Investigating effect of COVID-19 on NO₂ density using remote sensing products (case study: Tehran province)

Nadia Abbaszadeh Tehrani1 · Farinaz Farhanj1 · Milad Janalipour1

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Abstract The first case of COVID-19 was detected in Iran on February 19, 2020. From the beginning of the pandemic, some restrictions have been imposed to reduce the spread of the pandemic, which have led to the reduction or temporary closure of some industrial, construction, and transportation sectors. These sectors are typically some sources of pollutants induced to the atmosphere. The purpose of this study was to investigate the impact of the restrictions caused by the pandemic, on the concentration of nitrogen dioxide (NO₂) in the atmosphere of Tehran province. Average daily and monthly NO₂ concentrations from the TROPOMI sensor of Sentinel-5P satellite before and after the pandemic (i.e., February 20 to August 19, 2020, and February 20 to August 19, 2019) were used. The results showed that the average NO₂ concentration in the mentioned period in 2020 was equal to 168.09 μmol/m², which compared to 2019 (195.11 μmol/m²), had a decrease of 13.85%. Therefore, the imposed restrictions to reduce the prevalence of COVID-19 in Tehran province have an impact on the temporary decrease in NO₂ concentration. It is recommended that after the end of the pandemic and the reconstruction of economic and industrial activities, measures will be taken to monitor the urban environmental loads and improve the air quality.

Keywords COVID-19 · Google earth engine (GEE) · Nitrogen dioxide (NO₂) · Remote sensing · Tehran Province

1 Introduction

The first case of COVID-19 was observed in Wuhan, China, in December 2019 [1]. Common symptoms of COVID-19 include cold, fever, dry cough, sore throat, respiratory problems, fatigue, and body aches. These symptoms often occur severe in the elderly and people with underlying diseases. The approximate latency period of COVID-19 is 14 days. Travel restrictions, quarantine, and social distancing have been implemented in many countries to reduce the prevalence of this disease [2, 3].

The first case of COVID-19 in Iran was identified in the city of Qom in February 19, 2020, and then within a week it reached 245 cases, and after two weeks, on March 5, 2020, it was spread almost in all provinces [4, 5]. From February 24, 2022, 6,998,975 people have been infected with COVID-19, and 135,726 of them have died [6]. Due to the imposed restrictions, industrial, economic, commercial, construction, and social activities have been disrupted, and for this reason, the emission of air pollutants, especially nitrogen dioxide (NO₂) has been considerably decreased [4].

NO₂ is one of the gaseous air pollutants that emits to the atmosphere mainly due to human activities such as the combustion of fossil fuels caused by urban traffic jams, industrial facilities such as power plants, and factories, and biomass fuel [7]. Some studies have concluded that NO₂ poses serious risks to human health [8, 9]. For instance, longer exposures to this pollutant decrease the immune system and increase respiratory diseases, bronchoconstriction, airway inflammation, and respiratory infections including cold, flu, sinus infection, and COVID-19 [10–12].

In Iran, the highest levels of NO₂ concentration have been recorded in Tehran, Alborz, Qazvin, and Qom provinces in 2019. The maximum and minimum average monthly values
of this pollutant have been observed in June and October, respectively [13]. In general, Gharibi and Shayesteh [13] have shown that NO$_2$ has had a declining trend in winter and summer, and a rising trend in spring.

NO$_2$ can be monitored by both ground air pollution stations, and satellite sensors. Ground-based air pollution stations measure NO$_2$ concentration on a point-by-point basis, therefore they have high accuracy but only cover the area around the stations and are unable to estimate the concentration of this pollutant at distances farther from them. Moreover, a considerable amount of money is needed for constructing, equipping, and maintaining them. Thus, it seems that satellite-based sensors that measured NO$_2$ levels with global coverage are a low-cost technology for providing these data [14]. One of these satellites is Sentinel-5P. This satellite was launched by the European Space Agency (ESA) on October 13, 2017, and orbited at an altitude of 824 km above the Earth’s surface. The TROPOMI (TROPOspheric Monitoring Instrument) imaging spectrometer mounted on this satellite is a passive nadir-viewing spaceborne sensor [15]. This sensor collects data in the ultraviolet and visible spectrum (270 to 500 nm), near-infrared (675 to 775 nm), and short-wave infrared (2305 to 2385 nm) [3]. The TROPOMI is designed to provide accurate observations for studying air quality and climate. It retrieves the concentration of pollutants in the atmosphere, including NO$_2$, SO$_2$, O$_3$, CO, formaldehyde, and methane, and the percentage of cloud cover affecting climate [2, 3, 7]. The mentioned pollutants are daily measured at a spatial resolution of 0.01 degrees (1.11 km) in atmospheric columns from the Earth’s surface to the troposphere (at a distance of 10 km from the Earth’s surface) [8, 16, 17]. The TROPOMI NO$_2$ product is produced by the global 3-dimensional Tracer Model 5—the massively parallel version (TM5-MP) chemistry transport model as a retrieval-assimilation-modeling system [18]. Some researchers have established that the accuracy of Sentinel-5P on monitoring NO$_2$ varying from 0.5 to 0.75 in Europe [19], 0.68 in Finland [15], 0.68 in Canada [20], and 0.81 in India [14]. Veefkind et al. [21] have also shown that the accuracy of Sentinel-5P on monitoring NO$_2$ meets the requirements.

At the beginning of the COVID-19 epidemic, the US National Aeronautics and Space Administration (NASA), ESA, and some researchers around the world have published several reports about the reduction of NO$_2$ emissions in countries due to the restrictions [1, 3, 22]. For example, a reduction of 70 and 20 to 30 percent in NO$_2$ emissions were observed in India and China in 2020, respectively. Moreover, NO$_2$ emissions in European countries such as Spain, Italy, and France reduced by 20 to 30% in 2020 [3]. ESA has announced that due to the reduction or non-observance of control measures in some countries and the continuation of daily activities in 2021, the emission of NO$_2$ pollutants will return to the same level of emission concentrations before the outbreak [23]. Oo et al. [3] examined the change of NO$_2$ emissions in time-series using the Sentinel-5P satellite in Thailand and Bangkok. They concluded that the concentration of this pollutant in Bangkok during the COVID-19 epidemic have decreased by 4.8%. Biswal et al. [1] investigated the impact of quarantine on the emission of NO$_2$ in India from the OMI sensor mounted on the Aura satellite. They concluded that emissions during the first to fourth weeks of the restrictions (March 25 to April 18, 2020) decreased by 12.7%, 13.7%, 15.9%, and 6.1%, respectively. Hasnain et al. [24] investigated the extent of changes in PM$_{10}$, PM$_{2.5}$, sulfur dioxide (SO$_2$), NO$_2$, carbon monoxide (CO), and ozone (O$_3$) pre-lockdown (October 1 to December 31, 2019), during lockdown (January 1 to March 31, 2020) and after lockdown (April 1 to June 30, 2020) in Nanjing, China. They concluded that lockdown reduced PM$_{10}$ and PM$_{2.5}$ pollutants by 27.71% and 5.09%, respectively. SO$_2$, NO$_2$, and CO pollutants decreased by 32.90, 34.66, and 16.85% during the lockdown, respectively. O$_3$ emissions also increased by approximately 25.45%. After quarantine, PM$_{2.5}$, PM$_{10}$, and NO$_2$ pollutants also decreased, but SO$_2$, O$_3$, and CO pollutants increased. Bassani et al. [7] examined the amount of NO$_2$ emissions using the Sentinel-5P satellite before and during the lockdown in Rome, Italy. They concluded that during the lockdown, the concentration of this pollutant decreased due to reduced urban and interurban traffic. Nakada and Urban [25] examined the air quality indicators taken from meteorological stations during restrictions due to the reduction of the prevalence of COVID-19 in the Brazilian state of Sao Paulo. The results showed a decrease of 77.3%, 54.3%, and 64.8% in NO, NO$_2$, and CO, respectively, and an increase of 30% in O$_3$ in 2020 compared to the average monthly values of the last 5 years due to the reduction of urban traffic in this state. Singh et al. [14] reported a reduction of 38% in Aerosol Optical Depth (AOD), 10% in NO$_2$, 31% in SO$_2$, 5% in CO, 55% in PM$_{2.5}$, 61% in PM$_{10}$, and 1% in methane (CH$_4$) over Haryana state in India during COVID-19 lockdown. Tehrani et al. [17] studied time series analysis of NO$_2$ from February 20, 2020, to April 19, 2020, by the Mann–Kendall test and found a significant decrease over Alborz, Bushehr, Isfahan, Qum, and Semnan provinces of Iran.

The objective of this study was to investigate the impact of the COVID-19 restrictions on the nitrogen dioxide (NO$_2$) concentration changes in Tehran province, Iran. This work has been conducted from three perspectives of the comparison of the average daily, monthly, and 6-months values of NO$_2$ during the first six months of the COVID-19 pandemic, from February 20 to August 19, 2020, compared to the same period in the previous year, February 20 to August 19, 2019. These comparisons allow policymakers to know the association between COVID-19 restrictions and air quality in one of the most polluted provinces in the world. To the best of our knowledge, this research has not been studied before in Tehran.

The remainder of this study is organized as follows: Sect. 2 introduces materials and methods used in this paper,
including the description of the study area, datasets, and methodology; Sect. 3 discusses the results of this research, and finally, Sect. 4 presents the conclusion part.

2 Materials and methods

2.1 Study area

The study area is Tehran province, central north of Iran. It is located at the latitude of 34 to 36.5 degrees North and the longitude of 50 to 53 degrees East with an approximate area of 12,981 km². According to the census conducted in 2016, the population living in it was more than 13 million (17.5% of the total population of Iran). This province has 16 cities. Trade, mining, agriculture, construction, services, industry, communications, and transportation are the main activities for earning a living. Sources of pollution in Tehran include urban and interurban traffic, industrial activities, power plants, solid fuel heating, fire, and incineration of municipal waste and agricultural waste. Figure 1 shows the geographic location of the study area in Iran and Iran’s relative position to other countries in the Middle East. It should be noted that the shape-file of the study area was taken from the Open Street Map database [26].

2.2 Data used

In this study, the mean of daily NO₂ concentrations measured in atmospheric columns by Sentinel-5P, TROPOMI for the first 6-months of COVID-19 pandemic, from February 20 to August 19, 2020, and for the same period mentioned for the previous year, from February 20 to August 19, 2019, was used to compare and evaluate the changes of NO₂ in the mentioned duration.

The Google earth engine (GEE) was used to obtain the required data in GeoTIFF format. GEE is an open-source cloud computing system with high efficiency in storing and processing a large set of calibrated geospatial data and satellite imagery in remote sensing research. GEE enables researchers and users to process, visualize, and analyze time series of remote sensing data simply and quickly [3, 8, 17].

2.3 Methodology

Environmental monitoring is an important task of remote sensing satellites. Piri et al. [27] introduced an optimal way to identify suitable regions for the medicinal plants in Bahar Mountain catchment of Jajarm using Remote Sensing (RS), Geographic Information System (GIS), and Analytic Hierarchy Process (AHP). Ardakani et al. [28] recognized the potential spatial distribution of groundwater of Semnan in Iran using RS and GIS. Malamiri et al. [29] improved the separation of agricultural spices using the fusion of Landsat 8 and Unmanned Aerial Vehicle (UAV) images in Yazd province located in Iran. Arabi Aliabad et al. [30] examined the geological map of the Yazd-Shirkooh watershed using Landsat 7 satellite images. They concluded that RS technology is an efficient tool for monitoring the urban environment.
As mentioned, restrictions regarding COVID-19 may affect on conditions of the environment [31–33]. In this study, changes in the concentration of NO2 in the air of Tehran province were studied and compared from three perspectives. In the First perspective, the changes in the time series of the average daily values of NO2 concentration over all pixels in the province during the first 6-months of the pandemic of COVID-19, from February 20 to August 19, 2020, compared to the same period in the previous year, February 20 to August 19, 2019 (Eq. 1), were discussed [34, 35].

\[ M_{t,y} = \frac{\sum_{p=1}^{P} X_{p,t,y}}{P} \quad (t = 1, 2, \ldots, 182; y = 2019, 2020; p = 1, 2, \ldots, 14053) \]

where \( t \) represents a specific day between February 20 to August 19 in 2019 and 2020 \((t = 1, 2, \ldots, 182)\), \( y \) represents the year 2019 or 2020, \( p \) represents a specific pixel of the studied area \((p = 1, 2, \ldots, 14053)\), \( P \) is the total number of pixels in the studied area \((P = 14053)\); \( M_{t,y} \) is the average daily values of NO2 concentration over all pixels in the studied area in day \( t \) of the year \( y \), and finally \( X_{p,t,y} \) is the daily value of NO2 concentration of pixel \( p \) of the studied area in day \( t \) of the year \( y \), which is obtained by GEE.

In the second perspective, the comparison of the average monthly values of NO2 concentration in each pixel of the province in 7 months between February and August (February 20 to February 29, March, April, May, June, July, and August 1 to August 19) in 2019 and 2020 (Eq. 2), and the differing values between one month in 2020 to another in 2019 (Eq. 3) were done.

\[ M_{m,y} = \frac{\sum_{t=1}^{D} X_{d,m,y}}{D} \quad (m = 1, 2, \ldots, 7; y = 2019, 2020; d = 1, 2, \ldots, \text{the numbers of days in month } m) \]

\[ \text{Difference}_{m} = M_{m,2020} - M_{m,2019} \quad (m = 1, 2, \ldots, 7) \]

where \( m \) represents a specific month between February to August 19 in 2019 and 2020 \((m = 1, 2, \ldots, 7)\); \( d \) represents a specific day of the month \( m \)

\[ \text{Mean}_{m,y} = \frac{\sum_{p=1}^{P} M_{p,m,y}}{P} \quad (m = 1, 2, \ldots, 7; y = 2019, 2020; p = 1, 2, \ldots, 14053) \]

\[ \text{Min}_{m,y} = \min \{M_{p=1,m,y} : M_{p=14053,m,y}\} \quad (m = 1, 2, \ldots, 7; y = 2019, 2020) \]

\[ \text{Max}_{m,y} = \max \{M_{p=1,m,y} : M_{p=14053,m,y}\} \quad (m = 1, 2, \ldots, 7; y = 2019, 2020) \]

\[ \text{RelativeChange}(\text{Mean}_{m,2020}, \text{Mean}_{m,2019}) = \frac{\text{Mean}_{m,2020} - \text{Mean}_{m,2019}}{\text{Mean}_{m,2019}} \times 100 \quad (m = 1, 2, \ldots, 7) \]

\[ \text{RelativeChange}(\text{Min}_{m,2020}, \text{Min}_{m,2019}) = \frac{\text{Min}_{m,2020} - \text{Min}_{m,2019}}{\text{Min}_{m,2019}} \times 100 \quad (m = 1, 2, \ldots, 7) \]

\[ \text{RelativeChange}(\text{Max}_{m,2020}, \text{Max}_{m,2019}) = \frac{\text{Max}_{m,2020} - \text{Max}_{m,2019}}{\text{Max}_{m,2019}} \times 100 \quad (m = 1, 2, \ldots, 7) \]
where in Eq. 4, Mean\textsubscript{\textit{m},\textit{y}} is the mean value of the average monthly NO\textsubscript{2} concentrations over all pixels in the province \((p = 1 : 14053)\) in month \textit{m} of the year \textit{y}, and \textit{M}\textsubscript{p,m,y} is the average monthly values of NO\textsubscript{2} concentration of pixel \textit{p} of the studied area in month \textit{m} of the year \textit{y}. In Eqs. 5, and 6, Min\textsubscript{m,y} and Max\textsubscript{m,y} represent the minimum and the maximum values of the average monthly NO\textsubscript{2} concentrations over all pixels in the province \((p = 1 : 14053)\) in month \textit{m} of the year \textit{y}. In Eqs. 7, 8, and 9, Relative\textsubscript{Change}(\textit{Mean}_{\textit{m},\textit{y}},\textit{Mean}_{\textit{m},\textit{y}}^{2019}), Relative\textsubscript{Change}(\textit{Min}_{\textit{m},\textit{y}},\textit{Min}_{\textit{m},\textit{y}}^{2019}), and Relative\textsubscript{Change}(\textit{Max}_{\textit{m},\textit{y}},\textit{Max}_{\textit{m},\textit{y}}^{2019}) are the relative change rates (%) between the mean, the minimum, and the maximum values of the average monthly NO\textsubscript{2} concentrations over all pixels in the province in 2020 compared to 2019, respectively.

In the third perspective, the 6-months average values of NO\textsubscript{2} concentration in each pixel (Eq. 10), and then over all pixels (Eq. 11) of the province during the first 6-months of the pandemic of COVID-19, from February 20 to August 19, 2020, compared to the same period in the previous year, February 20 to August 19, 2019, were examined [38].

\begin{equation}
Z_{\textit{y}} = \frac{\sum_{\textit{t}=1}^{\textit{T}} X_{\textit{ty}}}{\textit{T}} \quad (\textit{t} = 1, 2, \ldots, 182; \textit{y} = 2019, 2020) \quad (10)
\end{equation}

\begin{equation}
\textit{Mean}_{\textit{y}} = \frac{\sum_{\textit{p}=1}^{\textit{P}} Z_{\textit{py}}}{\textit{P}} \quad (\textit{p} = 1, 2, \ldots, 14053; \textit{y} = 2019, 2020) \quad (11)
\end{equation}

where in Eq. 10, \textit{t} represents a specific day between February 20 to August 19 in 2019 and 2020 (\textit{t} = 1, 2, \ldots, 182); \textit{T} represents the total number of days between February 20 to August 19 (\textit{T} = 182). \textit{Z}_{\textit{y}} is the 6-months average values of NO\textsubscript{2} concentration in each pixel of the province in the year \textit{y}, and finally, \textit{X}\textsubscript{\textit{ty}} is the daily values of NO\textsubscript{2} concentration in day \textit{t} of the year \textit{y}. In Eq. 11, \textit{Mean}_{\textit{y}} is the 6-months average values of NO\textsubscript{2} concentration over all pixels in the province \((p = 1, 2, \ldots, 14053)\).

In this perspective, the relative change rates (%) between the 6-months average values of NO\textsubscript{2} concentration in each pixel of the province in 2020 compared to 2019 were also calculated using Eq. 12 [36, 37].

\begin{equation}
\text{Relative\textsubscript{Change}}(Z_{2020}, Z_{2019}) = \frac{Z_{2020} - Z_{2019}}{Z_{2019}} \times 100 \quad (12)
\end{equation}

where \textit{Z}_{2019} and \textit{Z}_{2020} are the 6-months average values of NO\textsubscript{2} concentration in each pixel of the province in 2019 and 2020, respectively; and \text{Relative\textsubscript{Change}}(Z_{2020}, Z_{2019}) is the relative change rates (%) between the 6-months average values of NO\textsubscript{2} concentration in 2020 compared to 2019. It should be noted that in all studies, the values of NO\textsubscript{2} pollutant in units of mol/m\textsuperscript{2} are multiplied by \textit{10}\textsuperscript{6} and converted to μmol/m\textsuperscript{2}.

The high absolute rates of the relative changes indicate the high deviation in NO\textsubscript{2} values in 2020 compared to 2019. In a normal situation, it is expected that the relative change rates during the COVID-19 restrictions will be negative with high absolute values. Relative change in addition to indicating changes in NO\textsubscript{2} emissions also eliminates the cumulative or multiplicative deviations of the NO\textsubscript{2} concentrations retrieved by the TROPOMI sensor [37].
3 Results and discussion

The time series of the average daily values of NO$_2$ concentration over all pixels in Tehran province during the first 6-months of the pandemic of COVID-19, from February 20 to August 19, 2020, compared to the same period in the previous year, February 20 to August 19, 2019, (the first perspective) is shown in Fig. 2. The vertical axis represents the average daily values of NO$_2$ concentration in $\mu$mol/m$^2$ and the horizontal axis represents the time of the study period, from February 20 to August 19. The time series of changes in daily NO$_2$ concentrations and the trend of changes in 2019 and 2020 are marked in blue and red, respectively. A decrease in NO$_2$ concentrations in the months of February to August in both 2019 and 2020 is seen, because the concentration of this pollutant in the cold seasons of the year (February 20 to March 19) is higher as compared to the warm seasons (March 20 to August 19). It is also observed that the amount of NO$_2$ concentration in February 2020 compared to February 2019 in Tehran province has been significantly reduced. The range of this pollutant in February 2019 and 2020 was $[153.431-520.014]$ and $[103.639-305.613]$ $\mu$mol/m$^2$ respectively. A decrease in NO$_2$ concentration is observed in March 2019 and 2020. Because of the new year’s holiday and traveling outside the cities by most of the residents and as a result of reducing urban traffic congestion, the concentration of air pollutants has decreased. NO$_2$ emissions in March 2020 have decreased significantly compared to 2019, which can be due to quarantine restrictions and limitations on reducing the prevalence of COVID-19. The range of changes in the concentration of this pollutant in this month in 2019 was $[114.192-812.096]$ $\mu$mol/m$^2$ and in 2020 was $[101.581-332.296]$ $\mu$mol/m$^2$.

Figure 2 also reveals that the changes in NO$_2$ emissions in April to August of 2019 and the same months in 2020 were not significant, with NO$_2$ concentration values ranging from 100 to 200 $\mu$mol/m$^2$ on most days of these five months. The average total daily values of NO$_2$ concentration in the studied period (February 20 to August 19) throughout Tehran province for 2019 and 2020 were $[179.376-157.313]$ $\mu$mol/m$^2$. The concentration over all pixels in Tehran province during the first 6-months of the pandemic of COVID-19, from February 20 to August 19, 2020, compared to the same period in the previous year, February 20 to August 19, 2019, (the second perspective). In these figures, the amount of changes in the average monthly concentration of NO$_2$ is shown from green to red. Green and red indicate lower and higher levels of NO$_2$ in atmospheric columns, respectively. It can be concluded that the main emission of NO$_2$ is in the center of Tehran and the surrounding cities, namely Shemiranat, Pardis, Pakdasht, Islamshahr, Quds, and Shahriyar. The maximum monthly average concentration of NO$_2$ in February 2019 (Fig. 3a) reached 2085.49 $\mu$mol/m$^2$ in the eastern region of Tehran, which after the epidemic of COVID-19 (Fig. 3b), its maximum value reached 1671.87 $\mu$mol/m$^2$. In contrast, in general, the emission of NO$_2$ in cities located on the eastern, western, and southern borders of the province, namely Firoozkooh, Varamin, Rey, and Mallard is less than in other cities. From the average monthly NO$_2$ levels in February 2019 and 2020, it can be concluded that the imposed restrictions have reduced the emission of NO$_2$ in the cities of Shemiranat, Pardis, Damavand, Rey, and Robat Karim. The rate of emission of this pollutant in February 2020 compared to February 2019 in the cities of Tehran, Pakdasht, Qarchak, Quds, and Shahriyar was still high. In March 2020 (Fig. 3d), compared to March 2019 (Fig. 3c), we have observed a greater decrease in the emission of NO$_2$ in most cities of Tehran province, especially in Tehran, Shemiranat, Pardis, Islamshahr, Quds, Shahriyar, Damavand, and Mallard. The average monthly emissions of this pollutant in April 2020 (Fig. 3f) compared to April 2019 (Fig. 3e), have not increased or decreased significantly, and in these months, the NO$_2$ concentration in Tehran and south of Shemiranat was higher than in other cities. In May 2020 (Fig. 3b), a significant decrease in NO$_2$ emissions in Tehran compared to May 2019 (Fig. 3g) is observed. In June 2020 (Fig. 4b), compared to June 2019 (Fig. 4a), NO$_2$ emissions in all cities of Tehran province except Pakdasht have not increased or decreased significantly. In July 2020 (Fig. 4d), an approximate increase of NO$_2$ in Tehran and Pakdasht is observed. In contrast, in August 2020 (Fig. 4f), compared to August 2019 (Fig. 4e), NO$_2$ emissions in Tehran and Pakdasht are reduced. Overall, Fig. 3 and Fig. 4 reveal that the NO$_2$ emission rate in the cold months of the year during the study period, February and March, was higher than the warm months of the study period, i.e., April, May, June, July, and August. Pollutant concentrations in June and July were lower than in other months in most cities of Tehran province. It can also be concluded that the emission of this pollutant in general in the first 6-months of the pandemic of COVID-19 in 2020 was lower than the same period of these months in 2019.

Figure 5 shows the spatial distribution of the differing values of NO$_2$ concentration between one month in 2020 to another in 2019. In February (Fig. 5a), the NO$_2$ differing values ranged from $-1464.85$ at Pardis, Shemiranat, and Tehran to 439.59 $\mu$mol/m$^2$ at Quds. In March (Fig. 5b), these values ranged from $-498.21$ at Tehran, western regions of Shemiranat and Islamshahr to 100.08 $\mu$mol/m$^2$ at southern regions of Shemiranat and Pardis. In April (Fig. 5c), these values ranged from $-115.40$ in central regions of Tehran and Pardis to 95.98 $\mu$mol/m$^2$ at Shemiranat. In May (Fig. 5d), these values ranged from -112.91 at Tehran, Shemiranat,
and Pardis to 46.71 μmol/m² at Pakdasht. In June (Fig. 5e), these values ranged from -63.70 in the western regions of Tehran to 159.50 μmol/m² at Pakdasht and Pardis. In July (Fig. 5f), these values ranged from -50.95 at central regions of Pakdasht to 173.57 μmol/m² at central regions of Tehran, eastern regions of Pakdasht, and Robat Karim. In August (Fig. 5g), these values ranged from -149.26 at Tehran, Shemiranat, and eastern regions of Pakdasht to 90.44
μmol/m² at western and central regions of Pakdasht. Overall, Fig. 5 reveals that the spatial distribution of the differing values of NO₂ concentration did not have the same pattern in the cities in months.

Results related to the mean, the minimum, and the maximum values of the average monthly NO₂ concentrations over all pixels in Tehran province, and the relative change rates (%) between them for each month in 2020 compared to 2019 are given in Table 1. As can be seen, on February 20–29, 2020, a significant decrease of 28.13, 16.35, and 28.31% in the minimum, maximum and average values of this pollutant, respectively, compared to February 20–29, 2019 is observed. Decreases of 14.39%, 18.36%, and 22.50% are observed in the minimum, maximum, and average monthly NO₂ values in March 2020 compared to March 2019, respectively. In April 2020, there is a decrease of 13.04% in the minimum, 1.72% in the maximum, and 9.91% in the average amount. Also in May 2020, a decrease of 14.57, 16.02, and 11.18% in the minimum, maximum, and average monthly values of NO₂ pollutants compared to May 2019 is concluded. In June and July 2020, an increase of 2.21 and 9.96% of the maximum amount, and 7.91% and 4.37% of the average amount of this pollutant have been seen compared to June and July 2019, respectively. The amount of NO₂ from August 1 to 19, 2020 compared to August 1 to 19, 2019 has decreased again (a decrease of 9.58% in the minimum, 14.08% in the maximum, and 9.58% in the average amount). The highest decrease in the average monthly values of NO₂

Fig. 4 The spatial distribution of the average monthly values of NO₂. June, a 2019, b 2020, July, c 2019, d 2020, August, e 2019, and f 2020
is observed in February, followed by March. Therefore, it can be concluded that the COVID-19 restrictions, reduction of industrial and construction activities, and traffic jams have decreased NO₂ emissions in the atmosphere [24].

The average 6 month value of NO₂ concentration over Tehran province in the period from February 20 to August 19, 2020, was equal to 195.11 μmol/m² and in 2020 after the outbreak of the COVID-19 pandemic in the same period was equal to 168.09 μmol/m². Therefore, in the study period, a 13.85% decrease in the concentration of NO₂ in 2020 compared to 2019 throughout Tehran province was observed. The 6-months average values of NO₂ concentration in each pixel of the studied area during the first 6-months of the pandemic of COVID-19, from February 20 to August 19, 2020, compared to the same period in the previous year, February 20 to August 19, 2019 (the third perspective), are shown in Fig. 6a and Fig. 6b, respectively. From the average 6 month values of NO₂ in 2019 and 2020, it was concluded that the average NO₂ levels in Shemiranat, Pardis, and surrounding areas of Tehran were more than in

Fig. 5 The spatial distribution of the differing values of NO₂ concentration between one month in 2020 to another in 2019. a February, b March, c April, d May, e June, f July, and g August
other cities in Tehran province during the pandemic. The relative change rates between the 6-months average values of NO₂ concentration in each pixel of the Tehran province in 2020 compared to 2019 is shown in Fig. 6c. The relative change values of this pollutant in 2020 compared to 2019 show the largest decrease in the average 6 month NO₂ levels with a darker red spectrum. From this figure, it can be concluded that the range of relative changes in the average 6 month NO₂ values in 2020 compared to 2019 in Tehran province was -57.64% and 26.87%. It is clear that the concentration of NO₂ in most areas of Tehran province has been decreased. It is also concluded that the highest decrease in the average 6 month values of this pollutant is observed in the southern regions of Shemiranat and the central regions of Tehran counties and then in the Qarchak and the eastern regions of Rey counties. It can also be concluded that the concentration of NO₂ has increased only in the northern regions of Shemiranat.

The results of this study are consistent with the results of other researches. For example, Paital et al. [39] concluded in their study that restrictions on reducing the prevalence of COVID-19 and quarantine have decreased the

Table 1 The mean, the minimum, and the maximum values of the average monthly NO₂ concentrations over all pixels in Tehran province, and the relative change rates (%) between them for each month in 2020 compared to 2019

| NO₂ concentrations | Minimum (µmol/m²) | Relative change of minimum compared to 2019 (%) | Maximum (µmol/m²) | Relative change of maximum compared to 2019 (%) | Mean (µmol/m²) | Relative change of mean compared to 2019 (%) |
|--------------------|-------------------|-----------------------------------------------|-------------------|-----------------------------------------------|----------------|-------------------------------------------|
| February           | 71.82             | 51.62                                         | -28.13            | 2085.49                                       | 338.64         | -28.31                                     |
| March              | 67.14             | 57.48                                         | -14.39            | 1281.31                                       | 268.13         | -22.50                                     |
| April              | 71.93             | 62.56                                         | -13.04            | 548.78                                        | 163.61         | -9.91                                      |
| May                | 75.36             | 64.39                                         | -14.57            | 533.01                                        | 160.52         | -11.18                                     |
| June               | 71.76             | 70.22                                         | -2.15             | 434.07                                        | 136.39         | 7.91                                       |
| July               | 71.87             | 63.85                                         | -11.16            | 393.44                                        | 135.83         | 4.37                                       |
| August             | 69.53             | 62.87                                         | -9.58             | 565.82                                        | 162.68         | -9.58                                     |

Fig. 6 The 6-months average values of NO₂ concentration, a during the COVID-19, from February 20 to August 19, 2020, and b the same period in the previous year, 2019, and c the relative change rates
emission of air pollutants, especially NO$_2$, in many polluted cities around the world. It has also been concluded that the imposed restrictions have reduced the amount of NO$_2$ emissions in the cities of Mashhad, Tabriz, Isfahan, and Tehran located in Iran [40], Lagos, Ibadan, Kano, Abuja, Owerri, and Onitsha located in Nigeria [8], Delhi, Haryana state, and Indo-Gangetic plain located in India [14, 37, 41], Islamabad located in Pakistan [42], Madrid, Valencia, and Barcelona located in Spain, Milano in Italy, Paris in France, London in United Kingdom, Frankfurt in Germany [19, 43], and Afghanistan, Sri Lanka, and Bangladesh located in South Asia [2].

4 Conclusion

In this paper, the impact of imposed restrictions to reduce the spread rate of COVID-19 on NO$_2$ emissions from the Sentinel-5P satellite in Tehran province were investigated. From the first perspective, it was concluded that the average daily levels of NO$_2$ pollutants in the period from February 20 to August 19 in 2020 have decreased compared to the same period in 2019 throughout Tehran province, especially in February, March, and April. The results of the second perspective showed that the average levels of this pollutant in February, March, April, May, and August 2020 decreased by 28.31, 22.50, 9.91, 11.18, and 9.58%, respectively, compared to the same months in 2019. The results of the third perspective indicated that the average 6 month concentrations of this pollutant in the Tehran province in the period from February 20 to August 19, 2020, and in the same period in 2019, were 168.09 μmol/m$^2$ and, 195.11 μmol/m$^2$, respectively. The highest rate of reduction of NO$_2$ was observed in the southern regions of Shemiranat, the central regions of Tehran, Qarchak, and the eastern regions of Rey counties. Therefore, in general, it can be deduced that the restrictions imposed to reduce the prevalence of COVID-19 such as travel restrictions, night-time traffic ban, social distancing, closure of schools, universities, and some businesses, telecommuting, traffic restrictions, and reduction of industrial, economic, construction, and other daily human activities decrease the average concentration of tropospheric NO$_2$ pollutants by 13.85% throughout Tehran province.

One of the limitations of this work is that the validation of the Sentinel 5-P satellite-based NO$_2$ concentration product has not been done using ground-based measurements of the air pollution stations of the study area. However, because in this study, the comparison of the NO$_2$ concentration at different times has been considered, it seems that the use of only satellite-based data has not had a significant impact on the final results. In addition, our precaution in the absence of the ground-based measurements was to compute relative change rates between the values of the NO$_2$ concentrations to eliminate systematic cumulative or multiplicative deviations in the Sentinel 5-P satellite derivations. For more accurate results, it is suggested to validate NO$_2$ concentration retrieved from Sentinel 5-P in the study area. It is also suggested that the values of the relative monthly changes of this pollutant during the pandemic will be compared to its average values over a longer period of five years or more. Furthermore, the extent of changes in biomass burning, which is one of the main sources of NO$_2$ emissions, be examined during the COVID-19 epidemic and previous years. The results of this research can be helpful for planning strategies to reduce air pollution and improve environmental conditions. It should be noted that the reduction of NO$_2$ emissions during COVID-19 is a short-term and temporary change.

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Data availability The data will be available on request to the corresponding author.

Code availability The code will be available on request to the corresponding author.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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