Spatiotemporal Analysis of NO₂ Production Using TROPOMI Time-Series Images and Google Earth Engine in a Middle Eastern Country

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Abstract: Like many developing countries, Iran faces air pollution, especially in its metropolises and industrial cities. Nitrogen dioxide (NO₂) is one of the significant air pollutants; therefore, this study aims to investigate the spatiotemporal variability of NO₂ using Tropospheric Monitoring Instrument (TROPOMI) sensor mounted on the Sentinel-5P (S5P) satellite and the Google Earth Engine (GEE) platform over Iran. In addition, we used ground truth data to assess the correlation between data acquired by this sensor and ground stations. The results show that there is a strong correlation between products of the TROPOMI sensor and data provided by the Air Quality Monitoring Organization of Iran. The results also display that the correlation coefficient (R) of NO₂ between ground truth data and the TROPOMI sensor varies in the range of 0.4 to 0.92, over three years. Over an annual period (2018 to 2021) and wide area, these data can become valuable points of reference for NO₂ monitoring. In addition, this study proved that the tropospheric NO₂ concentrations are generally located over the northern part of Iran. According to the time and season, the concentration of the tropospheric NO₂ column shows higher values during winter than in the summertime. The results show that a higher concentration of the tropospheric NO₂ column is in winter while in some southern and central parts of the country more NO₂ concentration can be seen in the summertime. This study indicates that these urban areas are highly polluted, which proves the impact of pollutants such as NO₂ on the people living there. In other words, small parts of Iran are classified as high and very highly polluted areas, but these areas are the primary location of air pollution in Iran. We provide a code repository that allows spatiotemporal analysis of NO₂ estimation using TROPOMI time-series images within GEE. This method can be applied to other regions of interest for NO₂ mapping.

Keywords: air pollution; spatiotemporal analysis; tropospheric NO₂ concentration; Sentinel-5P; Google Earth Engine

1. Introduction

The World Health Organization (WHO) has defined air pollution as a factor that disrupts the balance in society [1], as well as population and technological growth; moreover, improper use of natural resources can cause adverse consequences such as air quality degradation [2]. Deliberate release of air pollutants because of the origin and evolution of humankind has intensively changed the face of the Earth, and in some aspects, it has reduced air quality [3]. Urbanization and economic growth result in rapid change and noticeable air pollution in countries [4]. Urban air pollution is impacted by several factors such
as temperature, wind, precipitation, population, pollutants, excessive use of fossil fuels, and inefficient urban transportation systems [5]. Motor vehicles are one of the most significant sources of air pollution and release different chemical gases, among which is NO2, one of the most well-known air pollutants that significantly impact atmospheric chemistry.

Ozone (O3) is another pollutant in the atmosphere. O3 is caused mainly by reactions between photochemical nitrogen oxide (NOx = NO + NO2) and volatile organic compounds (VOCs), and a high concentration of NOx is combined with very fine particles. As a result, fog, photochemical smoke, and acid rain are produced, which endanger human health [6]. Apart from these effects, NOx absorbs some part of solar irradiance, reduces atmospheric visibility, and can lead to climate change [7]. In addition, NO2, as one of the most important pollutants in the troposphere, directly or indirectly impacts human health (respiratory or cardiovascular diseases) and changes the ecosystem destructively [8,9]. Consumption of fossil fuels, biomass burning, and lightning are the primary sources of NO2 production [10,11]. Vehicles, power plants, and industries are other sources that produce NO2 [12]. The highest amounts of nitrogen are found in the most populous and industrialized regions of the world, such as eastern regions of China, western countries of Europe, eastern parts of the United States, and India [13,14]. A severe increase in NO2 pollution is because of the growing number of industrial sites and traffic volume [15]. Many factors might cause NO2 concentration over space and time [16,17]. Air pollution monitoring is one of the essential issues that should be considered in monitoring and managing air pollutants in metropolises and countries. However, the installation and maintenance of many monitoring stations impose high costs on municipalities and governments. Furthermore, air pollution is rapidly varying over space and time; in other words, it is a spatiotemporal problem. As a result, researchers are looking for a method to simultaneously monitor air quality that covers high temporal and spatial resolution. Although ground stations can measure air quality in high spatial and temporal resolution, they can measure limited areas close to their locations, and their numbers directly impact the final results [18]. In recent decades, remote sensing (RS) has become a reliable source for earth observations such as soil erosion [19], land use and land cover change maps [20–22], and urban study [23–25]. Remotely sensed data can usually provide global coverage and make it possible to measure various parameters such as air pollution, emission of gases, and suspended particles in the atmosphere, without direct contact with these phenomena [26].

In the last two decades, numerous studies have been performed to monitor NO2 pollutants using RS [6,7,27–33]. The temporal and spatial changes in NO2 were monitored in China from 2005 to 2018 using the Ozone Monitoring Instrument (OMI) sensors [6]. The annual concentration of NO2 was studied in southeastern Ukraine using a Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) [34]. In addition for studying the spatiotemporal variations in this pollutant, several studies have been conducted on the origin of these gases in different world regions. Based on analyzing the Airborne PRISM Experiment (APEX) sensor data in the city of Zurich, a highly NO2-polluted area was observed in the central urban area and landfill areas [35]. Another study in China introduced industrial activities as the main factor behind NO2 production, and power plants, traffic, and residential resources are other factors producing this gas [36]. In another study, NO2 concentration was studied in China between 1996 and 2005 using SCIAMACHY and Global Ozone Monitoring Experiment (GOME) sensors. The results of this study indicate that the concentration of the tropospheric NO2 column in the eastern part of China is higher than that in the western part of this country due to the high density of population and industrial sites [37].

Given that NO2 is one of the most critical components of air pollution in metropolitan areas and industrial cities and sites, the assessment of this pollutant at the national level in developing and industrialized countries such as Iran is very important for monitoring air pollution [38]. Iran is one of the developing countries in which the level of air pollutants has gradually increased since the beginning of the industrialization of the country in the 1970s until now. The air pollution level has reached a critical level in some of its major
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2. Materials and Methods

2.1. Study Area

Iran is an oil-based economy. The country is 1.87 million km² and is located in the Middle East. Figure 1 shows the digital elevation model (DEM) and air pollution measuring stations. The range of temperature spans from −36 to 60 centigrade. The precipitation range varies from less than 25 mm in Bam city to more than 2000 mm in Anzali, and the long-term mean precipitation value is about 250 mm. The climate of the country is mainly covered by an arid and semi-arid climate, and the Zagros and Alborz Mountain ranges have a semi-arid environment. Iran is the first country responsible for climate change in the Middle East, approximately releasing up to 616,741 million tons of carbon dioxide (CO₂) yearly [44]. The high-level contribution of Iran to greenhouse gas emissions is because of significant rapid urbanization and the production of gas and oil [44].

Figure 1. Study area.
2.2. Data Description

In this study, we used TROPOMI, ground station data between 2018 and 2021, population data, and the location of industrial cities and sites. More details about these datasets are described in Table 1. Additionally, the thematic maps of population density and the number of industrial units in each county can be seen in Figure 2.

Table 1. Description of datasets included in the study.

| Name                             | Dataset Provider                  | Dataset Availability | Range                                  |
|----------------------------------|-----------------------------------|----------------------|----------------------------------------|
| Copernicus Sentinel-5P           | European Union/ESA/Copernicus     | 2018 to 2021         | 0 to 20 \(10^{15}\) molecules cm\(^{-2}\) |
| Ground air quality data          | Air Quality Control Monitoring Organization | 2018–2021 | 0 to 120 µg/m\(^3\)                     |
| Population                       | Statistical Center of Iran        | 2016                 | 7402 to 8,737,510 persons per county   |
| Industry                         | OpenStreetMap (OSM)               | 2020                 | 0 to 114 industrial units in the counties |

Figure 2. Data used: (a) the population density (person per km\(^2\)) and (b) the number of industrial units in Iran.

2.2.1. TROPOMI (S5P)

In recent years, the TROPOMI instrument mounted on the S5P satellite has become one of the most used sensors for air pollution monitoring. S5P was launched on 13 October 2017 as a part of the Copernicus space program series of the European Space Agency (ESA). TROPOMI sensor monitors Earth in ultraviolet and visible (270–495 nm), near-infrared (675–775 nm), and short-infrared wavelength intervals (2305–2385 nm), using a push-broom scanner [45,46]. NO\(_2\), O\(_3\), SO\(_2\), and HCHO can be retrieved using this sensor’s ultraviolet and visible range. This sensor provides high spatial resolution, global coverage, and a low signal-to-noise ratio (SNR). It also provides high spatial, temporal, and spectral resolution than previously launched sensors such as OMI and SCIAMACHY [47,48].
2.2.2. Ground Air Quality Data

In this study, we obtained air quality data provided by the Iran Air Pollution Monitoring System (APMS), which are publicly available through their website (see https://aqms.doe.ir (accessed on 15 October 2021 for details)). In total, 130 stations are available in Iran, and most of these stations are located in megacities of Iran (e.g., Tehran, Isfahan, Tabriz, and Ahvaz). In general, Middle Eastern countries have a limited number of air quality stations, and the distribution of these stations does not match land use, dispersion dynamics of each pollutant. These stations are mainly limited to major metropolitan cities in these countries. The statistics in Table 2 show that nearly half of these stations in our study area are in Iran, located in metropolitan cities. Therefore, air pollution assessment using terrestrial data alone cannot be representative of the pollution situation in the whole country. Therefore, using RS products along with ground station observations data can play an important role in monitoring and completing the data. The locations of these stations are depicted in Figure 1 with blue markers. We compared the retrieved NO\textsubscript{2} using TROPOMI data with ground air quality data. Table 2 displays more details about the validation data used in this study. In total, the number of ground observations taken for atmospheric NO\textsubscript{2} validation was equal to 1188 observations, of which 161, 378, 398, and 256 observations were belonged to the years, 2018, 2019, 2020, and 2021, respectively.

Table 2. Statistics of validation points.

| City Name | Number of Stations | Number of Observations (2018 to 2021) | Average NO\textsubscript{2} (µg/m\textsuperscript{3}) | Standard Deviation (µg/m\textsuperscript{3}) |
|-----------|--------------------|--------------------------------------|-----------------------------------------------|---------------------------------------------|
| Tehran    | 23                 | 478                                  | 59                                            | 25                                          |
| Isfahan   | 16                 | 22                                   | 13                                            | 9                                           |
| Tabriz    | 8                  | 36                                   | 31                                            | 13                                          |
| Ahvaz     | 5                  | 15                                   | 22                                            | 21                                          |
| Total     | 52                 | 551                                  | 31                                            | 17                                          |

2.3. NO\textsubscript{2} Retrieval Using TROPOMI

Satellite RS is a widely used approach to monitor NO\textsubscript{2} pollution worldwide [49]. TROPOMI is one of the newest sensors capable of monitoring the amount of NO\textsubscript{2} in the atmosphere. The TROPOMI NO\textsubscript{2} data used in this research are based on the algorithm developed for the DOMINO-2 product and the EU QA4ECV NO\textsubscript{2} [50]. In this study, the concentration of the tropospheric NO\textsubscript{2} column was processed using the GEE platform. Additionally, we used the GEE platform (see https://earthengine.google.com (accessed on 15 October 2021 for details)) for part of our processing that includes resampling of pixels (nearest-neighbor methods used by default), converting the format, clipping data, filtering the data, retrieving time series, and generating monthly averaged data.

2.4. Accuracy Assessment

Accuracy validation is an essential part of any RS research project. We compared the satellite product with available ground air quality stations [51]. In this study, validation was performed using the correlation coefficient (R) of ground truth data with the TROPOMI product. The R formula compares our fitted regression line with a baseline model. Equation (1) is a mathematical formula for calculating the coefficient of determination index [52], which is defined as

$$ R = \sqrt{1 - \frac{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{N}(y_i - \bar{y})^2}} $$

where \(y_i\) is the actual value, \(\hat{y}\) is the predicted value of \(y_i\) (SSP data), and \(\bar{y}_i\) is the mean of the \(y_i\) values.
Figure 3 illustrates the research workflow. This workflow consists of the following four parts: (1) processing data from the GEE Database, APMS, and OSM; (2) accuracy validation; (3) processing data, including extracting time series and calculating monthly average tropospheric NO$_2$ column using coding in GEE platform; (4) investigating the relationship between NO$_2$ pollution, location of industrial cities and sites, and population density.

![Flowchart methodology of this research](image)

3. Results

In this research, we used the GEE platform to preprocess and analysis monthly average images of tropospheric NO$_2$ column concentration from September 2018 to August 2021. We used ground air quality stations to evaluate our results. For validating TROPOMI NO$_2$, we calculated the correlation between the tropospheric NO$_2$ column data retrieved by TROPOMI (unit of values are $10^{15}$ molecules cm$^{-2}$) and ground station data for each month. We then estimated the spatiotemporal variation in NO$_2$ over Iran using the GEE platform.

3.1. Correlation between NO$_2$ Surface Concentration (APMS) and TROPOMI NO$_2$

Thus far, several studies have been performed to prove the correlation of the tropospheric NO$_2$ column concentration from RS data with terrestrial data. Correlation coefficients greater than 0.91 were obtained in this research, which indicates that satellite images and products have reasonable accuracy. They can describe the characteristics of the atmosphere (such as cloud cover, aerosol, and air pollutants) with reasonable accuracy [11,53,54].

To evaluate the results, we used the APMS data in Iran as a surface NO$_2$ data source. For this purpose, we calculated the correlation between terrestrial and satellite data in four seasons, and the results are presented in Figure 4. The results showed that the highest and lowest correlations between RS images and terrestrial data were observed in spring and autumn, respectively. The results showed that the seasonal and monthly correlation between terrestrial data and satellite observations fluctuates from 0.74 to 0.90 and 0.4 to...
0.92, respectively. The results in Figure 4 show that the concentration of the tropospheric NO$_2$ column data extracted using the TROPOMI sensor is highly correlated with the air quality monitoring stations data. In the autumn season, fewer ground-level monitoring stations were active; so there were fewer observations for calculating correlation and this issue caused lower correlation values (especially in October and November).

![Figure 4](image-url)

**Figure 4.** The regression between ground NO$_2$ data (µg/m$^3$) and TROPOMI tropospheric NO$_2$ column concentration (10$^{15}$ molecules cm$^{-2}$) at different times of the year. (a) Spring. (b) Summer. (c) Autumn. (d) Winter. (e) monthly scale (black line in the chart is the trend line for NO$_2$).
3.2. Spatiotemporal Characteristics of Tropospheric NO$_2$ Columns

Figure 5 shows the monthly map of the tropospheric NO$_2$ columns from September 2018 to August 2021. In Iran, the concentration of the tropospheric NO$_2$ column is significant in the northern areas and drops in the southern parts. The results indicate that most regions of the study area have less concentrations than 10$^{15}$ molecules cm$^{-2}$ (such as Sistan and Baluchestan, Kerman, Hormozgan, and South Khorasan). These areas are mainly located in the southern and central parts of Iran and have low rainfall, hot and dry climate, severe temperature changes, and are often located in flat and low plains. In addition, due to the lack of urban development and climate conditions, these areas are less populated, and industrial activities are very low. Therefore, in these areas, the tropospheric NO$_2$ column concentration is often small.

![Figure 5. Iran's monthly tropospheric NO$_2$ column concentration (10$^{15}$ molecules cm$^{-2}$) (2018–2021).](image)

Figure 6 shows seasonal variations in the tropospheric NO$_2$ column concentrations. Considering the climatic condition as well as the location of Iran in the Northern Hemisphere, the seasons in this paper are as follows: Spring (March, April, and May), Sum-
mer (June, July, and August), Autumn (September, October, and November) and Winter (December, January, and February). As Figure 6 shows, the seasonal average of the tropospheric NO$_2$ column concentration is high in winter and low in summer and spring. This part of the results is consistent with other studies [53–56]. Because of various factors such as the type of air pollution, some results might be different [57]. The results also indicate that the lowest values of NO$_2$ concentration were observed in May and April ($0.16 \times 10^{15}$ molecules cm$^{-2}$), and the lowest values were detected during December and January ($0.3 \times 10^{15}$ molecules cm$^{-2}$), the values of which are shown in Table 3. Additionally, examination of changes in monthly values of tropospheric NO$_2$ columns in Iran shows that significant changes in the amount of this gas are observed in different months (Table 3).

Figure 6. Seasonal tropospheric NO$_2$ column concentration ($10^{15}$ molecules cm$^{-2}$) in Iran (2018–2021), Spring (March, April, and May); Summer (June, July, and August); Autumn (September, October, and November); Winter (December, January, and February).
Table 3. Statistical values of NO$_2$ using S5P in 2018–2021.

| Month | July | August | September | October | November | December | January | February | March | April | May | June |
|-------|------|--------|-----------|---------|----------|----------|---------|----------|-------|-------|-----|------|
| Min   | 0.01 | 0.04   | 0.05      | 0.19    | 0.00     | 0.00     | 0.00    | 0.00     | 0.00  | 0.00  | 0.00| 0.00 |
| Max   | 2.97 | 2.90   | 4.80      | 7.95    | 15.00    | 19.00    | 15.80   | 12.04    | 9.00  | 3.87  | 4.00| 3.20 |
| Mean  | 0.20 | 0.23   | 0.22      | 0.19    | 0.25     | 0.28     | 0.30    | 0.24     | 0.18  | 0.16  | 0.17| 0.18 |
| STD   | 0.11 | 0.11   | 0.15      | 0.20    | 0.33     | 0.40     | 0.41    | 0.28     | 0.24  | 0.11  | 0.12| 0.11 |

For monitoring monthly NO$_2$ change during 2018 and 2021, we selected 12 provinces (Figure 7), because they were suitable candidates for air quality monitoring. The results indicate that air pollution is at the maximum level in industrial and densely populated cities in winter (December, January, and February). In sparsely populated and non-industrial cities, changes in air pollution in different months and seasons are not significant, and the maximum amount of pollution is often observed in summertime.

Figure 7. Cont.
Figure 7. Monthly fluctuation of tropospheric NO$_2$ columns (10$^{15}$ molecules cm$^{-2}$) in some industrial and densely populated provinces (Tehran and Isfahan) and some non-industrial and sparsely populated provinces (Sistan and Baluchestan). (Red lines in the charts are trend lines for NO$_2$).

The monthly average concentration of tropospheric NO$_2$ column data obtained using the TROPOMI sensor was extracted for each county. The NO$_2$ map was classified into five classes: very low, low, medium, high, and very high. Finally, the area and population of each class were extracted, and the results are listed in Table 4. As can be seen from the results, less than 0.5% of the area of cities are in the severe and very severe classes of tropospheric NO$_2$ column, and 15% of the total population of Iran (more than 13 million people) live in this area. This shows the importance of population density in increasing air pollution. In addition, Table 4 shows about 73% of the population of Iran lives in the low and very low air pollution classes.
Table 4. Specifications of population statistics using NO$_2$ ($10^{15}$ molecules cm$^{-2}$) classes.

| Pollution Class | Value ($10^{15}$ Molecules cm$^{-2}$) | Cities Count | Area (km$^2$) | Percentage of Area | Population | Percentage of Population |
|-----------------|---------------------------------------|--------------|--------------|--------------------|------------|--------------------------|
| Very Low        | <0.2                                  | 194          | 1,048,152.2  | 64.3               | 18,948,295 | 23.7                     |
| Low             | 0.2–0.5                               | 193          | 544,494.7    | 33.4               | 39,106,088 | 48.9                     |
| Moderate        | 0.5–1                                 | 27           | 28,341.2     | 1.74               | 8,582,952  | 10.7                     |
| High            | 1–2                                   | 9            | 5102.4       | 0.31               | 2,894,314  | 3.6                      |
| Very High       | >2                                    | 6            | 2704.9       | 0.16               | 10,394,621 | 13.1                     |
| **Sum**         | **429**                               | **1,628,795**| **100**      | **79,926,270**     | **100**    |                          |

3.3. Correlation Analysis

In this study, we calculated the correlation between this pollutant, the population density of each county, and industrial units’ density, and the results are presented in Figure 8. The results show a significant relationship between two parameters of population density and industrial units’ density with NO$_2$. The value of linear correlation between NO$_2$ and population density, and the industrial density is 0.6–0.92 and 0.56–0.87, respectively. In conclusion, the amount of NO$_2$ air pollution concentration in each region directly and strongly relates to its population size and urbanization, which has been mentioned in similar studies [13,56].

Figure 8. (a) Correlation between population density and tropospheric NO$_2$ columns concentration ($10^{15}$ molecules cm$^{-2}$); (b) correlation between industrial units’ density and tropospheric NO$_2$ columns concentration ($10^{15}$ molecules cm$^{-2}$).
4. Discussion

Validation of the results confirms the reliability of the data and methodology employed in NO₂ pollution monitoring. The tropospheric NO₂ column concentration of the satellite-based S5P products (10¹⁵ molecules cm⁻²) were statistically correlated with independent datasets of ground station observations of NO₂ concentrations (µg/cm³). After validating the accuracy of the data and the spatio-temporal monitoring of this pollutant in Iran, it is necessary to discuss the cause and severity of this pollutant in more detail. In several other regions in Iran, there is a high concentration of NO₂ in small cities, including Quds, Fardis, Khomeini Shahr, Falavarjan, Abyek, Assaluyeh, and Binalood (Figure 9). This is generally due to the activity of industries and the pollution caused by vehicles. Rapid economic development and population growth have led to increased human NO₂ emissions around urban areas. For this reason, in most provinces in Iran, the concentration of NO₂ gas in urban centers is higher than the average NO₂ gas in the corresponding province [57–61]. Similar to the results of [58], in the northern parts and metropolitan areas of Iran, the concentration of the tropospheric NO₂ column is more than 2 × 10¹⁵ molecules cm⁻², including cities such as Tehran, Rasht, Sari, Isfahan, Karaj, Tabriz, and Mashhad. In these areas, air pollution has risen because of a growing number of power plants and industries and an increase in urbanization, transportation, and population density. Tehran is one of the main centers of NO₂ production in the world due to its high population density and the number of vehicles [59]. The results of a study on carbon monoxide (CO) using the TROPOMI sensor on a global scale, indicated that Tehran, Isfahan, Mashhad, and Qom are among the cities suffering from severe air pollution [62]. In a study, NO₂ pollutant was investigated using the OMI satellite in the country, and the results of this study showed that the capital of the provinces, including the cities of Tehran, Mashhad, Tabriz, Ahvaz, and Arak, are in a critical situation in terms of air pollution [58]. Ahvaz, Mahshahr, and Abadan, industrial cities of Khuzestan Province, are the main centers of petrochemicals and refineries with severe air pollution. Industrial activities could be known as the main cause of NO₂ air pollution in Mahshahr port [63].
It can be inferred that human activities have a significant impact on air pollution. Generally, air pollution due to human activities and increased use of fossil fuels in wintertime is more than in summertime. However, the temporal behavior of pollution may not be the same in all areas. Depending on the source of pollution, the minimum and maximum levels of pollution in different places, and times may show different behavior. However, factors such as increased use of heating devices, fossil fuels, lack of direct radiation, and temperature inversion phenomena are very influential in intensifying and continuing pollution in wintertime. The results of this study can be viewed in the GEE environment at: https://code.earthengine.google.com/?accept_repo=users/MohsenSaber/SP5_NO2_Monitoring (accessed on 1 December 2021).

5. Conclusions

In this paper, we investigated spatiotemporal characteristics and factors affecting the concentration of tropospheric NO\textsubscript{2} columns over Iran between 2018 and 2021. For this purpose, we used NO\textsubscript{2} products of the TROPOMI sensor data mounted on the S5P satellite. These results showed that the products of this sensor have high correlations with the data published by the Iran APMS, and the range of correlation changes in different seasons varies from 0.4 to 0.92 (as discussed in Section 3.1). The following observations were made in our analysis of spatio-temporal characteristics of tropospheric NO\textsubscript{2} column concentration:

(a) Monthly fluctuations of the tropospheric NO\textsubscript{2} column concentration over the study area are significant;
(b) The pattern of spatial changes in NO\textsubscript{2} concentration in the troposphere shows that the amount of NO\textsubscript{2} gaseous air pollutants in the study area’s northern part is more than in the central and southern regions;
(c) The results show that about 15% of the population of Iran (about 13 million people) who live in 0.5% of the total area of Iran live in areas with severe air pollution.

The results of this study can be used for effective planning to reduce NO\textsubscript{2} emissions and air pollution in Iran and countries with similar environmental and socioeconomic conditions. In the first stage, NO\textsubscript{2} pollution in Iran has significant spatial differences that should be considered in future planning to tackle NO\textsubscript{2} pollution. The number of industries and companies producing air pollutants should be limited in cities, such as Tehran, Karaj, Mashhad, Isfahan, Tabriz, Ahvaz, Mahshahr, Abadan, Arak, and Qom. At the same time, the government should urge industries to increase their investment in new technologies to minimize the direct emission of NO\textsubscript{2} gaseous air pollutants (such as optimization of combustion conditions of the vehicle and using renewable energy). The results and outputs of this research can be used in industrial site selection and other studies on environmental inequality and justice. Although the pattern of spatiotemporal changes and the factors affecting the distribution of the tropospheric NO\textsubscript{2} column concentrations over Iran were analyzed. We are fully aware that this article has some limitations and shortcomings. Among these limitations, we can mention the incompleteness and relative lack of socioeconomic statistics, which severely limit the analysis of the factors affecting NO\textsubscript{2} pollution. Therefore, in future studies, the effect of these factors on the concentration of air pollutants should be investigated. Since only data from 2018 onwards was available, it was not possible to study changes, such as annual changes, over longer periods of time in Iran with this sensor. Collecting the tropospheric NO\textsubscript{2} column concentration data and analyzing air pollutant fluctuations in the longer term, especially during the COVID-19 pandemic, will also be of interest to future researchers.

The GEE repository is publicly available at: https://code.earthengine.google.com/?accept_repo=users/MohsenSaber/SP5_NO2_Monitoring (accessed on 1 December 2021). As the code is available publicly, future improvements to this methodology may be implemented based on user feedback. We also provided an overview of the results of this study in the GEE environment. All the results via GEE view are accessible at: https://mohsensaber.users.earthengine.app/view/iranno2sp5 (accessed on 1 December 2021).
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Abbreviations

The following abbreviations are used in this manuscript:

| Abbreviation | Description |
|--------------|-------------|
| AQG          | Air quality guideline |
| AQMO         | Air quality monitoring organization |
| APEX         | Airborne PRISM experiment |
| CO₂          | Carbon dioxide |
| CO           | Carbon monoxide |
| DEM          | Digital elevation model |
| ESA          | European Space Agency |
| GEE          | Google Earth Engine |
| GOME         | Global Ozone Monitoring Experiment |
| HCHO         | Formaldehyde |
| HNO₃         | Nitric acid |
| NO₂          | Nitrogen dioxide |
| O₃           | Ozone |
| OMI          | Ozone Monitoring Instrument |
| OSM          | OpenStreetMap |
| RS           | Remote sensing |
| SCIAMACHY    | Scanning Imaging Absorption Spectrometer for Atmospheric Cartography |
| SSP          | Sentinel-5P |
| SNR          | Signal-to-noise-ratio |
| SO₂          | Sulfur dioxide |
| TROPOMI      | Tropospheric Monitoring Instrument |
| VOCS         | Volatile organic compounds |
| WHO          | World Health Organization |

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