



Changes in short-lived climate pollutants during the COVID-19 pandemic in Tehran, Iran

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Abstract This study investigates the changes of short-lived climate pollutants and other air pollutants during the COVID-19 pandemic in Tehran, Iran. Concentrations of air pollutants were obtained from 21 monitoring stations for the period from 5 January 2019 to 5 August 2019, representing normal conditions unaffected by COVID-19, and the period 5 January 2020 to 5 August 2020, i.e., during the COVID-19 crisis. We concentrated our analysis on three time windows (23 February 2020 to 15 March 2020, 18 March 2020 to 3 April 2020, and 5 April 2020 to 17 April 2020) during the lockdown when different sets of measures were taken to limit the

spread of COVID-19. In comparison to the period not affected by COVID-19 measures, mean concentrations of pollutants were increased during the first lockdown period; when the number of COVID-19 patients increased sharply compared to the other periods, the mean surface concentrations of NO₂, SO₂, and CO were decreased and concentrations of other pollutants (i.e., O₃, PM₁₀, and PM_{2.5}) were increased during the second lockdown period compared to the corresponding period in 2019. In the third period, the mean concentrations were decreased compared to the corresponding period in 2019. For the full period, decreases in mean concentrations of O₃, NO₂, SO₂, CO, and PM₁₀ and increases in PM_{2.5} were observed during the COVID-19 crisis, compared to 2019. Overall, the strongest reductions, 12% and 6%, respectively, were observed for CO and NO₂, pointing to reduced emissions from traffic as a result of lockdown measures. The concentrations of other pollutants changed little, suggesting that the lockdown measures did not result in strong changes in the emissions from stationary sources.

Highlights

- The changes of short-lived climate pollutants and air quality during the COVID-19 pandemic in Tehran were investigated.
- Concentrations of air pollutants in 2020, i.e., during the COVID-19 crisis, were compared to the 2019, representing period not affected by COVID-19 measures.
- The changes in air quality in 2020 compared to 2019 were quite modest, despite stringent COVID-19 lockdown measures in 2020.

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Introduction

The COVID-19 virus outbreak was first identified in December 2019 in Wuhan, China (WHO, 2020). On 19 February 2020, the first cases of pneumonia associated with COVID-19 (Coronavirus) were reported in Iran. Thereafter, the number of infected people increased quickly and the outbreak led to a national crisis. Iranian authorities shut down travel and transportation in and out of cities. They also established numerous quarantines and reduced local business travel, closed down colleges, universities, and schools in order to reduce the propagation of the disease.

Since restrictive measures were applied due to the Coronavirus outbreak, Tehran and some other cities have enjoyed cleaner air than under normal conditions. Medical doctors and some scientists argue that there may be a potential link between compromised lung capacity and long-term exposure to air pollution, which could make an individual exposed to high levels of air pollution more likely to develop a severe form of COVID-19 (Yongjian et al., 2020). The most important air pollutants in Tehran are nitrogen dioxide (NO_2), tropospheric ozone (O_3), carbon monoxide (CO), sulfur dioxide (SO_2), and particulate matter ($\text{PM}_{2.5}$ and PM_{10}). $\text{PM}_{2.5}$ and PM_{10} are defined as the fractions of particles with aerodynamic diameters smaller than respectively 2.5 and 10 μm . An important component of $\text{PM}_{2.5}$ is black carbon (BC), which is thought to be particularly harmful to human health (Sasser et al., 2012; EEA, 2013). The above mentioned pollutants are also short-lived climate pollutants (SLCPs), which are substantial contributors to climate change (e.g., Randall, 2008; Stohl et al., 2015; Retama et al., 2015; Kindbom et al., 2019). SLCPs contribute as much as 40% to climate change (IPCC, 2013). These pollutants, directly or by formation of secondary pollutants, have harmful influences on both air quality and climate (Stocker et al., 2013).

The effects of COVID-19 measures on air quality have already been studied for some regions. For example, for Spain, Ogen (2020) showed that out of 4443 fatality cases due to COVID-19, 3487 (78%) were in five regions in central Spain. Additionally, the same

five regions experienced large-scale subsidence, which prevented an efficient dispersion of air pollution. Menut et al. (2020) concluded that in Spain, the lockdown influence on atmospheric composition, particularly through reductions in traffic, has been significant for several short-lived atmospheric species, with a relatively small reduction in PM concentrations and a large reduction in the concentrations of NO_2 . Sicard et al. (2020) concluded that, during the lockdown in 2020, the mean daily concentrations of O_3 at urban stations were higher by 14% in Rome, 2.4% in Valencia, 24% in Nice, 36% in Wuhan, and 27% in Turin in comparison to the same period in 2017–2019. The increase in O_3 concentrations in urban areas is mainly due to less O_3 titration by NO as a result of the reduction in NO_x emissions primarily in the form of NO (Sicard et al., 2020). A significant reduction of concentrations of pollutants in Quito during the 4 weeks of quarantine was reported by Zalakeviciute et al. (2020). Kumar (2020) investigated the pollutants and aerosols and compared them with the number of COVID-19 cases. The concentrations of aerosols and other pollutants were rapidly reduced from 25 March to 15 April during lockdown in India (Kumar, 2020).

Mannucci (2020) showed a remarkable decrease of NO_2 in the north of Italy during the COVID-19 pandemic based on the ESA satellite Sentinel 5P records. Martelletti and Martelletti (2020) showed that Northern Italy, which was most strongly affected by COVID-19, also had high concentrations of particulate matter (PM_{10} and $\text{PM}_{2.5}$) that exceeded the legislative standards (i.e., $50 \mu\text{g m}^{-3}$) in February 2020. Sanita di Toppi et al. (2020) studied the possible relationship between air pollution, primarily airborne $\text{PM}_{2.5-10}$, and the spread of COVID-19 in Northern Italy.

The objective of this study is to quantify the changes in air pollutant levels during the COVID-19 lockdown in Tehran. For this, we compare the concentrations of O_3 , NO_2 , SO_2 , CO, PM_{10} , and $\text{PM}_{2.5}$ at 21 air quality monitoring stations in Tehran during the time periods from 5 January 2019 to 5 August 2019 (representing a baseline period not affected by COVID-19 measures) and 5 January 2020 to 5 August 2020 (i.e., during the COVID-19 crisis).

Study area

Tehran ($35^\circ 41' \text{ N}$ and $51^\circ 23' \text{ E}$), the capital of Tehran Province and Iran (Fig. 1) and with a population of 8.7

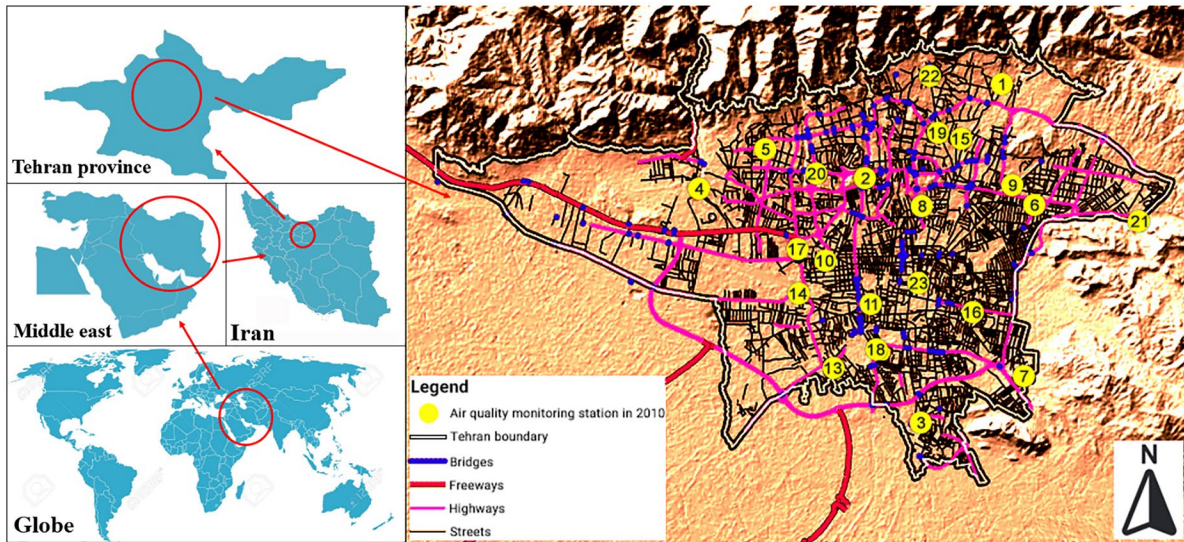


Fig. 1 The locations of the air quality monitoring stations in Tehran city; 1: Aqdasiyeh, 2: Sharif University, 3: Ray, 4: District 21, 5: Punak, 6: Golbarg, 7: Masoudieh, 8: Tarbiat Modares University, 9: District 4, 10: District 10, 11: Fath Sq.,

12: Setad Bohran, 13: District 19, 14: Shad Abad, 15: Darrous, 16: Mahallati, 17: Region 22, 18: District 16, 19: Sadr, 20: Rose Park, 21: Piroozi, 22: District 2, 23: District 11

million people, the largest city in western Asia, covers an area of 751 km². The city is limited by the Alborz Mountains in the north and the central desert in the south with approximate elevations of respectively 1980 m and 1117 m above sea level. The Alborz Mountains are acting as a barrier to the humid northerly air flow from the Caspian Sea. The topography also favors the formation of thermal inversions that trap polluted air in Tehran.

The annual minimum and maximum temperatures in Tehran are -15 and 43 °C and the average relative humidity is 40%. The annual total rainfall in Tehran is 220 mm. The metropolis of Tehran is divided into 22 municipal districts. Automobile and motorcycle emissions have a striking contribution to Tehran air pollution (Hassani & Hosseini, 2016). In early 2018, over four million vehicles, including three million motorcycles, were registered in Tehran (MOHME, 2020); 400,000 of these vehicles were more than 15 years old and they accounted for about 32% of the capital's air pollution (MOHME, 2020).

Measurement data and methods of analysis

In this study, we compare measurement data obtained during the period of 5 January 2019 to 5 August 2019, which serves as a baseline not affected by

the COVID-19 measures, and data obtained during the COVID-19 crisis period of 5 January 2020 to 5 August 2020. This allows to study the impact of the COVID-19 measures on the Tehran air quality, even though differences in the meteorological conditions between the 2 years may also have had an influence on air pollution levels. We used data from 21 monitoring stations (Fig. 1) that were obtained from the Tehran Department of Environment (DOE) and Tehran Air Quality Control Company (AQCC). The monitoring stations of Sharif University, Golbarg, Tarbiat Modares University, Setad Bohran, District 19, Mahallati, Region 22, District 16, Piroozi, and District 2 are urban stations. Also, traffic-related monitoring stations are Aqdasiyeh, Ray, District 21, Punak, Masoudieh, District 4, District 10, Fath Sq., Shad Abad, Darrous, Sadr, Rose Park, and District 11 (AQCC, 2020). The monitoring stations of Darrous and Rose Park were inactive during data recording of this study.

DOE and AQCC monitoring stations used UV absorption (O₃ 42 Model) to measure the O₃ concentration according to ISO 13964, 2008/50/EC, en 14625, EN 15267. 40 cfr part 53, and 40 cfr part 58. All stations used chemiluminescent sensors (Model APNA-370 of Horiba, Japan; AC 32 M of Environment SA, France, and EC 9841 of Ecotech, Australia) to measure NO₂.

UV Fluorescent Sensor (LSI-Babuc/A Made by LSI Company in Italy) were used to record SO₂ concentrations. Monitoring stations used non-dispersive infrared spectrometry (NDIR) analyzers to measure the CO concentration. Analysis of inorganic gaseous pollutants (i.e., NO₂, SO₂, and CO) performed according to the European Air Quality Directive 2008/50/EC and recent revision 2015/1480/EC. The measuring method for PM₁₀ and PM_{2.5} concentrations was tapered-element oscillating microbalance, TEOM (Dust Trak TSI, Model Echo Pm, Made by TCI Tecora Company in Italy), according to the AAQ NEPM standard. Recording system follows QA/QC (i.e., quality assurance/quality control) procedures that, under ideal circumstances, ensure the instruments are calibrated and checked every 2 weeks.

The concentrations of O₃, NO₂, SO₂, CO, PM₁₀, and PM_{2.5} were measured hourly. The average of hourly values from all 21 monitoring stations was taken as representative for the conditions in Tehran as a whole, and then hourly values were averaged to daily values. The pollution data are validated for each monitoring station during the study period. Zero and negative values and the data that were very inconsistent with other data due to some local phenomena such as fire were removed from the database. Stations with more than 75% available hourly concentrations data were considered valid. Accordingly, all 21 stations were valid for data processing. To determine the statistical significance, one sample test was used. The statistical parameters of the database utilized in this study are presented in Table 1.

Table 1 Statistical analysis of database of pollutants and AQI

| Pollutants & AQI | Dataset | 2019 (Normal conditions) | | | | 2020 (During COVID-19 pandemic) | | | |
|-------------------|---------------|--------------------------|-------|-------|-------|---------------------------------|-------|-------|-------|
| | | Max | Min | Mean | SD | Max | Min | Mean | SD |
| O ₃ | All data | 46.70 | 6.50 | 25.13 | 9.38 | 44.12 | 4.47 | 24.55 | 10.33 |
| | First period | 23.67 | 10.93 | 17.63 | 2.75 | 23.95 | 9.16 | 16.98 | 3.68 |
| | Second period | 33.07 | 14.33 | 24.30 | 4.81 | 31.84 | 20.47 | 24.75 | 3.06 |
| | Third period | 30.67 | 18.20 | 24.26 | 3.43 | 27.33 | 13.26 | 21.79 | 5.00 |
| NO ₂ | All data | 76.17 | 33.13 | 47.59 | 7.35 | 72.06 | 23.89 | 44.86 | 9.44 |
| | First period | 53.38 | 39.94 | 47.99 | 3.83 | 65.11 | 37.94 | 52.01 | 7.83 |
| | Second period | 46.40 | 33.13 | 39.47 | 2.98 | 34.78 | 23.89 | 29.75 | 3.09 |
| | Third period | 46.13 | 40.27 | 42.70 | 1.87 | 45.55 | 32.22 | 39.20 | 4.34 |
| SO ₂ | All data | 10.06 | 2.40 | 4.80 | 1.50 | 10.61 | 2.56 | 4.79 | 1.59 |
| | First period | 9.56 | 3.44 | 5.52 | 1.58 | 7.67 | 3.94 | 5.79 | 1.14 |
| | Second period | 5.19 | 2.40 | 3.45 | 0.71 | 4.56 | 2.56 | 3.17 | 0.50 |
| | Third period | 5.60 | 2.53 | 3.78 | 0.77 | 5.17 | 2.67 | 3.53 | 0.64 |
| CO | All data | 3.22 | 0.87 | 1.57 | 0.41 | 2.56 | 0.75 | 1.38 | 0.34 |
| | First period | 2.06 | 1.29 | 1.61 | 0.22 | 2.56 | 0.94 | 1.61 | 0.38 |
| | Second period | 1.76 | 0.88 | 1.17 | 0.22 | 1.31 | 0.75 | 0.98 | 0.13 |
| | Third period | 1.59 | 1.06 | 1.32 | 0.15 | 1.44 | 0.94 | 1.17 | 0.19 |
| PM ₁₀ | All data | 162.44 | 25.44 | 66.77 | 23.56 | 114.00 | 18.63 | 63.42 | 18.66 |
| | First period | 75.81 | 41.56 | 55.97 | 10.38 | 101.12 | 35.71 | 65.07 | 15.92 |
| | Second period | 53.13 | 25.43 | 33.53 | 7.55 | 61.00 | 18.63 | 35.89 | 11.33 |
| | Third period | 71.69 | 39.50 | 50.75 | 12.37 | 47.75 | 22.25 | 37.14 | 7.93 |
| PM _{2.5} | All data | 57.33 | 10.27 | 24.71 | 8.20 | 65.25 | 9.38 | 25.69 | 8.95 |
| | First period | 35.53 | 15.47 | 22.35 | 5.35 | 65.25 | 14.31 | 29.64 | 11.99 |
| | Second period | 25.40 | 10.27 | 14.88 | 4.05 | 23.38 | 9.38 | 15.77 | 3.62 |
| | Third period | 22.60 | 15.67 | 18.99 | 2.35 | 26.00 | 12.50 | 18.91 | 3.88 |
| AQI | All data | 160.00 | 32.00 | 75.85 | 26.58 | 161.00 | 30.00 | 83.49 | 26.19 |
| | First period | 93.00 | 38.00 | 67.38 | 15.10 | 136.00 | 30.00 | 86.00 | 25.82 |
| | Second period | 98.00 | 33.00 | 49.47 | 17.89 | 80.00 | 39.00 | 59.35 | 11.31 |
| | Third period | 59.00 | 35.00 | 46.23 | 7.35 | 84.00 | 39.00 | 56.69 | 13.78 |

Max maximum, Min minimum, SD standard deviation

Table 2 The *P*-value for pollutants and AQI

| Dataset | O ₃ | NO ₂ | SO ₂ | CO | PM ₁₀ | PM _{2.5} | AQI |
|---------------|----------------|-----------------|-----------------|---------|------------------|-------------------|--------|
| All data | 0.539 | 0.0009* | 0.919 | 0.0000* | 0.103 | 0.241 | 0.002* |
| First period | 0.492 | 0.030* | 0.495 | 0.987 | 0.024* | 0.010* | 0.004* |
| Second period | 0.750 | 0.0000* | 0.194 | 0.005* | 0.479 | 0.504 | 0.064 |
| Third period | 0.156 | 0.016* | 0.369 | 0.036* | 0.003* | 0.949 | 0.026* |

**P* < 0.05

Student’s *t*-test (Ju et al., 2020) was used to determine whether the differences of the mean concentrations in 2019 and 2020 were significant. Table 2 presents the *P*-value for each pollutant and AQI. In the current research, the *P*-value < 0.05 was considered as statistically significant.

As an overall measure of air quality, we calculated a so-called air quality index (AQI) (US EPA, 2011), which combines information about several pollutants (i.e., O₃, NO₂, SO₂, CO, PM₁₀, and PM_{2.5}). The AQI calculation was conducted in two steps: (1) the maximum values of 1- and 8-h O₃, maximum 1-h NO₂, maximum values of 8-h CO, and maximum 24 h and maximum values for PM₁₀, PM_{2.5}, and SO₂ were extracted, and (2) the AQI was calculated as following:

$$\rho_p = \frac{\rho_{HI} - \rho_{LO}}{BP_{HI} - BP_{LO}} \times (C_p - BP_{LO}) + \rho_{LO} \quad (1)$$

$$AQI = \max(\rho_{O_3}, \rho_{NO_2}, \rho_{SO_2}, \rho_{CO}, \rho_{PM_{10}}, \rho_{PM_{2.5}}) \quad (2)$$

where ρ_p is the index for pollutant *p*, the C_p is the rounded concentration of pollutant *p*, BP_{HI} is the concentrations of pollutants that is higher than or equal to C_p , BP_{LO} is the concentrations of pollutants that is lower than or equal to C_p , ρ_{HI} is the AQI value corresponding to BP_{HI} , and ρ_{LO} is the AQI value corresponding to BP_{LO} .

Table 3 Standard levels for air pollutants (WHO, 2003; US EPA, 2011)

| Pollutant | Averaging time | Level |
|-------------------|----------------|-------------------------|
| CO | 8 h | < 9.4 ppm |
| NO ₂ | 1 h | < 100 ppb |
| O ₃ | 8 h | < 70 ppb |
| PM _{2.5} | 24 h | < 35 µg/m ³ |
| PM ₁₀ | 24 h | < 150 µg/m ³ |
| SO ₂ | 24 h | < 140 ppb |

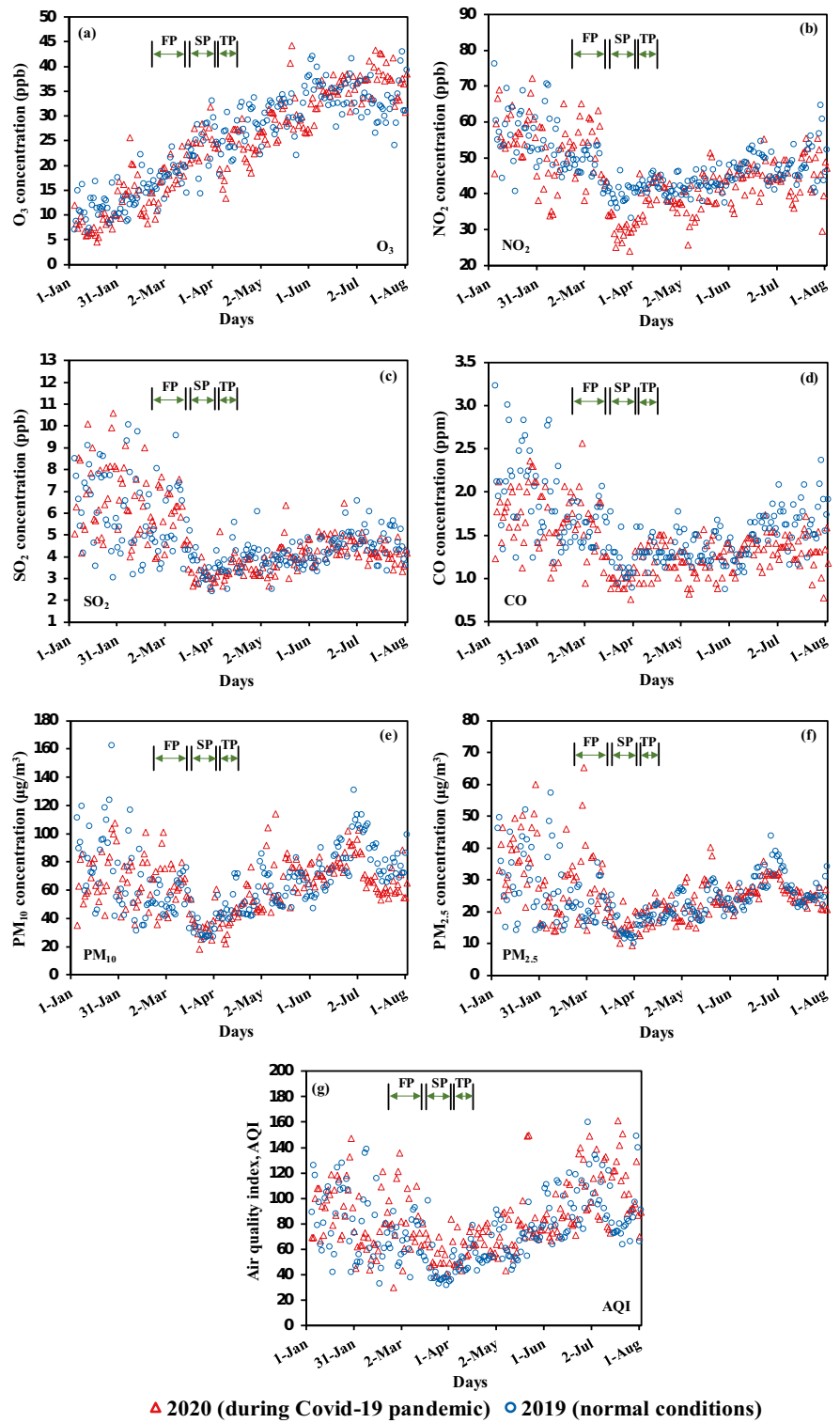
The AQI (developed by United States Environmental Protection Agency, US EPA, 2011) ranges from 0 to 500 and is an indicator of the overall air quality. Values of 0–50 correspond to good air quality, 51–100 to moderate, 101–150 to unhealthy for sensitive groups, 151–200 to unhealthy, 201–300 to very unhealthy, and 301–500 to hazardous conditions. Standard levels for air pollutants (WHO, 2003; US EPA, 2011) are presented in Table 3.

Results and discussion

The daily mean surface concentrations of O₃, NO₂, SO₂, CO, PM₁₀, and PM_{2.5}, averaged over the 21 air quality monitoring stations, are shown in Fig. 2a–f. Compared to our 2019 reference period that was not affected by COVID-19 measures, the mean concentrations of O₃, NO₂, SO₂, CO, and PM₁₀ in 2020 were lower by about 2.3%, 6%, 0.3%, 12%, and 5%, respectively, and the mean concentration of PM_{2.5} was higher by about 4% for the whole period considered (Fig. 2a–f). Carbon monoxide, which is strongly influenced by traffic sources, showed the strongest reduction compared to 2019, from 1.57 ppm in 2019 to 1.38 ppm in 2020. Both values are substantially below Iran’s clean air quality standard (i.e., 9 ppm) (Fig. 2d). The *t*-test results shown in Table 2 indicate that there was no significant difference between the mean concentration of O₃, SO₂, and PM_{2.5} in 2019 and 2020 (95% confidence interval), whereas a significant difference was observed between the mean concentrations of NO₂ and CO and also of the AQI level (*P*-value < 0.05).

The maximum AQI value, 161, in Tehran during the COVID-19 crisis was recorded on July 19, 2020 (Fig. 2g), due to high ozone concentrations. The mean AQI was higher by about 10% from January 5, 2020, to August 5, 2020, compared to the corresponding period in 2019 (Table 1). The air quality in Tehran during the study period (January 5, 2020, to August

Fig. 2 Time-series of daily mean surface concentrations averaged over 21 air quality monitoring stations for **a** O₃, **b** NO₂, **c** SO₂, **d** CO, **e** PM₁₀, **f** PM_{2.5}, **g** AQI (FT, first period; SP, second period; TP, third period)



5, 2020) was good, moderate, unhealthy for sensitive groups, and unhealthy, respectively, in 19, 143, 50, and 2 days. The corresponding values in 2019 were 36, 140, 37, and 1 days, respectively, reflecting a small shift to more unhealthy conditions in 2020.

The concentration of ozone at the beginning of 2020 was lower than that of the previous year. However, Fig. 2 shows that the ozone concentration gradually increased during the season, as conditions became more conducive to ozone formation (higher temperature and more sunlight). As a result, 2020 ozone concentration exceeded the 2019 values and eventually increased during the study period.

To clarify the effects of the measures to prevent the propagation of COVID-19 in Tehran, three time windows during the whole study period were examined.

First period: from 23 February 2020 to 15 March 2020

Although the Iranian government officially closed schools, universities, and banned religious and cultural gatherings in this period to contain the spread of COVID-19, huge crowds of people were still shopping in Tehran Grand Bazaar. Moreover, the streets leading to the bazaar were full of cars as Iranians were getting prepared for Nowruz, the New Year, which started on March 20, 2020. Traffic jams were clogging Tehran's streets as people were departing the city for a vacation. These worrying behaviors revealed that most Iranians were refusing to take social distancing seriously, squandering any chance to contain the outbreak. In this first period, during the COVID-19 pandemic, the mean concentration of O₃ decreased by 4% and the mean concentration of NO₂, SO₂, PM₁₀, and PM_{2.5} increased by 8%, 5%, 14%, and 25%, respectively, compared to the baseline period not affected by COVID-19 measures (Fig. 3a–f).

High concentrations of SLCPs in the first period can be attributed to the thermal inversion that occurs during the winter and prevents the dilution of pollutants. Available studies suggest that exposure to SO₂, NO₂, and CO is detrimental to health and increases the risk of respiratory diseases (e.g., Chen et al., 2007). The *t*-test results indicated that there was no significant difference between the mean concentration of O₃, SO₂, and CO in 2019 and 2020 (95%

confidence interval) during the first period, whereas a significant difference was observed between the mean concentration of NO₂ and PM₁₀, and PM_{2.5} as well as AQI level (*P*-value < 0.05) (Table 2).

When a person infected with the Coronavirus breathes vigorously, sneezes, coughs, and speaks loudly, the virus will be excreted from the body (Zoran et al., 2020). It may be dissolved in the aerosol and turns into bio-aerosols (Zoran et al., 2020). Atmospheric particulate matter sized 1–5 μm generally remains in the air and larger particles land on surfaces. Aerosols can travel hundreds of meters or more, whereas droplets spread about 1–2 m from the source of infection. Similar studies have shown that short-term exposure to air pollutants (i.e., O₃, NO₂, SO₂, CO, PM_{2.5}, and PM₁₀) is associated with increased risk of COVID-19 infection (Zou et al., 2020; Wu et al., 2020).

Second period: from 18 March 2020 to 3 April 2020

In the second period, the Iranian government ordered the bazaars and shopping centers across the country to be closed for the whole 17-day holiday. Only pharmacies and supermarkets were kept open. However, ignoring the recommendations of the health officials, some Iranians took trips during Nowruz holidays. During this period, the mean concentration of O₃ in Tehran increased (from 2019 to 2020) from 24.3 to 24.7 ppb (< 70 ppb) (Fig. 4a), while the mean concentrations of SO₂, NO₂, and CO in Tehran decreased from 3.45 to 3.17 ppb (< 140 ppb), from 39.5 to 29.7 ppb (< 100 ppb), and from 1.17 to 0.98 ppm (< 9.4 ppm) (Fig. 4b, c, and d), respectively. This can be attributed to the decrease in urban transport and economic activity during lockdown and Nowruz holidays. These changes are relatively small, except for NO₂ that was reduced quite substantially (by 25%). These results are consistent with the finding of Gautam (2020) who found that the NO₂ concentrations were substantially reduced in Asian and European countries after going into COVID-19 lockdown. The NO₂ reduction is likely mostly due to the reduction in traffic, which is an important source of NO_x. Cameletti (2020) also showed that the air quality considerably changed during the intervention only at a single NO₂ station located in a heavy traffic zone.

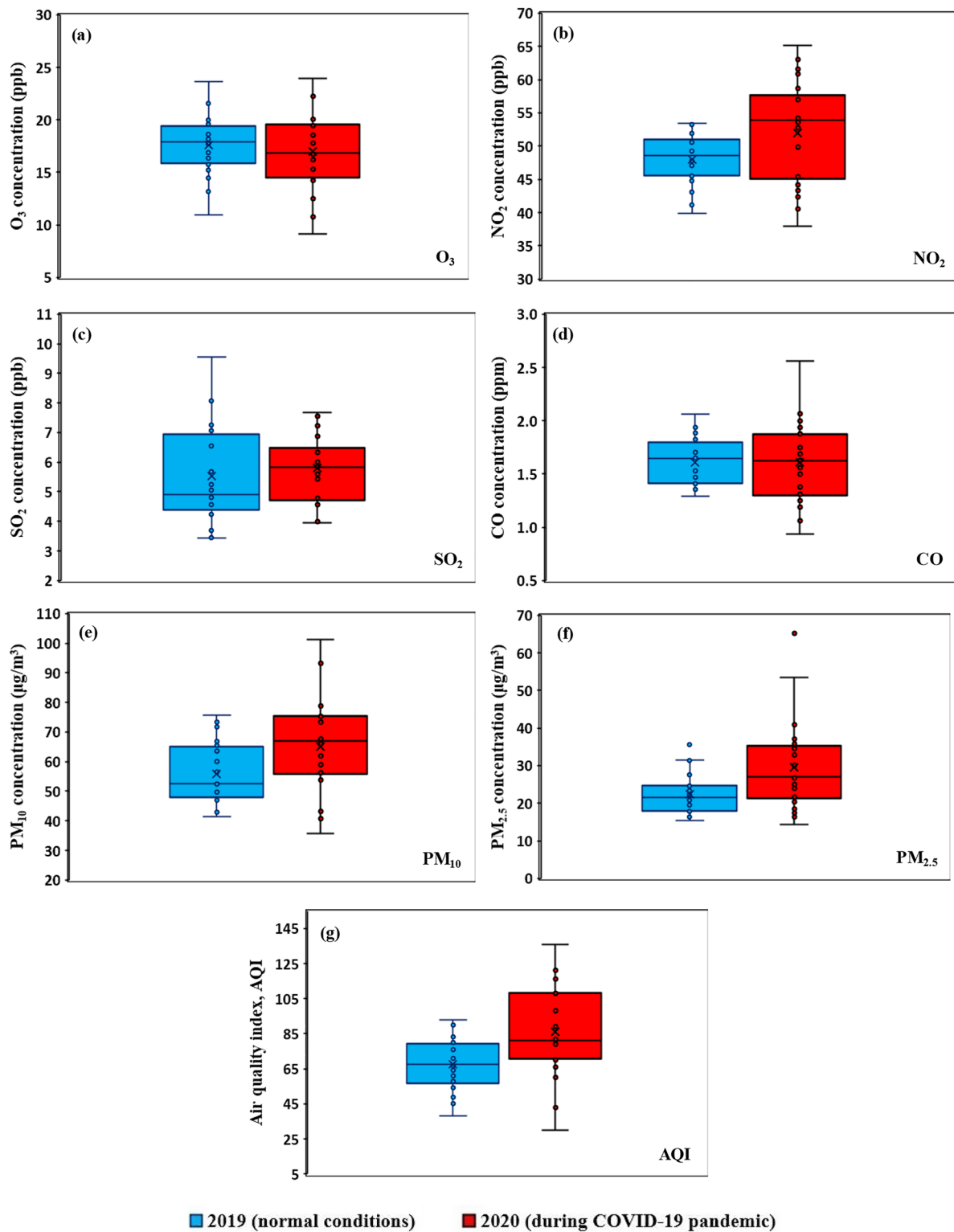


Fig. 3 Box-and-whiskers plots of the frequency distributions of daily pollutant concentrations in Tehran (average of 21 stations within the city) for 2019 and 2020 during the period 23 February to 15 March for **a** O₃, **b** NO₂, **c** SO₂, **d** CO, **e** PM₁₀, **f** PM_{2.5}, **g** AQI

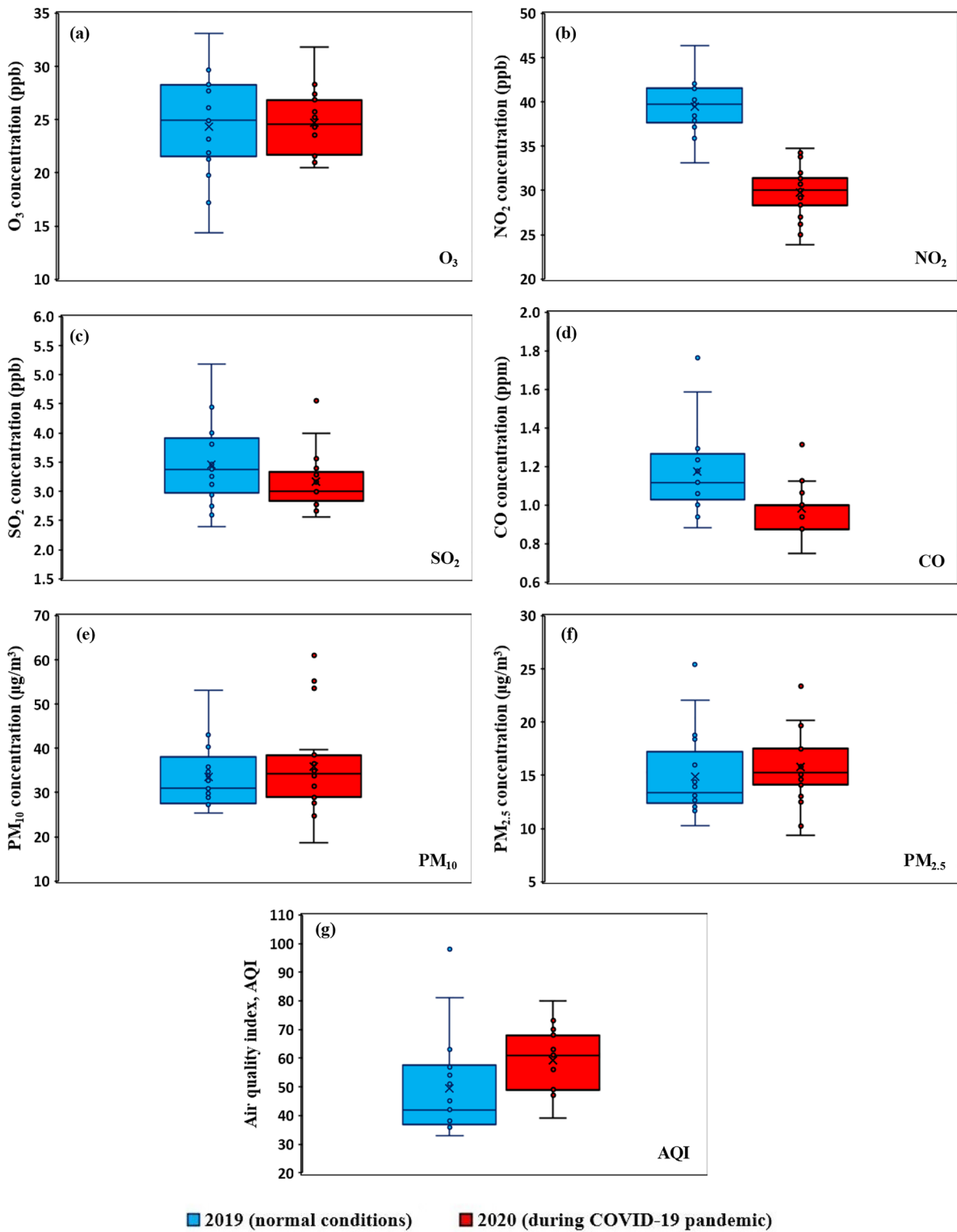


Fig. 4 Box-and-whiskers plots of the frequency distributions of daily pollutant concentrations in Tehran (average of 21 stations within the city) for 2019 and 2020 during the period 18 March to 3 April for **a** O_3 , **b** NO_2 , **c** SO_2 , **d** CO, **e** PM_{10} , **f** $PM_{2.5}$, **g** AQI

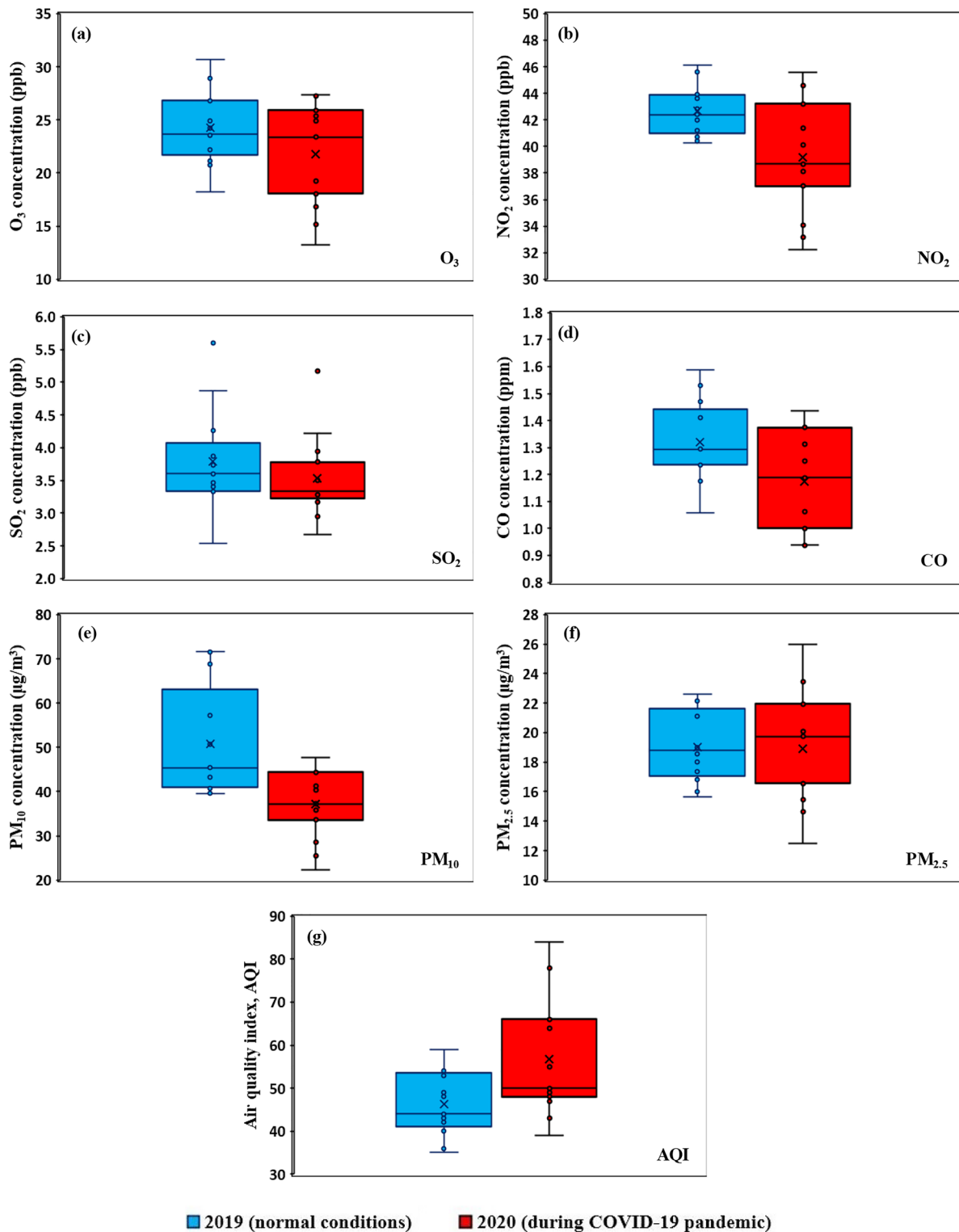


Fig. 5 Box-and-whiskers plots of the frequency distributions of daily pollutant concentrations in Tehran (average of 21 stations within the city) for 2019 and 2020 during the period 5 April to 17 April for **a** O₃, **b** NO₂, **c** SO₂, **d** CO, **e** PM₁₀, **f** PM_{2.5}, **g** AQI

The mean concentration of $PM_{2.5}$ and PM_{10} increased from 14.9 and 33.5 $\mu\text{g m}^{-3}$ to 15.8 ($< 35 \mu\text{g m}^{-3}$) and 35.9 $\mu\text{g m}^{-3}$ ($< 150 \mu\text{g m}^{-3}$) during Nowruz holidays and the Coronavirus outbreak compared to the previous year in the second period (Fig. 4e, f). As presented in Table 2, the *t*-test results related to the second period indicated a significant difference between the mean concentration of NO_2 and CO as well as AQI level (P -value < 0.05), although no significant difference was found between the mean concentration of O_3 , SO_2 , PM_{10} , and $PM_{2.5}$ in 2019 and 2020 (95% confidence interval).

Unfavorable meteorological conditions hindered the dispersion of pollutants during study period. Stationary sources can be considered one of the reasons for the increase in suspended particles. In the second period of the COVID-19 crisis, the mean value of AQI increased by about 20%, compared to the corresponding period in 2019 (Fig. 4g and Table 1). In this period, due to the low vehicle traffic in Tehran, the blowing wind from the south of Tehran was identified as the only factor increasing the index. This suggests that the pollution caused by industries and stationary sources located in the south of Tehran caused the increases in the concentration of pollutants in the second period.

Third period: from 5 April 2020 to 17 April 2020

In the third period, offices and manufacturing and service businesses reopened extensively after the Coronavirus outbreak. However, because of meteorological conditions, during third period, the mean concentration of O_3 , NO_2 , SO_2 , CO, PM_{10} , and $PM_{2.5}$ decreased by about 10%, 8%, 7%, 11%, 27%, and 1%, respectively, compared to the corresponding period in 2019 (Fig. 5a–f). On April 10, 2020, O_3 concentration decreased from 26.93 to 13.26 ppb (< 70 ppb). Due to the reduced vehicle traffic on April 10, 2020, and the establishment of favorable weather conditions, air quality was probably in a clean and healthy range. The wind speed reduction and the vehicle traffic increase after April 11, 2020, relatively increased the concentration of pollutants and, consequently, the establishment of unfavorable conditions could not be unexpected. The *t*-test results indicated that although there was no significant difference between the mean concentration of O_3 , SO_2 , and CO in 2019 and 2020 (95% confidence interval) in the third period, there was a significant difference between the mean concentration of NO_2 and PM_{10} , and $PM_{2.5}$ as well as the AQI level (P -value < 0.05) (Table 2).

Conclusions

In this study, the concentrations of air pollutants in Tehran city were obtained from 21 monitoring stations for the period from January 5, 2019, to August 5, 2019, representing a period unaffected by COVID-19 measures, and from January 5, 2020, to August 5, 2020, which was during the COVID-19 pandemic. Analyses were performed for three time windows (February 23, 2020, to March 15, 2020; March 18, 2020, to April 3, 2020, and April 5, 2020, to April 17, 2020) during lockdown when different sets of measures were taken to prevent the spread of COVID-19. During the first lockdown period, in comparison to the period not affected by COVID-19 measures, the mean concentration of NO_2 , PM_{10} , and $PM_{2.5}$ increased. The mean surface concentration of NO_2 , SO_2 , and CO decreased and that of PM_{10} and $PM_{2.5}$ increased during the second lockdown period compared to the corresponding period in 2019. In the third period, the mean concentration of O_3 , NO_2 , SO_2 , CO, and PM_{10} decreased compared to the corresponding period in 2019. In the entire period, the mean concentration of CO reduced by about 12% during the COVID-19 crisis, compared to 2019. Moreover, the concentration of NO_2 decreased by 6% during the full period.

In summary, the changes in air quality in 2020 compared to 2019 were quite modest, despite stringent COVID-19 lockdown measures in 2020. There were clear reductions in average CO and NO_2 concentrations in Tehran, mainly related to reductions in traffic emissions. On the other hand, the concentrations of ozone within the city were not reduced, and there were days with quite high pollutant levels overall, resulting in higher average values of the air quality index (AQI), corresponding to worse air quality, in 2020 than in 2019.

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Data availability The database analyzed during the present study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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