of human health risks, and a value of 1 is determined for it. Also, other compounds have their toxic equivalency factor (TEF) based on their carcinogenicity.

$$TEQ = \sum (Ci \times TEFi)$$

The 3 main dust exposure routes are ingestion, inhalation, and dermal contact. To estimate the environmental PAH exposure risk, the incremental lifetime cancer risk (ILCR) was established according to the US EPA standards (Chen & Liao, 2006; Peng et al., 2011). Table 3 represents the coefficients used in ILCR based on 3 exposure routes.

Cancer slope factor (CSF) is a carcinogenic slope factor ($\text{mg kg}^{-1} \text{ day}^{-1}$). CSF ingestion, CSF inhalation, and CSF dermal of BaP were listed as 7.3, 3.85, and 25 ($\text{mg kg}^{-1} \text{ day}^{-1}$), respectively, as determined by the cancer-causing ability of BaP (Peng et al., 2011). Other parameters are presented in Table 3. The cancer risk is estimated as the sum of ILCR ingestion, ILCR inhalation, and ILCR dermal.

Results and discussion

Spatial-temporal distribution of dust in the area

Figure 2 shows the time series of dust in the region from 2001 to 2018. This time series was determined using the AOD product. According to Fig. 2, the optical depth of the aerosols had the highest value in the early months of 2009. We had more dust in the middle of the year and summer, given that the area is dustier in spring and summer. Figure 3c depicts a MODIS image from September 10, 2008 in the region. This figure shows the extent of the dust mass obtained with the BTM dust mask. According to this figure, the western and southwestern areas of Iran, which include cities such as Abadan, expose more to dust storms. More dust in these areas originates from countries such as Iraq, which have high levels of dust storms in the spring and summer due to dry land and high wind speeds. Figure 3b indicates the area with more exposure to dust. According to this map, the study area in Abadan City has the highest frequency of dust events. Figure 3a depicts the origins and pathways of air masses arriving in Abadan City based on the HYSPLIT results. This figure illustrates that the

Table 3 Parameters used in ILCR assessment (Peng et al., 2011)

Exposure variable	Unit	Child	Adult
Body weight (BW)	kg	15	55.9
Exposure frequency (ED)	d year ⁻¹	350	350
Exposure duration (ED)	year	6	24
Inhalation rate (IR _{Inhalation})	m ³ day ⁻¹	5	20
Soil intake rate (IR _{Ingestion})	mg day ⁻¹	200	100
Dermal exposure area (SA)	cm ²	1800	5000
Dermal exposure factor (AF)	mg cm ⁻²	0.2	1
Dermal adsorption fraction (ABS)	Unitless	0.1	0.1
Averaging life span (AT)	year	70	70
Soil dust producer factor (PEF)	m ³ kg ⁻¹	1.32×10^9	1.32×10^9

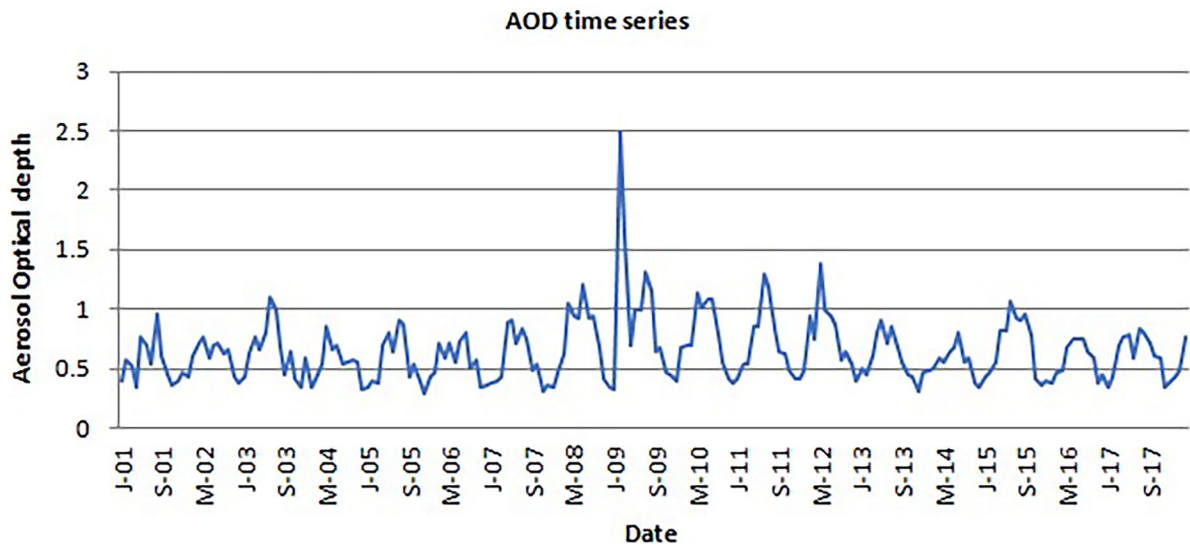


Fig. 2 Dust time series in the region from 2001 to 2018

main origins of dust storms were Syria and Iraq. The northwesterly winds could transport a huge amount of dust particles from susceptible areas in neighboring countries.

Statistical analysis

The Pearson correlation test among wind speed, temperature, dew point, pressure, PM_{10} , $PM_{2.5}$, $\Sigma PAHs$, HMW, and LMW was performed in all climate conditions. The tables of correlation coefficients (Table 4) show a correlation coefficient at the level of 0.05. Meteorological parameters showed significant correlations with PM_{10} , $PM_{2.5}$, and PAHs. The correlation of LMW PAHs was more powerful than other

compounds, indicating that LMW PAH concentrations are more prone to meteorological parameters because these compounds are more volatile. Negative values between wind speed and southeasterly wind dust indicate that the PAH concentration is inversely related to wind speed. This result is in agreement with Li et al. (2006) and Sikalos et al. (2002). However, wind speed on dusty days has a positive relationship with dust in northwesterly winds, showing that with increasing wind speed in the northwest, we have an increase in dust. The relationships of PM_{10} and $PM_{2.5}$ with PAHs were different on dusty and normal days. PM_{10} and $PM_{2.5}$ showed a weak correlation ($r=0.5$; $P<0.05$) with total PAHs, confirming that these pollutants originated from different emission sources.

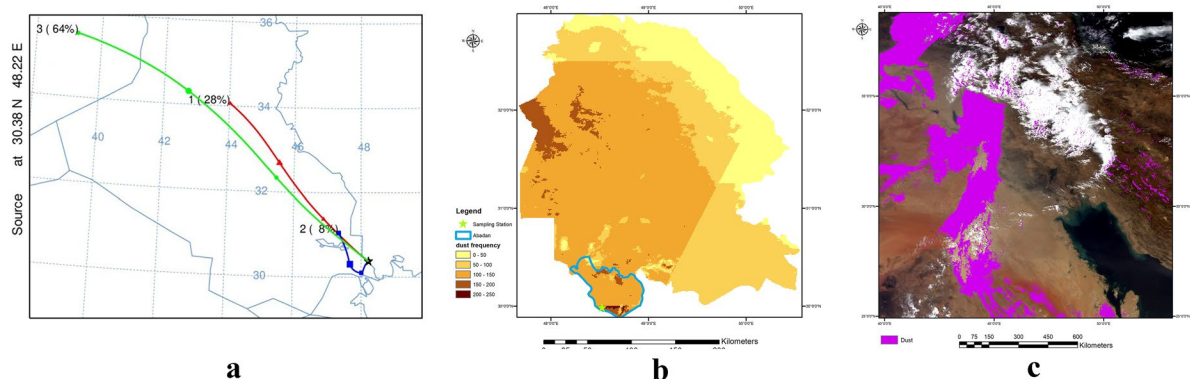


Fig. 3 HYSPLIT model results: the air mass arrived in the study area during the summer of 2018 (a), the frequency of dust events in Khuzestan Province based on AOD higher than 1 (b), and dust storm mask using MODIS images and BTDA algorithm (c)

Table 4 Correlation among wind speed, temperature, dew point pressure, PM₁₀, PM2.5, Σ PAHs, HMW, and LMW in 4 climate conditions

Normal days	Wind speed	Temperature	Dew point	Pressure	PM10	PM2.5	Σ PAHs	HMW	LMW
Wind speed	1.000								
Temperature	-0.065	1.000							
Dew point	0.148	-0.132	1.000						
Pressure	-0.274	-0.467	0.004	1.000					
PM10	-0.145	-0.089	0.112	0.269	1.000				
PM2.5	0.089	-0.360	0.285	0.201	0.355	1.000			
Σ PAHs	0.040	-0.359	0.185	0.183	0.228	0.358	1.000		
HMW	0.047	-0.326	0.144	0.178	0.311	0.403	0.628	1.000	
LMW	0.031	-0.326	0.198	0.162	0.281	0.302	0.550	0.585	1.000
Dust days	Wind speed	Temperature	Dew point	Pressure	PM10	PM2.5	Σ PAHs	HMW	LMW
Wind speed	1.000								
Temperature	-0.583	1.000							
Dew point	-0.006	-0.118	1.000						
Pressure	-0.201	-0.802	-0.119	1.000					
PM10	0.210	-0.056	-0.226	0.214	1.000				
PM2.5	0.316	0.099	-0.296	-0.109	-0.152	1.000			
Σ PAHs	0.297	0.100	-0.248	-0.110	-0.153	-0.107	1.000		
HMW	0.322	0.103	-0.280	-0.134	-0.169	-0.129	0.606	1.000	
LMW	0.260	0.097	-0.240	-0.143	-0.144	-0.091	0.455	0.561	1.000
Dust-NW	Wind speed	Temperature	Dew point	Pressure	PM10	PM2.5	Σ PAHs	HMW	LMW
Wind speed	1.000								
Temperature	0.449	1.000							
Dew point	-0.177	-0.216	1.000						
Pressure	-0.614	-0.854	0.028	1.000					
PM10	0.225	-0.123	-0.208	0.015	1.000				
PM2.5	0.252	0.149	-0.333	-0.101	-0.041	1.000			
Σ PAHs	0.155	0.151	-0.235	-0.102	-0.041	-0.106	1.000		
HMW	0.172	0.151	-0.263	-0.121	-0.044	-0.113	0.679	1.000	
LMW	0.132	0.147	-0.220	-0.100	-0.039	-0.102	0.439	0.477	1.000

Table 4 (continued)

Dust-SE	Wind speed	Temperature	Dew point	Pressure	PM10	PM2.5	Σ PAHs	HMW	LMW
Wind speed	1.000								
Temperature	−0.581	1.000							
Dew point	0.477	−0.024	1.000						
Pressure	0.056	−0.776	−0.270	1.000					
PM10	−0.519	0.010	−0.251	0.421	1.000				
PM2.5	−0.072	0.052	−0.268	−0.120	−0.269	1.000			
Σ PAHs	−0.073	0.052	−0.269	−0.122	−0.271	−0.111	1.000		
HMW	−0.077	0.058	−0.306	−0.151	−0.299	−0.149	0.554	1.000	
LMW	−0.068	0.050	−0.268	−0.191	−0.254	−0.084	0.487	0.664	1.000

Previous studies have demonstrated a weak or moderate relationship between PAHs and particulate matter concentrations in dry environments (Najmeddin & Keshavarzi, 2019). The correlation between dust and PAHs was positive on normal days but negative on dusty days (northwesterly and southeasterly winds). The reason for this difference is that natural resources (dust) have fewer aromatic compounds than human resources on normal days (traffic/industry).

One-way ANOVA was used to compare PAH means in all climate conditions. The homogeneity of variances was assessed with the Levene test. The results indicate that at least 1 group's mean is different from other groups ($P < 0.1$). Furthermore, an LSD post hoc analysis was performed to determine homogenized groups. The results of LSD indicated that PAHs on normal days are in a group, and PAHs on other days (i.e., dusty days, dust with northwesterly winds, and dust with southeasterly winds) are in another group.

PAH concentrations and ring profiles

Different levels of 16 PAHs were measured in the air samples of Abadan City. The total amount of 16 PAHs varied from 46.22 to 90.96 ng/m³. According to Fig. 4 and Table 5, the total concentrations of PAHs were higher on normal days, southeasterly winds, dusty days, and northwesterly winds, respectively, indicating the inverse relationship between dust and PAH concentrations. The PAH concentration was higher in the southeast direction than in the northwest direction because the dust passes Mahshahr and Bandaramam cities (petrochemical zone), and the concentration of PAHs increases. Compared to the concentrations reported in other studies (Table 6), the average concentrations of PAH are higher in Abadan City than Tehran, and the city of Ahvaz has a higher mean. This significant difference can be attributed to various factors such as traffic, congestion traffic, industrial/petrochemical activities, and population size (Najmeddin et al., 2018; Soltani et al., 2015). Therefore, the pollution of petroleum hydrocarbons in Abadan City is a severe problem and requires much attention. Goudarzi et al. (2021) investigated ILCR based on PAHs bound to PM₁₀ in Ahvaz, Abadan, and Asaluyeh cities. There are many differences among observed PAH concentrations in related studies. One of the main reasons for these differences may

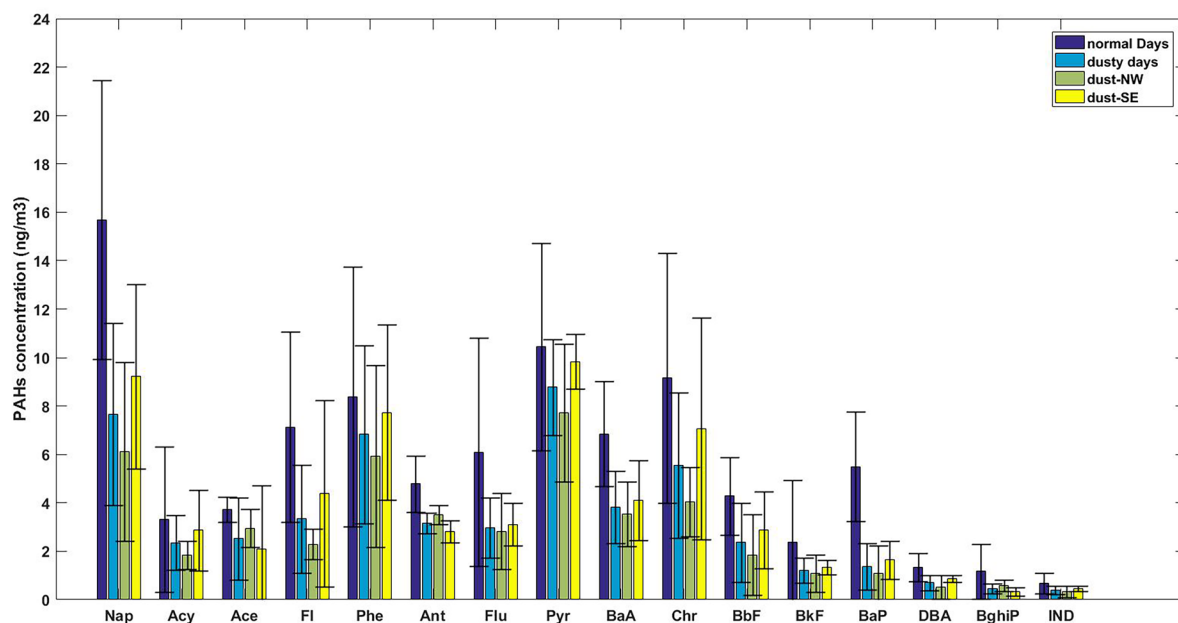


Fig. 4 Average concentration (ng/m^3) of PAHs \pm standard deviation

be the source of PAHs and the impacts of meteorological parameters on PAH concentrations. This study focused on Abadan City, and ILCR was calculated based on a long period of data observation.

In aromatic compounds, 4-ring PAHs (Flu, Pyr, BaA, and Chr) have the highest value, followed by 3-ring compounds (Acy, Ace, Fl, Phe, and Ant), 2-ring compound (Nap), 5-ring compounds (BkF, BbF, and BaP), and 6-ring compounds (DBA, BghiP, and IND). Some PAHs are signatures of their sources, thus regarded as indicators. For example, combustion sources are reflected by Flu, Chr, B(b+k)F, Phe, Ind, and BghiP. Ace shows vehicle emissions, Ant reflects petroleum sources, and Fl represents PAHs coming from coking ovens. Furthermore, Fl, Flu, Pyr, BbF, and Ind are signatures of oil combustion (Najmeddin & Keshavarzi, 2019). In low to moderate temperatures, LMW PAHs (3 rings) are frequent, but in high temperatures, HMW PAHs (4 rings and above) are abundant (Wu et al., 2016).

Figure 5 depicts that PAHs with 3 and 4 rings are abundant in Abadan samples, and the HMW PAH concentrations are high. This result may be due to HMW compounds' adherence (Wang et al., 2011). Furthermore, a high percentage of HMW PAHs in total PAHs reflects that they likely originate from

the combustion of petroleum products (Liu et al., 2007); also, pyrogenic sources could generate PAHs with more than 4 rings (Bandowe & Nkansah, 2016; Dahle et al., 2003). Pyrogenic sources from fossil fuel combustion generate HMW PAHs (in urban areas), and petrogenic sources from oil leaks generate LMW PAHs (in industry areas).

Source identification: diagnostic ratios and PCA

The diagnostic ratios have been widely used for PAH source identification (Ambade et al., 2021a, c, d, 2022; Hoseini et al., 2016; Kurwadkar et al., 2022; Najmeddin & Keshavarzi, 2019). Table 7 and Fig. 6 show calculated ratios of $\text{Phe}/(\text{Phe} + \text{Ant})$, $\text{BaA}/(\text{BaA} + \text{Chr})$, $\text{Flu}/(\text{Flu} + \text{Pyr})$, and BaP/BghiP . The ratios of $\text{Phe}/(\text{Phe} + \text{Ant})$ for all climate conditions were lower than 0.7, except on normal days. This ratio illustrates that PAHs on normal days have pyrogenic origins while the other conditions have petrogenic origins. It is worth mentioning that the values of these ratios vary between 0.6 and 0.7. These values revealed that PAHs in all climate conditions might have pyrogenic sources. The values of the $\text{BaA}/(\text{BaA} + \text{Chr})$ ratio were higher than 0.35, showing that PAHs have vehicular emission sources in all

Table 5 Average concentration (ng /m³) of PAHs ± standard deviation

	Nap	Acy	Ace	Fl	Phe	Ant	Flu	Pyr	BaA	Chr	BbF	BkF	BaP	DBA	BghiP	IND
Nor-mal days	15.69±5.74	3.32±2.99	3.72±0.50	7.13±3.94	8.38±5.35	3.29±1.16	6.09±4.71	10.44±4.28	6.85±2.16	9.16±5.15	4.28±1.59	2.36±2.56	5.50±2.26	1.34±0.57	1.17±1.14	0.68±0.42
Dusty days	7.67±3.76	2.35±1.13	2.52±1.71	3.34±2.24	6.83±3.68	3.16±0.43	2.97±1.23	8.78±1.98	3.82±1.49	5.55±3.00	2.36±1.63	1.21±0.53	1.37±0.97	0.70±0.31	0.46±0.21	0.40±0.17
Dust-NW	6.12±3.70	1.83±0.58	2.95±0.78	2.29±0.63	5.92±3.74	3.49±0.39	2.82±1.58	7.72±2.83	3.54±1.33	4.03±1.42	1.85±1.66	1.07±0.77	1.08±1.15	0.51±0.48	0.59±0.23	0.33±0.24
Dust-SE	9.22±3.80	2.87±1.66	2.09±2.62	4.38±3.84	5.72±3.61	2.81±0.46	3.10±0.88	9.83±1.13	4.09±1.64	7.06±4.57	2.87±1.58	1.33±0.28	1.64±0.79	0.87±0.14	0.33±0.17	0.46±0.11

Table 6 Comparison of mean concentrations of PAHs (ng /m³) with other studies

Locations	Nap	Acy	Ace	Fl	Phe	Ant	Flu	Pyr	BaA	Chr	BbF	BkF	BaP	DBA	BghiP	IND	Σ PAHs
Abadan dusty days	15.69	3.32	3.72	7.13	8.38	4.79	6.09	10.44	6.85	9.16	4.28	2.36	5.50	1.34	1.17	0.68	90.96
Ahvaz (Goudarzi et al., 2018)	13.99	2.11	2.97	10.45	4.06	14.76	9.38	5.43	5.01	9.78	5.39	1.84	6.13	ND	ND	ND	91.36
Tehran-(Hoseini et al., 2016)	8.75	5.97	2.61	11.54	9.97	4.27	5.66	7.75	3.59	4.25	2.78	9.21	1.87	1.71	1.84	1.25	83.00

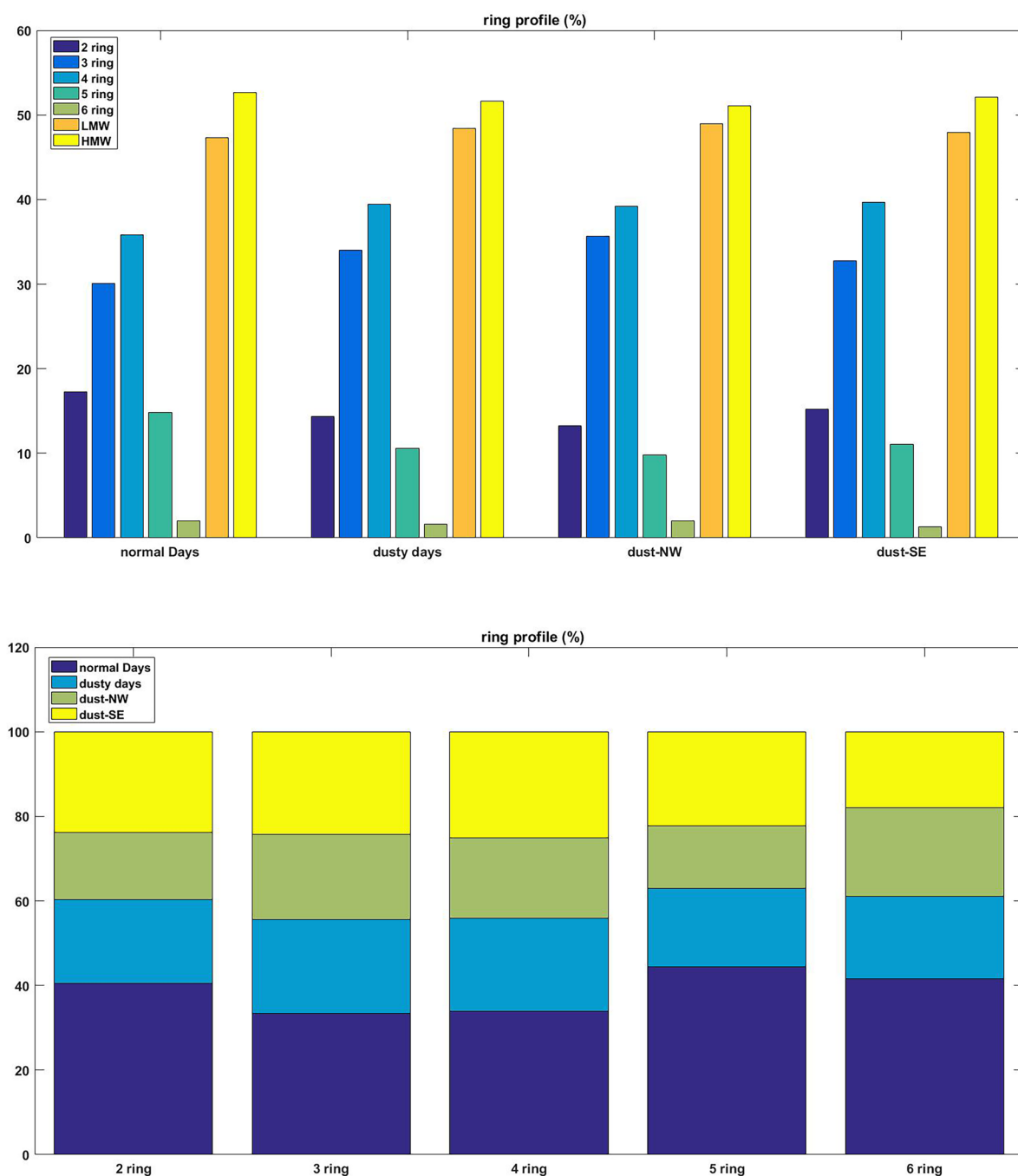


Fig. 5 Ring profile of PAHs with percentages in 4 different sampling conditions

conditions. The ratio of Flu/(Flu + Py) determines petrol and diesel emissions; values higher than 0.5 reveal diesel emission sources. This ratio was lower than 0.5, suggesting petrol emissions in all climate

conditions. The traffic and non-traffic emissions were determined using the BaP/BghiP ratio. The values of this ratio were higher than 0.6, indicating that PAHs have traffic emission origins in all climate conditions.

Table 7 Diagnostic ratios used in identification of PAHs pollution sources in the dust

Diagnostic ratio	Value range	Source assignment
Phe/(Phe + Ant)	< 0.7	Petrogenic
	> 0.7	Pyrogenic
BaA/(BaA + Chry)	0.2–0.35	Coal combustion
	> 0.35	Vehicular emissions
Flu/(Flu + Py)	< 0.5	Petrol emissions
	> 0.5	Diesel emissions
BaP/BghiP	< 0.6	Nontraffic emissions
	> 0.6	Traffic emission

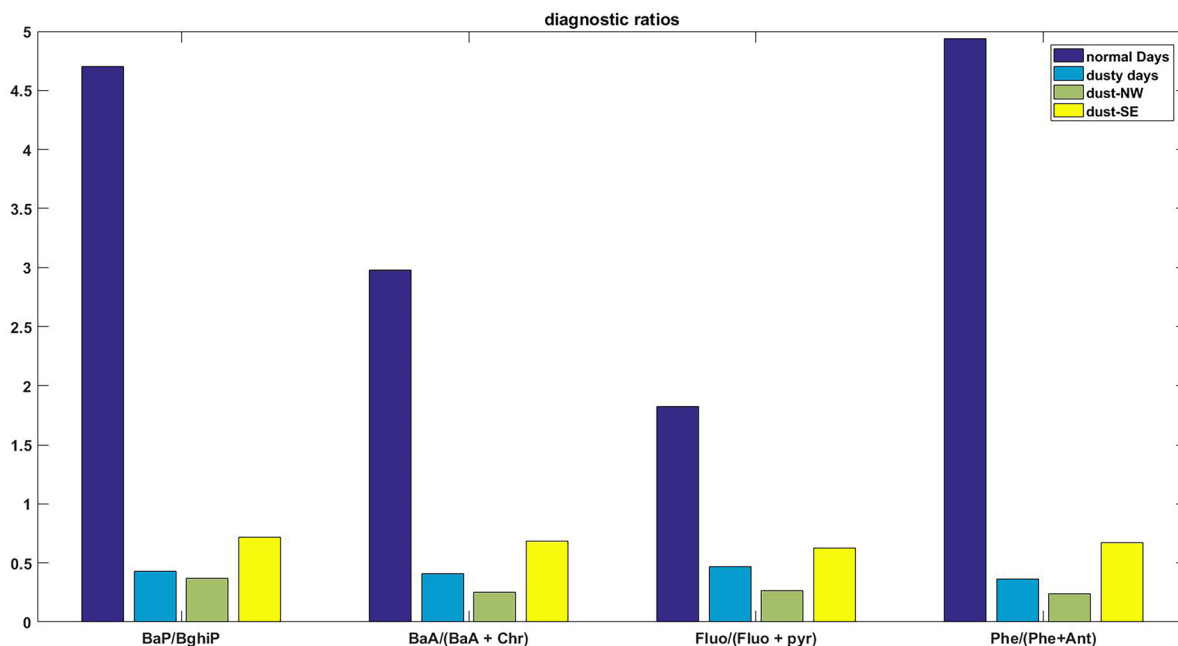
From Tobiszewski and Namieśnik (2012)

The disadvantage of the PAH ratios for source identification is that the ratios are assumed constant. However, due to their physicochemical properties, these ratios could change from sources to receptors in a multimedia environment. The advantage of this method is its simplicity, but qualitative results can be achieved (Chunhui et al., 2017).

Based on diagnostic ratios, Ambade et al. (2021c) identified the source of PAHs in drinking water. In India, the concentrations of 16 PAHs were measured in indoor and outdoor environments of urban and rural areas. Diesel exhaust, gasoline, biomass, and coal

combustion were the main sources of PAHs in the study area based on diagnostic ratios and PCA results (Ambade et al., 2021a). In the estuary sediment of Subarnarekha River, biomass and coal burning were identified as the main sources of PAHs based on diagnostic ratios and PCA results (Ambade et al., 2022). The abundance of 16 PAHs was investigated in the surface water and sediment samples of the Damodar River basin; also, concentration levels, sources, human health, and ecological risk assessment were evaluated. LMW PAHs (PAH-ACY and PAH-BaA) were identified more than HMW PAHs in the surface water. The petrogenic origin and fuel combustion were the major sources of PAHs (Ambade et al., 2021d). The 16 priority PAH compounds were evaluated in water and sediment samples from the Mahanadi River waterway. Potential human health risks were observed in the human health assessment. Diagnostic ratio results show that combustion, petrogenic processes, coal, grass, and wood-burning processes are the main sources of PAHs (Kurwadkar et al., 2022).

In the urban soil of Beijing, source identification revealed that vehicle exhaust and coal combustion were the primary sources, and atmospheric deposition of long-range transported PAHs was the secondary source of PAHs (Peng et al., 2011). In

**Fig. 6** Diagnostic ratios of PAHs in different conditions: normal days, dusty days, northwesterly winds, and southeasterly winds

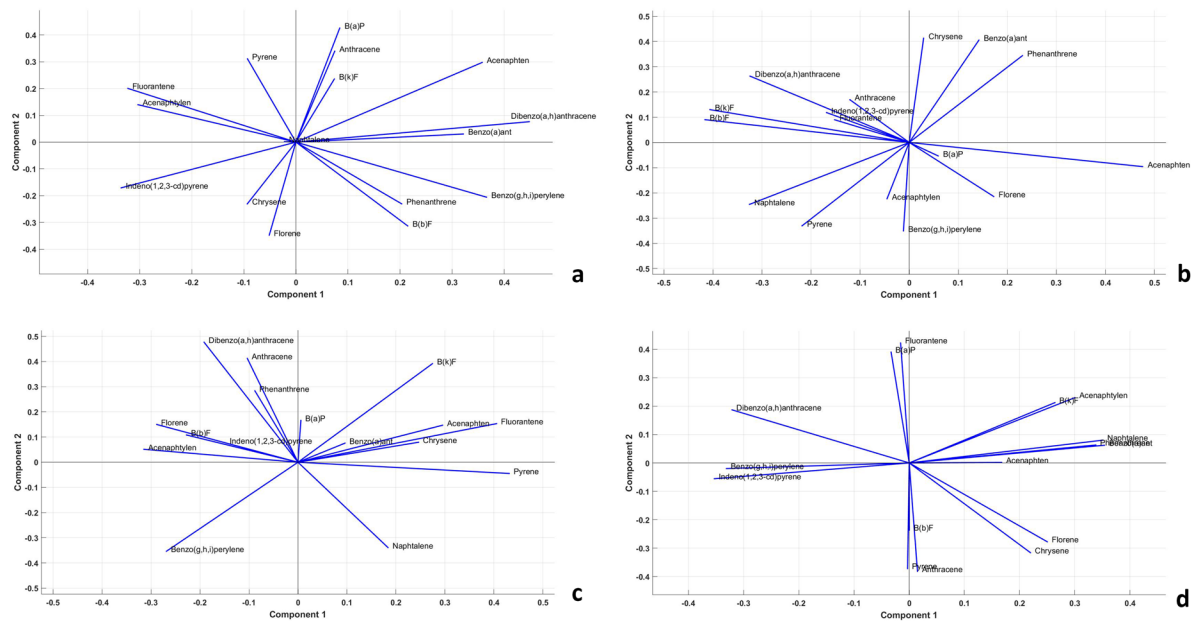


Fig. 7 PCA results in different conditions: normal days (a), dusty days (b), northwesterly winds (c), and southeasterly winds (d)

southern Thailand, carbonaceous aerosol compositions (organic carbon, elemental carbon, water-soluble ionic species, and PAHs of PM_{2.5}) were evaluated. The diagnostic ratio results of organic carbon/elemental carbon and estimations of secondary organic carbon (SOC) in this study suggest significant impacts of motor vehicle exhaust, fuel burning, and biomass burning. Long-range atmospheric transport of organic aerosols associated with biomass burning has significant impacts on carbonaceous aerosol compositions (ChooChuay et al., 2022).

Based on a hierarchical cluster analysis in the Chiang-Mai Province of Thailand, PM_{2.5} originated from mixtures of biomass burning, fossil fuel combustion (vehicles and energy production), coal combustion, and industrial emissions. PCA suggests that the sources of PM_{2.5} are vehicular exhaust, biomass burning, diesel emissions, sea-salt aerosols, and agricultural emissions (ChooChuay et al., 2020). The origin of the atmospheric pollutant could be shipping activities in coastal areas (Pongpiachan et al., 2021).

The positive matrix factorization (PMF) receptor model is a common method for PAH source identification (Chen et al., 2013). Determining the number of required factors to provide accurate results is a critical process in the PMF method (Saraga et al., 2010).

Compared to PCA and UNMIX methods, the PMF model could provide better results based on point-by-point estimates of uncertainty errors in the dataset (Yang et al., 2013). Another extensively used method is PCA. In this method, variables are reduced, and small numbers of latent factors are extracted.

Many studies have confirmed that PAH sources are mixed and have pyrolytic and petrogenic origins. Furthermore, in PMF and PCA methods, finding source profiles with characteristics similar to factor profiles are speculative, which may lead to inaccurate results. Beyond that, in diagnostic ratios, it is assumed that PAHs remain constant from sources to receptors. Thus, combining these methods provides better accuracy and reliable results for PAH source identification (Chunhui et al., 2017).

Therefore, in addition to diagnostic ratios, PCA was performed for all climate conditions. A KMO and Bartlett test was performed to measure sampling adequacy. On normal days, based on eigenvalue greater than 1, 7 PCs were extracted with 67% of the cumulative variance (Fig. 7a). On dusty days, 7 PCs were obtained with 90.6% of the cumulative variance (Fig. 7b). On dusty days with northwesterly winds (Fig. 7c), 6 PCs were estimated with 94.5% of the cumulative variance, and finally, 3 PCs were

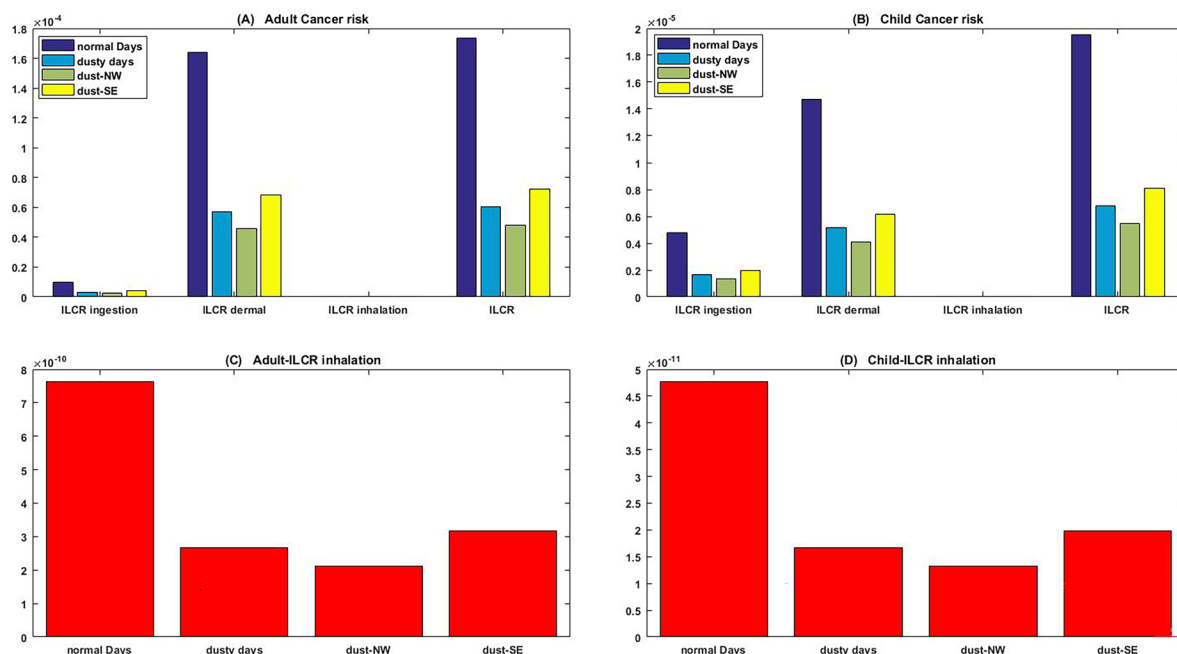


Fig. 8 Cancer risk in 4 different sampling conditions for children and adults

estimated on dusty days with southeasterly winds with about 100% of the cumulative variance (Fig. 7d). Diagnostic ratios and PCA suggest that PAHs mainly originate from mixed sources, including vehicular emissions, petrol emissions, and traffic.

Health risk assessment in Abadan City

PAHs have persistent toxic characteristics, which could distribute in water, air, soil, and sediment. PAHs have high mutagenic equivalent factor and toxic equivalent factor values, posing great ecological threats and health risks (Ambade et al., 2022). The risk assessment in this city was performed to assess the risk of cancer as a result of PAH exposure through 3 routes: inhalation, ingestion, and skin contact (Najmeddin & Keshavarzi, 2019). Risk assessment calculations were based on the average concentration of each studied PAH. The soil intake rate and soil dust producer factor (PEF) were considered for ingestion and inhalation exposure routes (US EPA, 2011; Peng et al., 2011). Figure 8 shows that the human health risk of exposure to PAHs is assessed by calculating ILCR and total cancer risk. As a result, the inhalation of particulate matter

through the nose and mouth was very low. According to Fig. 8, the highest cancer risk was observed for adults (1.73×10^{-4}) and children (1.95×10^{-5}) on normal days. The risk for adults on dusty days with southeasterly winds (7.21×10^{-5}) and dusty day climate conditions (6.03×10^{-5}) are in the next order, respectively. This result could be due to the higher human sources of PAHs on normal days than on dusty days. Furthermore, dust deposits from southeastern sources have more carcinogenic PAHs than those from northwestern sources. In general, the acceptable value for ILCR is equal to or less than 10^{-6} , while ILCR between 10^{-4} and 10^{-6} indicates a potential risk, and above 10^{-4} indicates high health potential (US EPA, 2011). Since the ILCR value in this study was between 10^{-4} and 10^{-6} for normal days, dusty days, northwesterly winds, and southeasterly winds, a potential health risk was observed in Abadan City in terms of exposure to PAHs. As a critical risk factor, relevant authorities should prevent, control, and reduce it.

The accuracy of human health assessments could increase with a better definition of probability distributions for inhalation CSF and particle-bound PAH-to-skin adherence factor (Chen & Liao, 2006).

Conclusion

The study of the temporal-spatial distribution of dust in the area shows a higher amount of dust in spring and summer in the region. Also, in the cities of southwestern Iran, the phenomenon of dust is influenced by surrounding countries. The highest concentration of Σ PAHs was observed on normal days (90.96 ng/m^3), and the lowest concentration of Σ PAHs was observed on dusty days with northwesterly winds (46.22 ng/m^3), showing the inverse relationship between the PAH concentration and dust. The highest amount of PAH was related to HMW aromatics and 4-ring PAHs (Flu, Pyr, BaA, Chr). An analysis of diagnostic ratios and PCA showed that PAHs mainly originated from mixed sources, including vehicular emissions, petrol emissions, and traffic. The relationship between meteorological parameters (wind speed, pressure, temperature, etc.) with PAH concentrations at a 5% level was significant. According to the results, the correlation between wind speed and PAHs on dusty days with northwesterly winds is positive, and on dusty days with southeasterly winds is negative. Also, due to the positive correlation between dust and PAHs on normal days and the negative correlation on dusty days, it can be concluded that natural resources have less PAH than human resources. ILCR showed that both children and adults are at potential risk for cancer, especially through skin contact, thus needing serious attention, management, and planning.

Author contribution Hossein Mohammad Asgari designed the study. Hossein Mohammad Asgari, Hoda Mojiri-Foroshani, and Mohammad Mahboubi analyzed the results. All authors read and approved the final manuscript.

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Availability of data and materials The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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