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Spatial homogeneity and heterogeneity of ambient air pollutants in Tehran

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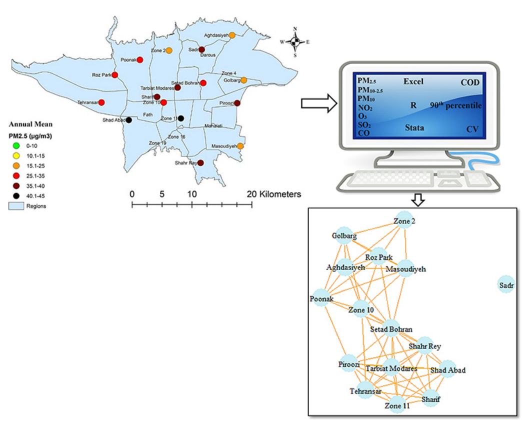
HIGHLIGHTS

- A considerable spatial inequality for exposing to ambient air pollutants was observed in Tehran.
- Ambient PM_{10}, $PM_{2.5}$ and NO_2 had the highest spatial homogeneity based on the COD values.
- Regarding CV, the highest and lowest spatial heterogeneity were found for ambient O_3 and PM_{10}.
- There was a remarkable agreement between the results of COD, 90th percentile, and CV approaches.

GRAPHICAL ABSTRACT



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ABSTRACT

To investigate spatial inequality of ambient air pollutants and comparison of their heterogeneity and homogeneity across Tehran, the following quantitative indicators were utilized: coefficient of divergence (COD), the 90th percentile of the absolute differences between ambient air pollutant concentrations and coefficient of variation (CV). Real-time hourly concentrations of particulate matter (PM) and gaseous air pollutants (GAPs) of twenty-two air quality monitoring stations (AQMSs) were obtained from Tehran Air Quality Control Company (TAQCC) in 2017. Annual mean concentrations of $PM_{2.5}$, $PM_{10-2.5}$, and PM_{10} (PM_X) ranged from 21.7 to 40.5, 37.3 to 75.0 and 58.0 to 110.4 μg m^{-3}, respectively. Annual mean $PM_{2.5}$ and PM_{10} concentrations were higher than the World Health Organization air quality guideline (WHO AQG) and national standard levels. NO_2, O_3, SO_2 and CO annual mean concentrations ranged from 27.0 to 76.8, 15.5 to 25.1, 4.6 to 12.2 ppb, and 1.9 to 3.8 ppm over AQMSs, respectively. Our generated spatial maps exhibited that ambient PM_X concentrations increased from the north into south and south-western areas as the hotspots of ambient PM_X in Tehran. O_3 hotspots

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Ambient air pollutants
Tehran

were observed in the north and south-west, while NO_2 hotspots were in the west and south. COD values of PM_X demonstrated more results lower than the 0.2 cut off compared to GAPs; indicating high to moderate spatial homogeneity for PM_X and moderate to high spatial heterogeneity for GAPs. Regarding CV approach, the spatial variabilities of air pollutants followed in the order of O_3 (87.3%) > SO_2 (65.2%) > CO (61.8%) > $PM_{10-2.5}$ (52.5%) > $PM_{2.5}$ (48.9%) > NO_2 (48.1%) > PM_{10} (42.9%), which were mainly in agreement with COD results, except for NO_2. COD values observed a statistically ($P < 0.05$) positive correlation with the values of the 90th percentile across AQMSs. Our study, for the first time, highlights spatial inequality of ambient PM_X and GAPs in Tehran in detail to better facilitate establishing new intra-urban control policies.

1. Introduction

As a sobering reality, exposure to ambient air pollution and its health effects has become the most notable environmental risk factor, particularly in developing countries (Huang et al., 2014, Cheng et al., 2016, Marlier et al., 2016, Song et al., 2016, Cohen et al., 2017, Faridi et al., 2018, Jiang and Bai, 2018, Schraufnagel et al., 2019). More recently, the Global Exposure Mortality Model (GEMM) estimated that 8.9 million premature deaths in 2015 were attributed to ambient $PM_{2.5}$ (Burnett et al., 2018). Tehran as the capital city of Iran has been receiving the great attention from the Iranian central government, public as well as national and international environmental researchers since it has faced intense ambient air pollution due to unsustainable development, incompatible and/or non-existent ambient air quality standards along with continued urbanisation, increasing mobile sources and associated emissions (Naddafi et al., 2012; Amini et al., 2017; Faridi et al., 2017; Faridi et al., 2018; Heger and Sarraf, 2018; Hoseini et al., 2018; Mohammadiha et al., 2018). Tehran with >17 million trips and approximately 7 million kilometers traveled per day has specific spatiotemporal traffic conditions. Moreover, daily gasoline, diesel and compressed natural gas consumptions in Tehran were reported approximately 11 and 3 million litres and 2 million cubic meters, respectively (Shahbazi et al., 2016a; Heger and Sarraf, 2018; Mohammadiha et al., 2018; http://traffic.tehran.ir/Default.aspx?tabid=152, 2019). Although numerous studies have been conducted in Tehran regarding various issues of ambient air pollution including investigation of chemical and toxicological characterization of ambient PM (Hassanvand et al., 2014; Hassanvand et al., 2015; Arhami et al., 2018; Faraji et al., 2018; Al Hanai et al., 2019), source apportionment of ambient PM (Taghvaee et al., 2018a, 2018b, 2018c), and ambient air pollutants-related health effects (Naddafi et al., 2012; Faridi et al., 2018; Yousefian et al. 2018), studies that investigate the spatial variation of air pollutants are relatively scarce, to date (Amini et al., 2014, Alizadeh-Choobari et al., 2016, Shahbazi et al., 2018). Exploring and understanding the spatiotemporal variations of ambient air pollutants in intra-urban areas is exceedingly important for controlling and reducing ambient air pollutants' levels, promoting air quality status and protecting public health with the development of appropriate sustainable control strategies and policies, since ambient air pollution is considered as a modifiable and reversible risk factor (Chai et al., 2014; Tan et al., 2014; Zhang and Cao, 2015; Marzouni et al., 2016; Li et al., 2017; Ji et al., 2019). Furthermore, for long- and short-term epidemiological reports as the health impacts studies, it is essential to apply spatiotemporal variabilities of ambient air pollutants (Wang et al., 2014; Dastoorpoor et al., 2016). Three quantitative indicators including COD, the 90th percentile of the absolute differences between ambient air pollutant concentrations and CV have extensively been used to better illustrate the spatial variabilities of ambient air pollutants across a city (Pinto et al., 2004; Wilson et al., 2005; Ghim et al., 2015; Tiwari et al., 2015; Guo et al., 2017; He et al., 2017; Jin et al., 2017; Song et al., 2017; Zhao et al., 2018; Saha et al., 2019). COD as an indicator has extensively used in numerical analyses to determine the resemblance between two different under study datasets (Kim et al., 2005). In fact, the values of COD provide more information regarding the degree of uniformity between the concentrations of ambient air pollutants, measuring simultaneously at various AQMSs across a city (Wongphatarakul et al., 1998; Kim et al., 2005; Krudysz et al., 2008). Besides, the 90th percentile of the absolute differences between ambient air pollutant concentrations across AQMSs was utilized to show an absolute measure of the degree of heterogeneity and homogeneity in their concentrations within a city (Pinto et al., 2004; Ghim et al., 2015). Moreover, CV indicator describes the dispersion degree of ambient air pollutant data across AQMSs (He et al., 2017; Song et al., 2017). However, it should be emphasized that using each approach alone might not be sufficient to determine the ambient air pollutant's homogeneity and heterogeneity across urban areas (Pinto et al., 2004). Consequently, investigation of spatial characteristics of ambient air pollutants using three popular methods mentioned above is therefore essential to create better awareness of the air quality status in different districts of urban areas to inform authorities and policy-makers for vigorously implementing the governmental and societal strategies of joint prevention and control of ambient air pollution and its health consequences.

Based on the above-mentioned concerns, the major objectives of this study are to **1)** investigate the spatial variations and depict hotspots of ambient PM_X and GAPs in Tehran in 2017, and **2)** compare their heterogeneity and homogeneity across different districts of Tehran based on COD, the 90th percentile of the absolute differences between ambient air pollutant concentrations and CV approaches across validated AQMSs.

2. Materials and methods

2.1. Air quality data gathering and processing

Real-time hourly average concentrations of each criteria air pollutant ($PM_{2.5}$, PM_{10}, NO_2, O_3, SO_2, and CO) for the year 2017 were obtained from the twenty-two ground-based AQMSs (Table 1) which belong to TAQCC (Shahbazi et al., 2018, http://airnow.tehran.ir/home/dataarchive.aspx, 2019). Fig. S1 (from Supplementary Information) shows the spatial distribution of all AQMSs in different districts of Tehran. At AQMSs, $PM_{2.5}$ and PM_{10}, O_3, NO_2, SO_2, and CO are monitored using the beta-attenuation, UV-spectrophotometry, chemiluminescence, ultraviolet fluorescence, and non-dispersive infrared absorption methods, respectively. As shown in Table 1, the hourly data coverage in active AQMSs ranged from 66.6 to 97.6%, 46.3 to 97.7%, 52.5 to 99.8%, 17.1 to 99.9%, 18.3 to 98.5%, and 36.8 to 98.5% in 2017 for $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, and CO, respectively. In the current study, air quality data processing at AQMSs has been checked based on the z-score method to reject spatial and temporal outliers (He et al., 2017; Song et al., 2017; Faridi et al., 2018; van Zoest et al., 2018). It should be highlighted that aforementioned air quality data processing method was only used on AQMSs with >75% completeness of the total hours

Table 1
Detailed information on AQMSs and their hourly data coverage for each ambient air pollutant.

No.	AQMSs	Location		Hourly data coverage (%)[a]					
	Name	Latitude	Longitude	$PM_{2.5}$	PM_{10}	O_3	NO_2	SO_2	CO
1	Roz Park	35.739	51.267	8305 (94.8)	8478 (96.8)	6779 (77.4)	2010 (22.9)	7478 (85.4)	8442 (96.4)
2	Poonak	35.762	51.331	7264 (82.9)	5841 (66.7)	5484 (62.6)	7509 (85.7)	6206 (70.8)	7209 (82.3)
3	Zone 2	35.777	51.368	7980 (91.1)	6931 (79.1)	6362 (72.6)	1494 (17.1)	1605 (18.3)	8177 (93.3)
4	Darous	35.770	51.454	0	0	0	0	0	0
5	Golbarg	35.731	51.506	7960 (90.9)	8072 (92.1)	7782 (88.8)	8009 (91.4)	5864 (66.9)	8455 (96.5)
6	Setad bohran	35.727	51.431	8506 (97.1)	7945 (90.7)	7604 (86.8)	7562 (86.3)	7229 (82.5)	7875 (89.9)
7	Sharif	35.702	51.350	8497 (97.0)	8559 (97.7)	8740 (99.8)	8260 (94.3)	5700 (65.1)	5873 (67.0)
8	Tarbiat Modares	35.717	51.385	8460 (96.6)	8503 (97.1)	5401 (61.7)	8660 (98.9)	8628 (98.5)	8550 (97.6)
9	Piroozi	35.695	51.493	7227 (82.5)	8486 (96.9)	7388 (84.3)	8489 (96.9)	8291 (94.6)	8569 (97.8)
10	Fath	35.678	51.337	0	7659 (87.4)	7703 (87.9)	7830 (89.4)	4896 (55.9)	5725 (65.4)
11	Zone 11	35.672	51.389	6723 (76.7)	0	0	4008 (45.8)	7010 (80.0)	8156 (93.1)
12	Zone 16	35.644	51.397	0	0	5287 (60.4)	8384 (95.7)	6322 (72.2)	8475 (96.7)
13	Shad abad	35.670	51.297	8142 (92.9)	8549 (97.6)	8504 (97.1)	8757 (99.9)	7985 (91.2)	0
14	Zone 19	35.635	51.362	0	6884 (78.6)	0	0	6662 (76.1)	4106 (46.9)
15	Masoudiyeh	35.630	51.499	8225 (93.9)	8050 (91.9)	5680 (64.8)	6035 (68.9)	7696 (87.9)	8554 (97.6)
16	Share rey	35.603	51.425	8486 (96.9)	7771 (88.7)	7697 (87.9)	6979 (79.7)	7967 (90.9)	8506 (97.1)
17	Zone 4	35.741	51.506	5832 (66.6)	0	5270 (60.2)	7072 (80.7)	6364 (72.6)	7184 (82.0)
18	Zone 10	35.697	51.358	7971 (91.0)	0	0	0	8186 (93.4)	0
19	Mahalati	35.661	51.466	0	4059 (46.3)	0	3487 (39.8)	4489 (51.2)	4270 (48.7)
20	Tehransar	35.697	51.243	8008 (91.4)	8077 (92.2)	4598 (52.5)	8300 (94.7)	8091 (92.4)	3220 (36.8)
21	Aghdasiyeh	35.795	51.484	8056 (92.0)	8225 (93.9)	0	4011 (45.8)	0	8625 (98.5)
22	Sadr	35.778	51.428	8548 (97.6)	0	5966 (68.1)	8109 (92.6)	5094 (58.2)	7507 (85.7)

[a] AQMSs with <75% valid hourly data available were excluded from the next analysis.

in 2017 for ambient PM_X and GAPs (De Hoogh et al., 2018). As can be seen from Table 1, based on the above-mentioned inclusion criterion, there were 16, 14, 9, 13, 13 and 14 eligible stations for ambient $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, and CO, respectively. Furthermore, the percentage of the missing data for ambient PM_X and GAPs in Tehran measured by the eligible stations was mainly <15% of total hours in 2017. Herein, the method of air quality data control is similar to that of our previous study (Faridi et al., 2018), with the exception of the second stage in z-score method. Firstly, the time series of hourly concentrations of each air pollutant was standardized using the z-score method, and then the air quality data were used in the subsequent computations if they meet the following conditions: **1)** an absolute z-score <4 ($|Z_t| < 4$); **2)** the increment from the previous hourly value being <6 (Z_t - $Z_{t-1} < 6$); and **3)** and the ratio of the z-score to its centered rolling average of order 3 (RA3) <2 (Z_t / RA3(Z_t) < 2) (He et al., 2017; Song et al., 2017). Consequently, <0.3% of air quality data for each air pollutant was removed from the hourly datasets and the subsequent computations. As such, after air quality data processing and cleaning, all eligible AQMSs were accepted as the validated AQMSs, and an annual average concentration was calculated for each mentioned air pollutant at station-level. Additionally, the hourly average concentration of each ambient air pollutant at a total city-level was calculated using the average of all hourly concentrations across all validated AQMSs. For the first time, herein, we reported the concentration of coarse particles; particles with an aerodynamic diameter between 2.5 and 10 μm ($PM_{10-2.5}$); at AQMSs and city-level in Tehran for the year 2017. $PM_{10-2.5}$ concentrations were calculated by the difference between the concentrations of PM_{10} and $PM_{2.5}$ at 12 validated AQMSs (Hassanvand et al., 2017; Wang et al., 2018).

2.2. Quantifying spatial variability

To examine spatial variabilities of ambient air pollutants and their heterogeneity and homogeneity in different districts of Tehran, the three quantitative indicators were used: 1) COD (Amini et al., 2017; Song et al., 2017); 2) 90th percentile of the absolute differences between 24-h (PM_X, NO_2, SO_2) and 8-h (O_3 and CO) air pollutant concentrations across AQMSs for a given year (Pinto et al., 2004; Mangia et al., 2013; Ghim et al., 2015); and 3) CV (He et al., 2017; Jin et al., 2017; Song et al., 2017). COD values were computed from validated AQMSs as follows (Wongphatarakul et al., 1998; Kim et al., 2005; Krudysz et al., 2008):

$$COD_{jk} = \sqrt{\frac{1}{p}\sum_{i=1}^{p}\left(\frac{APC_{ij} - APC_{ik}}{APC_{ij} + APC_{ik}}\right)^2}$$

Where, APC_{ij} and APC_{ik} represent ambient air pollutant concentrations for time *i* (*i* for PM_X, NO_2, and SO_2 is 24-h average concentrations, for O_3 and CO is moving 8-h average concentrations) at station *j* and *k*, *j* and *k* represent two datasets for two given AQMSs, and p is the number of 24- and 8-h average concentrations of ambient air pollutants for the whole year. If the two datasets related to air pollutant concentrations are similar, COD value approaches zero, otherwise, COD approaches one. Further, exactly similar to the complex network correlation model developed by N.-N. Zhang et al. (2019) and N.-N. Zhang et al. (2018) (Zhang et al., 2018; Zhang et al., 2019), we developed and created a complex network COD model to show heterogeneity and homogeneity of all ambient air pollutants across validated AQMSs in Tehran for 2017 using the igraph R Package. The following equation was used to calculate the 90th percentile of the absolute differences between ambient air pollutant concentrations at AQMSs (Pinto et al., 2004; Ghim et al., 2015):

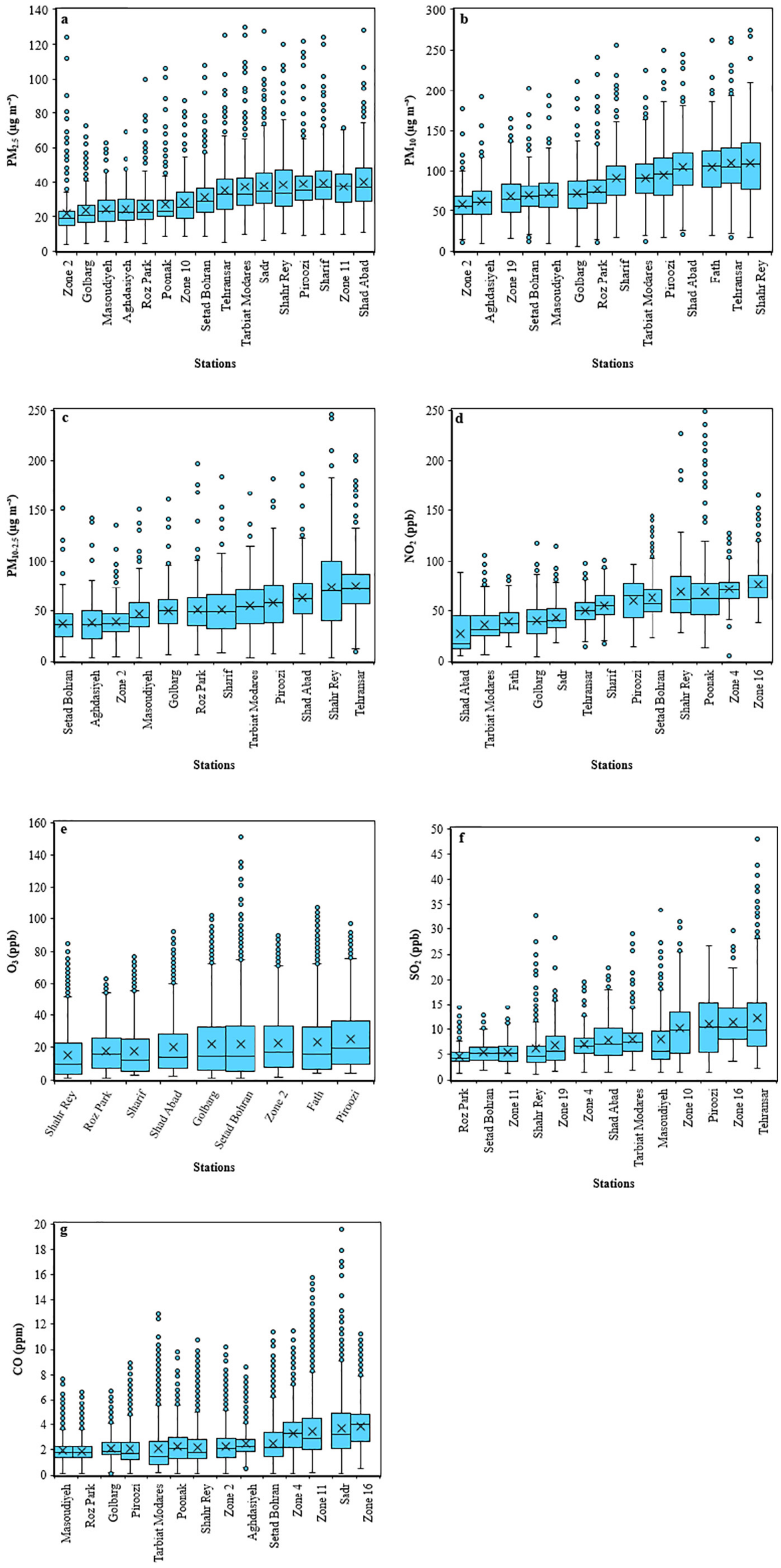
$$90^{th}\text{percentile} = ABS(APC_{ij} - APC_{ik})$$

APC_{ij} and APC_{ik} have previously been defined in detail. The CV indicator was calculated using the following equation (He et al., 2017; Song et al., 2017):

$$CV = \frac{STD}{\overline{X}}$$

$$STD = \sqrt{\frac{1}{p}\sum_{i=1}^{p}(APC_i - \overline{X})^2}$$

Where, STD is the standard deviation, APC_i represents ambient air pollutant concentrations for time *i* at AQMSs, $\overline{X}$ represents annual


a
PM2.5 (μg m⁻³)
Zone 2
Golbarg
Masoudiyeh
Aghdasiyeh
Roz Park
Poonak
Zone 10
Setad Bohran
Tehransar
Tarbiat Modares
Sadr
Shahr Rey
Pirozi
Sharif
Zone 11
Shad Abad
Stations
b
PM10 (μg m⁻³)
Zone 2
Aghdasiyeh
Zone 19
Setad Bohran
Masoudiyeh
Golbarg
Roz Park
Sharif
Tarbiat Modares
Piroozi
Shad Abad
Fath
Tehransar
Shahr Rey
Stations
c
PM10-2.5 (μg m⁻³)
Setad Bohran
Aghdasiyeh
Zone 2
Masoudiyeh
Golbarg
Roz Park
Sharif
Tarbiat Modares
Piroozi
Shad Abad
Shahr Rey
Tehransar
Stations
d
NO2 (ppb)
Shad Abad
Tarbiat Modares
Fath
Golbarg
Sadr
Tehransar
Sharif
Piroozi
Setad Bohran
Shahr Rey
Poonak
Zone 4
Zone 16
Stations
e
O3 (ppb)
Shahr Rey
Roz Park
Sharif
Shad Abad
Golbarg
Setad Bohran
Zone 2
Fath
Piroozi
Stations
f
SO2 (ppb)
Roz Park
Setad Bohran
Zone 11
Shahr Rey
Zone 19
Zone 4
Shad Abad
Tarbiat Modares
Masoudiyeh
Zone 10
Piroozi
Zone 16
Tehransar
Stations
g
CO (ppm)
Masoudiyeh
Roz Park
Golbarg
Piroozi
Tarbiat Modares
Poonak
Shahr Rey
Zone 2
Aghdasiyeh
Setad Bohran
Zone 4
Zone 11
Sadr
Zone 16
Stations

mean concentration for each air pollutant. In this study, to better show the correlation between the values of COD and 90th percentile, we introduced a Pearson correlation between them as a novel approach (Wang et al., 2014; Zhao et al., 2016; Xu et al., 2018). *P*-values <0.05 were considered as statistically significant.

3. Results and discussion

3.1. Spatial variabilities and hotspots of ambient air pollutants

Fig. 1 (a to g) reveals the annual average data on ambient PM_X, as well as on GAPs for all validated ground-based AQMSs in Tehran for 2017. In addition, to better highlight the most polluted areas and the changes in annual mean concentrations of ambient air pollutants, the map of spatial distribution of annual mean concentrations of ambient PM_X and GAPs was generated by using a Geographic Information System (Fig. 2). As shown in Fig. 1a, annual mean $PM_{2.5}$ concentrations measured at all AQMSs ranged from 21.7 to 40.5 μg m^{-3}, and are all approximately 2–4 times higher than the WHO AQG (10 μg m^{-3}), U.S. EPA and national levels (12 μg m^{-3}). Unfortunately, even the 25th percentile of mean $PM_{2.5}$ concentrations at all AQMSs exceeded above-mentioned recommendation and standards (Fig. 1a and Table S1). Interestingly, Tehran citizens who live around Shad Abad (40.5 μg m^{-3}) and Zone 11 (40.3 μg m^{-3}) stations were exposed to $PM_{2.5}$ at approximately two times higher levels compared with those in Zone 2 (21.7 μg m^{-3}) and Golbarg (23.6 μg m^{-3}) stations (Fig. 2). On the other hand, the highest to lowest annual mean ratio across AQMSs was around 2 and it is a clear inequality regarding exposure to ambient $PM_{2.5}$. Annual mean concentrations of $PM_{2.5}$ at 8 stations (out of 16 stations) including Setad Bohran, Zone 10, Poonak, Roz Park, Aghdasiyeh, Masoudiyeh, Golbarg and Zone 2 were less than the overall mean concentration (32.1 μg m^{-3}) for Tehran, whereas annual mean $PM_{2.5}$ concentrations at the other AQMSs were more than the overall mean concentration (Fig. 1a and 2). As illustrated in Fig. 2, $PM_{2.5}$ showed the highest annual mean concentrations in the south, south-east and central AQMSs. Further, annual average concentrations of $PM_{2.5}$ rose from the northern areas of Tehran megacity to its south (Fig. 2). Annual mean concentrations of PM_{10} spanned from 58.0 to 110.4 μg m^{-3} at all AQMSs, thereby 2.9–5.5 times higher than the WHO AQG (20 μg m^{-3}) (Fig. 1b and Table S2). Similar to $PM_{2.5}$, the 25th percentile of annual mean PM_{10} concentrations observed at all AQMSs was more than the WHO recommendation. Annual mean PM_{10} concentrations observed at Fath, Piroozi, Shad Abad, Shahr Rey, Tehransar, Sharif and Tarbiat Modares stations were greater than that of the overall mean concentration (84.9 μg m^{-3}) surveyed in Tehran in 2017 (Fig. 1a and 2). On the other hand, annual mean PM_{10} concentrations increased from the central to south areas, with the maximum in Share Rey station with 110.4 μg m^{-3}, followed by Tehransar station with 110.1 μg m^{-3} in the eastern areas of Tehran, as illustrated in Fig. 2. Similar to $PM_{2.5}$, exposure to PM_{10} indicated a clear spatial inequality across Tehran with the ratio of highest to lowest annual mean >2 (Fig. 2 and Table S2). In terms of $PM_{10-2.5}$, annual mean concentrations of $PM_{10-2.5}$ varied from 37.3 μg m^{-3} in Setad bohran station to 75.0 μg m^{-3} in Tehransar (Fig. 1c). As shown in Fig. 2 and Table S3, the value of inequality exposure to $PM_{10-2.5}$ between stations with the highest and lowest $PM_{10-2.5}$ annual mean in Tehran was nearly 2. Alike to PM_{10}, the highest annual mean concentrations of ambient $PM_{10-2.5}$ were found in the eastern and southern areas of Tehran megacity with 75.0 and 73.1 μg m^{-3} for Tehransar and Shahr Rey stations, respectively (Fig. 1c). The annual mean NO_2 concentrations exceeded the WHO AQG (22 ppb), by approximately 1.2- (Shad Abad with 27.0 ppb) to 3.5- (Zone 16 with 76.8 ppb) times (Fig. 1d and Table S4). Compared with the U.S. EPA and national levels (53 ppb), annual mean NO_2 concentration at 6 AQMSs (out of 13) in Tehran was less than the above-mentioned standard levels in 2017, whereas annual mean NO_2 concentration measured at 7 stations was more than the standard levels. Annual mean concentrations of O_3 were in the range of 15.5 (Shahr Rey station) -25.1 ppb (Piroozi station) (Fig. 1e and Table S5). As expected, O_3-8h concentrations displayed a different pattern of distribution to other air pollutants throughout Tehran (Fig. 2). O_3 concentrations can be decreased by high NO_X emissions as a result of titration effects (Jhun et al., 2015). Zone 16 and Zone 4 showed the aforementioned effect, with high concentrations in NO_2, but low O_3 (Fig. 2). The highest O_3 concentrations were observed in the northern and south-western parts of Tehran megacity; while the central areas demonstrated low to moderate concentrations (Fig. 2). NO_2 concentrations were higher in the west and south, while the eastern stations displayed the lowest concentrations (Fig. 2). In relation to stations-specific concentrations of SO_2, annual mean concentrations of SO_2 were between 4.6 ppb in Roz Park station and 12.2 ppb in Tehransar station (Fig. 1f and Table S6), while the CO concentrations at all AQMSs ranged from approximately 1.9 ppm (Roz Park) to 3.8 ppm (Zone 16) (Fig. 1g). Most areas of the city exhibited an acceptable concentration for SO_2 except for Tehransar (12.2 ppb) and Zone 16 (11.4 ppb), in the east and centre, respectively; these monitoring stations recorded the highest concentrations (Fig. 2). Such high figures can be attributed to the industry located within these regions of Tehran (Seifi et al., 2019). The detailed descriptive statistics are also provided in Table S1 to S7.

3.2. Spatial homogeneity and heterogeneity of ambient air pollutants

Fig. 3 (a to g) illustrates the network diagram of homogeneous and heterogeneous AQMSs based on COD values with 0.2 cut off for ambient air pollutants across Tehran. In addition, the values of COD and 90th percentile are shown in the Table S8 to S14 in detail. As discussed earlier, COD is an important factor to see the differences in absolute concentrations or source contribution, as a high r value does not necessarily indicate homogeneity of concentrations (Cyrys et al., 2008). Consequently, intra-urban regions with low absolute differences in ambient air pollutant concentrations tended to experience low COD values; <0.2. COD values of PM_X demonstrated more results lower than the 0.2 cut off compared to GAPs, indicating spatial homogeneity in the concentrations of ambient PM_X across the validated AQMSs in Tehran (Table S8 to S14). Additionally, the boxplots of COD values for both PM_X and GAPs are shown in Fig. S2. Overall, PM_{10} had the lowest mean COD value with 0.181, whereas SO_2 had the highest mean COD (0.318). For $PM_{2.5}$, $PM_{10-2.5}$, NO_2, O_3 and CO, mean COD was overall 0.216, 0.240, 0.292, 0.287 and 0.293, respectively (Table S15). Also, median COD values were above 0.2 for all ambient air pollutants, except for PM_{10}. However, even with twenty-two AQMSs across 730 km^2 of Tehran, COD values among some AQMSs indicate a considerable heterogeneous spatial distribution of air pollutants in different districts of Tehran. COD values ranged from 0.106 to 0.379 for $PM_{2.5}$, 0.068 to 0.328 for PM_{10} and 0.139 to 0.482 for $PM_{10-2.5}$ (Table S8 to S10). On the subject of $PM_{2.5}$, Setad Bohran and Sadr stations showed the highest homogeneity and heterogeneity with other stations, at 12 and 15 stations, respectively (Fig. 3a and Table S8). For PM_{10}, there was approximately a balance in homogeneity and heterogeneity, as Roz Park, Piroozi, Sharif and Tarbiat Modares showed the maximum homogeneity with 10 stations. With regard to PM_{10}, Aghdasiyeh station with 8 out of 13 stations showed the highest number of heterogeneity (Fig. 3b and Table S9). The number of heterogeneous stations for $PM_{10-2.5}$ was higher compared to other PM fractions; $PM_{2.5}$ and PM_{10}. Regarding $PM_{10-2.5}$, Sharif, Tarbiat Modares and Roz Park were spatially homogenous with 6 stations (Fig. 3c and Table S10). According to Table S8, for 24-h $PM_{2.5}$

Fig. 1. The station-specific boxplot of air pollutant concentrations ($PM_{2.5}$ (a), PM_{10} (b), $PM_{10-2.5}$ (c), NO_2 (d), O_3 (e), SO_2 (f), CO (g)) in Tehran (2017). Multiplication sign (X) in each box is the annual mean concentration of air pollutant at each AQMS.

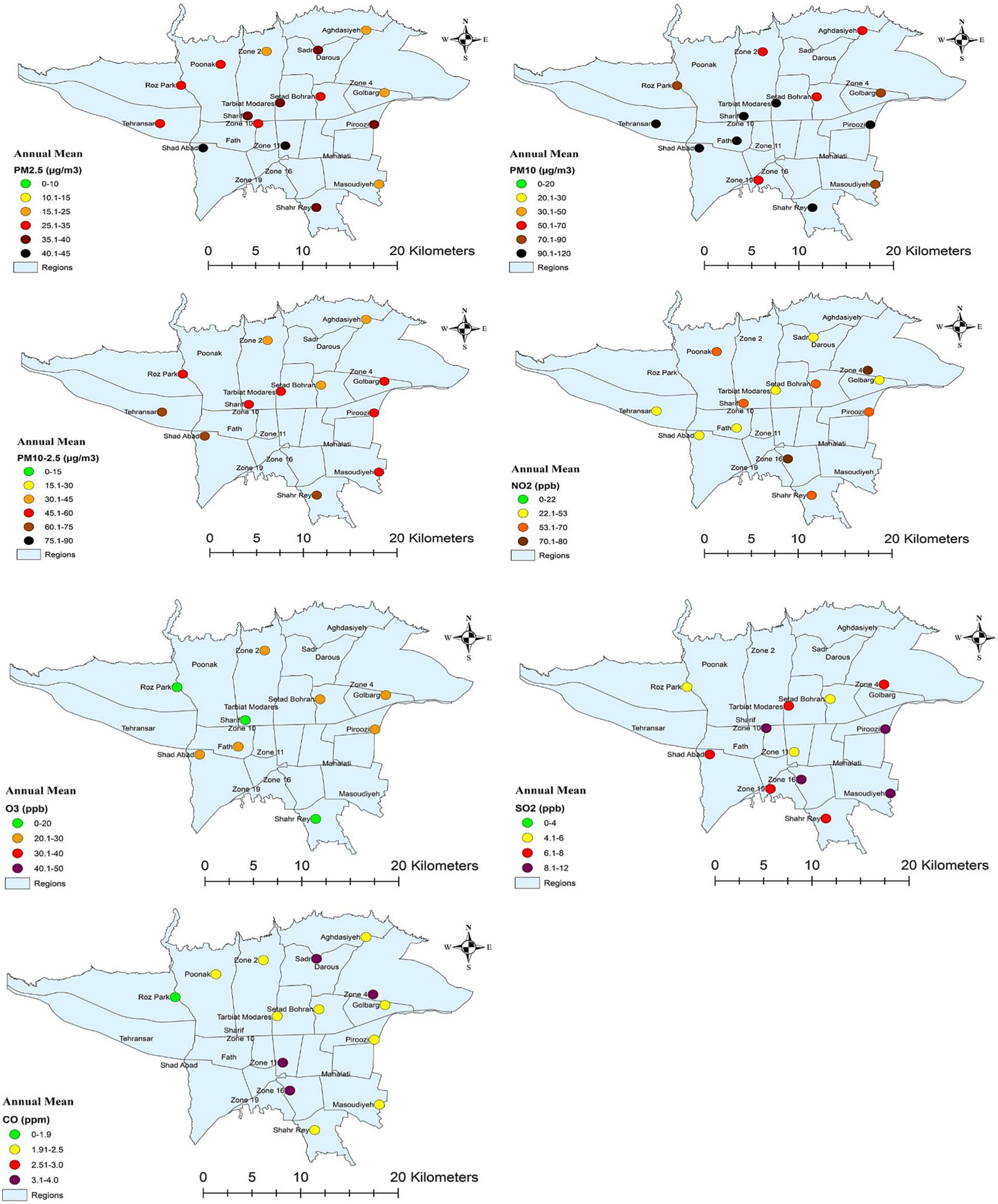
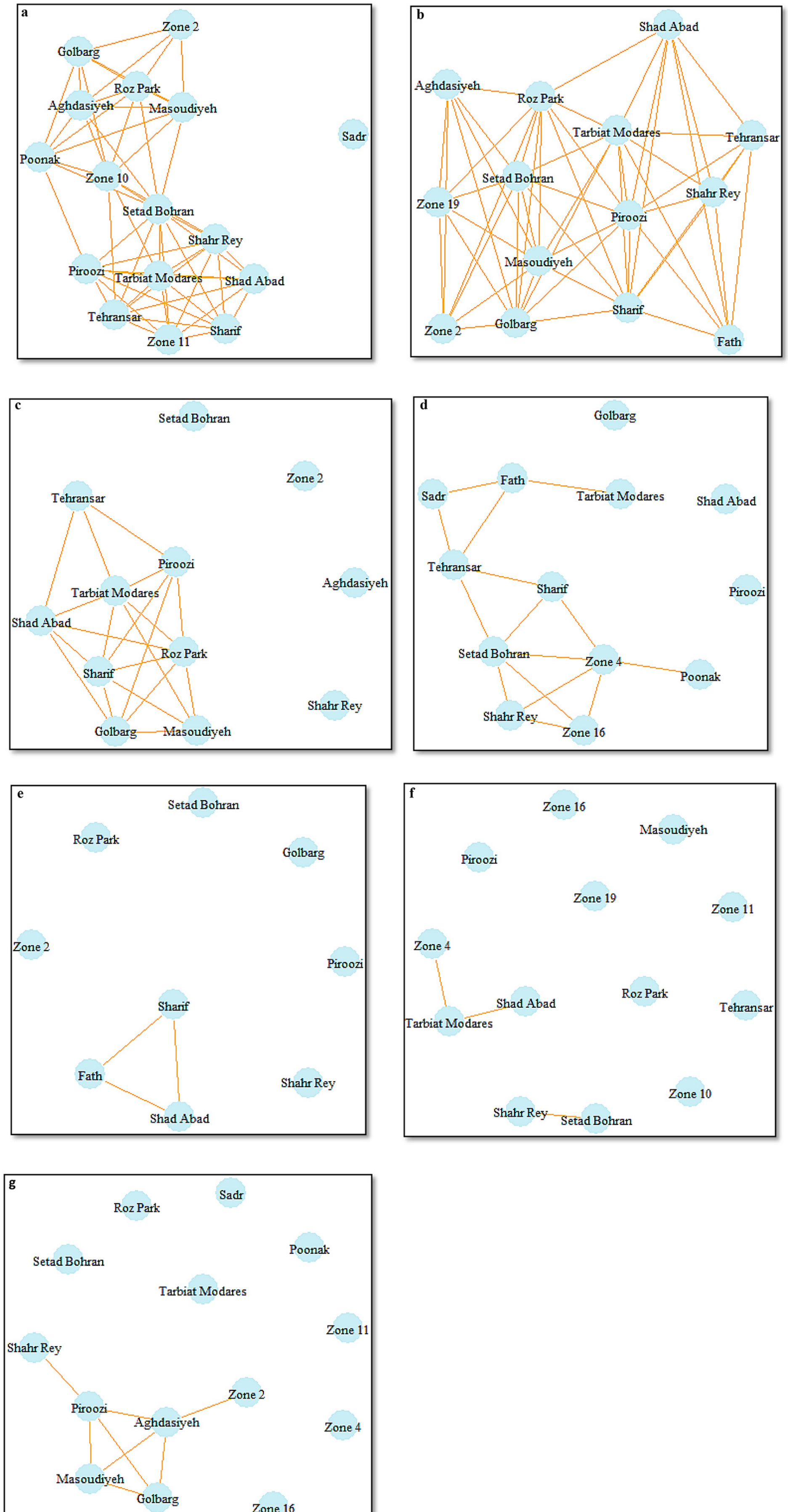


Fig. 2. Spatial distribution of annual mean concentration of ambient air pollutants across Tehran (2017).

Fig. 3. Network diagram of homogeneous and heterogeneous AQMSs based on COD values with 0.2 cut off for ambient air pollutants ($PM_{2.5}$ (a), PM_{10} (b), $PM_{10-2.5}$ (c), NO_2 (d), O_3 (e), SO_2 (f), CO (g)) across validated ground-based AQMSs within Tehran megacity (2017).


a
Zone 2
Golbarg
Roz Park
Aghdasiyeh
Masoudiyeh
Sadr
Poonak
Zone 10
Setad Bohran
Shahr Rey
Piroozi
Tarbiat Modares
Shad Abad
Tehransar
Sharif
Zone 11
b
Shad Abad
Aghdasiyeh
Roz Park
Tarbiat Modares
Tehransar
Setad Bohran
Shahr Rey
Zone 19
Piroozi
Masoudiyeh
Sharif
Zone 2
Golbarg
Fath
c
Setad Bohran
Zone 2
Tehransar
Piroozi
Aghdasiyeh
Tarbiat Modares
Shad Abad
Roz Park
Sharif
Shahr Rey
Golbarg
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d
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Tarbiat Modares
Shad Abad
Tehransar
Sharif
Piroozi
Setad Bohran
Zone 4
Poonak
Shahr Rey
Zone 16
e
Setad Bohran
Roz Park
Golbarg
Zone 2
Piroozi
Sharif
Fath
Shahr Rey
Shad Abad
f
Zone 16
Masoudiyeh
Piroozi
Zone 19
Zone 11
Zone 4
Shad Abad
Roz Park
Tarbiat Modares
Tehransar
Zone 10
Shahr Rey
Setad Bohran
g
Sadr
Roz Park
Poonak
Setad Bohran
Tarbiat Modares
Zone 11
Shahr Rey
Zone 2
Piroozi
Aghdasiyeh
Zone 4
Masoudiyeh
Golbarg
Zone 16

concentrations, Tarbiat Modares and Shahr Rey stations reveal the strong similarity between the two stations with a COD value equal to 0.106, followed by Tarbiat Modares and Sharif stations with COD value equal to 0.109. Furthermore, of all AQMSs across Tehran examined, the two most dissimilar monitoring stations were Zone 2 and Sadr (COD = 0.379), as well as Zone 2 and Zone 11 (0.357). Regarding 24-h PM_{10} concentrations, as shown in Table S9, among all studied AQMSs, Shad Abad and Fath stations exhibited the greatest similarity with a COD value of 0.068, followed by Shad Abad and Tehransar, Tarbiat Modares and Tehransar, Tarbiat Modares and Sharif stations with a COD values of 0.076, 0.078, and 0.078, respectively. Of all paired AQMSs investigated throughout Tehran, the highest spatial variability of 24-h PM_{10} concentrations was recorded between Zone 2 and Shar Rey stations with COD of 0.328, as well as Zone 2 and Tehransar stations with COD equal to 0.310 (Table S9). In regards to 24-h $PM_{10-2.5}$, the highest spatial uniformity in $PM_{10-2.5}$ concentrations was observed between Piroozi and Golbarg stations (COD = 0.139), followed by Tehransar and Shad Abad stations with a COD value equal to 0.143. In addition, the highest COD (0.482) for $PM_{10-2.5}$ concentrations was calculated for Piroozi and Shad Abad stations (Table S10). There are a number of reasons that could account for spatial variation in PM_X concentrations. Sporadic events such as land uses, construction and demolition activities, proximity to emission sources, transient emission events, or a meteorological occurrence, such as local circulations and topographic features, are the most significant reasons (Pinto et al., 2004). Ambient PM_X comprises a mixture of primary and secondary constituents. Significant differences on spatial and temporal characteristics can also be attributed to local sources of ambient PM_X. Moreover, based on recent conducted study by Taghvaee et al. (2018a, 2018b, 2018c), the source of ambient $PM_{2.5}$ in two central areas of Tehran arises mostly from mobile sources; an overall contribution equal to 77% and 73%, a high contribution of 74% and 63% in the warm season and 78% and 80% in the cold season (Taghvaee et al., 2018a, 2018b, 2018c). Also, previously conducted studies have reported these high contributions of vehicular emissions to ambient PM air pollutants (Shahbazi et al., 2016b, Arhami et al., 2017, Arhami et al., 2018, Taghvaee et al., 2018a, 2018b, 2018c). Therefore, high COD values suggest that the available ground-based AQMSs may be insufficient to accurately monitor of the whole area of the city (Guo et al., 2017). Compared to ambient PM_X, GAPs showed higher spatial variabilities between paired intra-urban AQMSs over districts of Tehran (Fig. 3d to g). In reality, CODs of GAPs revealed a higher heterogeneous spatial distribution between monitoring stations. As indicated in Table S11 to 14, NO_2 with more figures <0.2 had the highest spatial uniformity in comparison to other ambient GAPs. For NO_2, the maximum homogeneity was observed between Setad Bohran station and other five stations including Zone 4 (0.138), Tehransar (0.142), Sharif (0.150), Zone 16 (0.158), and Shahr Rey (0.182). The highest COD value calculated for Shad Abad and Zone 4 stations; 0.579 (Table S11). Moreover, Golbarg, Piroozi and Shad Abad stations were spatially heterogeneous with others (Fig. 3d). Similar to O_3, 24-h SO_2 and 8-h CO represented COD values >0.2 which might be associated with specific source emissions. Regarding 8-h O_3 (Fig. 3e to g and Tables S12 to S14), Shad Abad exhibited a low COD value, with Fath and Sharif exhibiting 0.194 and 0.181, respectively. Moreover, we observed a considerable homogeneity between Fath and Sharif stations with a COD value equal to 0.180. The results of COD for 24-h SO_2 concentrations demonstrated that only 5 out of 13 stations, such as Setad Bohran, Shad Abad, Shahr Rey, Zone 4 and Tarbiat Modares were spatially homogenous (Fig. 3f). 8-h CO concentrations displayed a high spatial heterogeneity at 8 stations in comparison with others (Fig. 3g). Further details about heterogeneous and homogenous sites are available in Table S8 to S14. In addition to calculation of COD for ambient PM and GAPs, herein we computed the 90th percentile of the absolute differences in air pollutant concentrations intra-urban of Tehran to show their spatial uniformity and dissimilarity. The results of the 90th percentile of the absolute differences in air pollutant concentrations across AQMSs are shown in Table S8 to S14. Our results revealed that when COD values decline, the values of 90th percentile of the absolute differences decreased, or vice versa (Table 2). Consequently, we introduced Pearson correlation between the values of COD and the 90th percentile of the absolute differences between ambient air pollutant concentrations as a novel approach to investigate the correlation of these approaches. Interestingly, there was a statistically positive correlation ($P < 0.05$) between the values of COD and the 90th percentile, indicating agreement between these approaches, as illustrated in Table 2. The coefficients of Pearson correlation between the values of COD and the 90th percentile for $PM_{2.5}$ (0.8905) and PM_{10} (0.8361), as the most notable markers of ambient air pollution globally, were higher than those for GAPs, including O_3, NO_2 and SO_2 (Table 2). Furthermore, similar to $PM_{2.5}$ and PM_{10}, CO was found with high coefficients (0.8918) of Pearson correlation between the values of COD and the 90th percentile. These findings confirm that in order to better understanding spatial variability of all ambient air pollutants, in addition to COD and the 90th percentile, the investigation of correlation between them could be appropriate. Fig. S3 summarizes the boxplot of the 90th percentile of the absolute differences between 24-h concentrations for PM_X, SO_2, NO_2 and 8-h concentrations for O_3 and CO. As shown in Fig. S3 and Table S16, the values of the 90th percentile of the absolute differences between 24-h concentrations for $PM_{2.5}$, PM_{10} and $PM_{10-2.5}$ was approximately in the range of 10.6–39.4, 15.4–100.1, and 18.1–79.9 μg m^{-3}, with the mean value of approximately 23.3, 49.7 and 39.3 μg m^{-3}, respectively. Furthermore, the mean value of the 90th percentile of the absolute differences for O_3, NO_2, SO_2 and CO was approximately 23.2, 46.9 10.0 ppb and 2.6 ppm, respectively. Detailed information regarding the 90th percentile is presented in Table S16. Based on the CV indicator (Fig. 4), the highest spatial variability at all validated AQMSs was recognized for ambient O_3 with 87.3%, followed by SO_2 (65.2%) > CO (61.8%) > $PM_{10-2.5}$ (52.5%) > $PM_{2.5}$ (48.9%) > NO_2 (48.1%) > PM_{10} (42.9%). Interestingly, we observed that among ambient GAPs, O_3 as a secondary air

Table 2
Pearson correlation coefficients between COD and 90th percentile in Tehran (2017), * $P < 0.05$.

COD 90th percentile	$PM_{2.5}$	PM_{10}	$PM_{10-2.5}$	O_3	NO_2	SO_2	CO
$PM_{2.5}$	0.8905*						
PM_{10}		0.8361*					
$PM_{10-2.5}$			0.6095*				
O_3				0.4874*			
NO_2					0.4840*		
SO_2						0.7894*	
CO							0.8918*

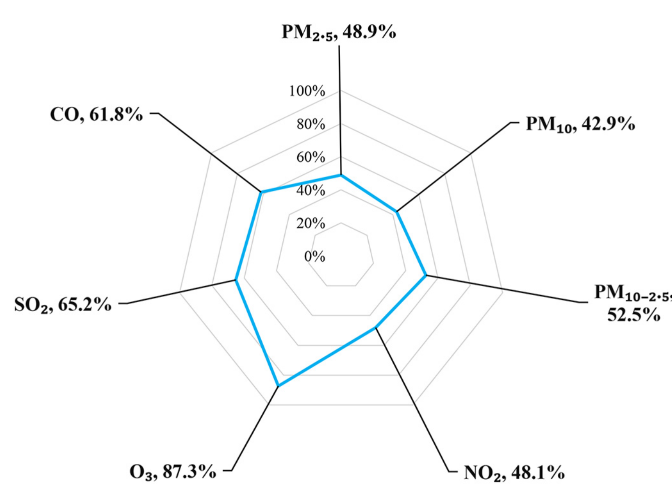

Fig. 4. The CV of ambient PM_X and gaseous air pollutants in Tehran (2017).

pollutant had the highest heterogeneity whereas its most important precursor and destroyer; ambient NO_2; showed the highest homogeneity, or vice versa. The results of spatial distribution from the CV indictor tended to be in agreement with those from COD indicator, except for NO_2.

4. Conclusion

To better understanding the status of ambient air pollutants in different districts of Tehran, the spatial variabilities of ambient PM_X and GAPs was investigated with using the approaches of COD, CV and the 90th percentile of the absolute differences between air pollutant concentrations across AQMSs. Based on our results, the annual mean concentrations of $PM_{2.5}$, PM_{10} and $PM_{10-2.5}$, NO_2, O_3 and SO_2, and CO were 32.1, 84.9 and 53.5 μg m^{-3}, 20.7, 53.4 and 8.1 ppb and 2.6 ppm in Tehran for 2017. Our spatial results demonstrated that Tehran citizens were exposed to various concentrations of ambient PM_X and GAPs across the different districts of Tehran in 2017. Regarding to annual $PM_{2.5}$, throughout monitoring stations, Shad Abad and Zone 2 observed the highest and lowest concentrations with 40.5 and 21.7 μg m^{-3}, respectively. Considering PM_{10}, annual mean concentrations were in the range of 58.0 (Zone 2) -110.4 μg m^{-3} (Shahr Rey). Furthermore, Tehran citizens experienced annual mean $PM_{2.5}$ and PM_{10} concentrations more than the WHO AQG and national standard levels at all investigated municipal districts of Tehran in 2017. Overall, hotspots for ambient PM_X pollution were mainly concentrated in the south, south-east and central regions of Tehran city. Considering three quantitative indicators to show spatial inequality of ambient air pollutants, the highest homogeneity was found for ambient PM_X air pollution in Tehran, whereas the highest heterogeneity was observed for ambient GAPs, except for NO_2. Moreover, the highest homogeneity was found for $PM_{2.5}$ and NO_2, as the most notable markers of traffic-related emissions in different districts of Tehran in 2017. Interestingly, the results of COD revealed that spatial pattern of O_3 and its most important precursor and destroyer; ambient NO_2; were inverse. The results of this study will help bring awareness to government, policy-makers, medical professionals, and the public about the spatial variation of ambient air pollutants, particularly ambient $PM_{2.5}$ as a major health concern globally, to facilitate establishing new local and intra-urban control policies.

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Declaration of competing interest

There is no actual or potential conflict of interest among authors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.134123.

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