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# Impact of COVID-19 lockdown on $NO_2$, $O_3$, $PM_{2.5}$ and $PM_{10}$ concentrations and assessing air quality changes in Baghdad, Iraq

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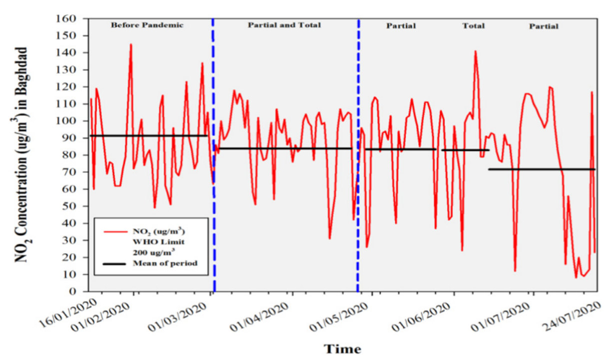
## HIGHLIGHTS

- $NO_2$ concentrations reduced by 6, 7, 8 and 20%, respectively in Baghdad during the lockdown.
- $O_3$ concentrations increased by 13%, 75%, 225% and 525%, for the same periods.
- AQI improved in Baghdad by 13%, compared to the pre-lockdown.
- $NO_2$ emissions reduced up to 35 to 40% in Iraq compared to the pre-lockdown.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Covid-19 was first reported in Iraq on February 24, 2020. Since then, to prevent its propagation, the Iraqi government declared a state of health emergency. A set of rapid and strict countermeasures have taken, including locking down cities and limiting population's mobility. In this study, concentrations of four criteria pollutants, $NO_2$, $O_3$, $PM_{2.5}$ and $PM_{10}$ before the lockdown from January 16 to February 29, 2020, and during four periods of partial and total lockdown from March 1 to July 24, 2020, in Baghdad were analysed. Overall, 6, 8 and 15% decreases in $NO_2$, $PM_{2.5}$, and $PM_{10}$ concentrations, respectively in Baghdad during the 1st partial and total lockdown from March 1 to April 21, compared to the period before the lockdown. While, there were 13% increase in $O_3$ for same period. During the 2nd partial lockdown from June 14 to July 24, $NO_2$ and $PM_{2.5}$ decreases 20 and 2.5%, respectively. While, there were 525 and 56% increase in $O_3$ and $PM_{10}$, respectively for same period. The air quality index (AQI) improved by 13% in Baghdad during the 1st partial lockdown from March 1 to April 21, compared to its pre-lockdown. The results of $NO_2$ tropospheric column extracted from the Sentinel-5P satellite shown the $NO_2$ emissions reduced up to 35 to 40% across Iraq, due to lockdown measures, between January and July, 2020, especially across the major cities such as Baghdad, Basra and Erbil. The lockdown due to COVID-19 has drastic effects on social and economic aspects. However, the lockdown also has some positive effect on natural environment and air quality improvement.

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## 1. Introduction

On December 31, 2019, China alerted the World Health Organization (WHO) of several cases of unusual pneumonia in Wuhan, a city in the central Hubei Province. On January 7, 2020, the identification of a new

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virus, named SARS-CoV-2, was announced (WHO, 2020a). On January 30, WHO declared worldwide public health emergency. In February, outbreaks begin in Iran, Italy and other countries around the globe. Subsequently, the epidemic turns into pandemic and by end of March half of the world population was under some form of lockdown (Tosepu et al., 2020). The recent outbreak of coronavirus disease, termed as COVID-19, has raised global concerns and led to total lockdown in many countries (WHO 2020a; Gautam and Trivedi, 2020; Bherwani et al., 2020; Wang et al., 2020). The disease is caused by severe acute respiratory syndrome coronavirus2 (SARS-CoV-2) (Gautam and Hens, 2020b). This fatal and novel coronavirus is likely to spread rapidly in humans with close contact to already infected people (Cascella et al., 2020; Bherwani et al., 2020). The spread of the virus may be contained by maintaining proper social distance, personal hygiene, avoiding gatherings, and visiting places like hospitals, meetings, and public transportations, which have a high risk of such virus contamination (WHO, 2020b; Bherwani et al., 2020; Gautam, 2020). Preliminary investigations on the origin of COVID-19 caused by the SARS-CoV-2 coronavirus suggests a zoonotic origin (Lu et al., 2020) because other coronavirus- related diseases, such as Middle East respiratory syndrome (MERS) and severe acute respiratory syndrome (SARS) created outbreaks due to human–animal interactions.

COVID-19 is an acute respiratory disease which may lead to pneumonia with symptoms such as fever, cough and dyspnea (Jiang et al., 2020) and has an approximate fatality rate of 2–3% (Rodriguez-Morales et al., 2020). As of July 24, 2020, there have been more than 15 million confirmed cases and around 628,000 deaths reported globally (www.covid19.who.int, 2020). As the cases spread, most of the countries adopted restrictions to the transportation, commerce and cultural activities, schools and universities were closed and exams were cancelled, and social distancing was imposed (Dantas et al., 2020).

The first confirmed case of Virus COVID-19 in Iraq appeared on February 24, 2020 in Najaf, southern Baghdad (WHO, situation report-36). To control the spread of the COVID-19 in Iraq, the Iraqi government announced a series of partial and total lockdown measures from 1 March, which included closing schools, universities, restricting transportation and the movement of people between provinces (Jebril, 2020). The total number of confirmed cases in Iraq was 104,711 and 4212 deaths from February 24 to July 24, 2020 (Ministry of Health, 2020).

The COVID-19 affects the world economy negatively, due to a sharp increase in the doubt of economic development, and due to the stop of economic activities as a result of restriction movement and transportation to control the spread of the pandemic. It is well-known that air pollution reduces with decreasing economic activities (Wang and Su, 2020).

The lockdown measures have shut down industries, halted vehicular traffic and have had a huge impact on the daily routine of the people. Due to this, considerable improvement in air quality levels of countries such as Spain (Tobías et al., 2020), India (Gautam, 2020), Brazil (Nakada and Urban, 2020), and China (Sharma et al., 2020) has been reported. The plummet in pollutant concentration is obvious, due to the restriction in anthropogenic activities.

The air is a vital element for the survival of all living beings; hence, it is necessary to keep it clean and safe. The anthropogenic activities are a major cause of ambient air pollution, due to emission of many harmful pollutants in high concentration, which are health damaging (Gautam and Hens, 2020a; Ghorani-Azam et al., 2016). The main causes of air pollution include economic development, urbanization, energy consumption, transportation and motorization, as well as the rapid increase of urban population (Kaplan et al., 2019). The biggest air pollutants encountered in our daily life are particulate matter (PM), sulfur dioxide ($SO_2$), nitrogen dioxide ($NO_2$), ozone ($O_3$), carbon monoxide (CO), and carbon dioxide ($CO_2$) (Chen et al., 2007). $NO_2$ is an important component of urban air pollution and a precursor to ground level ozone, particulate matter, and acid rain (Bechle et al., 2013). The main sources of $NO_2$ in the ambient atmosphere are the burning of fossil fuels such as coal, oil and gas. $NO_2$ is a highly reactive pollutant and emitted, especially from the combustion of fossil fuels. Transportation is considered as the major source of $NO_2$ emissions (Muhammad et al., 2020).

PM is a major pollutant, emitted from vehicles, residential, energy, industrial and dust (Guo et al., 2017; Guo et al., 2019). PM is responsible for respiratory infections, lung disease, and importantly compromised immune system (Kim et al., 2018). $PM_{2.5}$ specifically, has an impact as it passes through the respiratory system and provides high chances of getting deposited in lungs (Kim et al., 2018; Li et al., 2018). $O_3$ is a common oxidant gas in urban air, and exposure to ozone can induce oxidative stress causing airway inflammation and increased respiratory morbidities (Adhikari and Yin, 2020). Surface $O_3$ concentration depends on the magnitude and ratio of the emissions of precursor gases (e.g. NOx, and VOCs), photochemical reactions, atmospheric conditions (weather), removal processes at the earth's surface and hence on local, regional, seasonal factors. In most regions $O_3$ declines with decreasing NOx emissions; however, in some traffic-intensive urban regions dominated by high-NOx emissions, $O_3$ may initially increase in response to declining NOx emissions, but after transport of the urban plume to rural areas $O_3$ will eventually decrease (Dentener et al., 2020).

The energy sector (crude oil production) represents the backbone of the Iraqi economy and its exports. Iraq relies heavily on the use of fossil fuels for electricity production, which has increased from recent years, due to population growth and growing electricity consumption (Hashim et al., 2020). Electricity production, oil refining, natural gas flaring, transportation and population are among the most important sources of air pollution in Iraq (IEA, 2012). The absence of a reliable national electrical power network has led to the spread of different kinds of generators of various sizes servicing homes, farms, factories, and various governmental and non-governmental institutions. These sources led to the low air quality in Iraq, especially in large cities such as Baghdad and Basra (Ministry of Environment, 2016). A lot of sites in Iraq can be regarded as high density traffic sites especially in the capital Baghdad. An excess of pollution and high levels of emission of various pollutants due various reasons are produced. One of the major reasons is pollution, due to automobile fuel consumption which led to a negative impact on the economy and environment (Jassim et al., 2014).

Air quality changes due to the COVID-19 lockdown quickly became a new topic of recent research studies. Kerimray et al. (Kerimray et al., 2020) analyze the effect of the lockdown from March 19 to April 14, 2020, on the concentrations of air pollutants in Almaty, Kazakhstan. Daily concentrations of $PM_{2.5}$, $NO_2$, $SO_2$, CO and $O_3$ were compared between the periods before and during the lockdown. During the lockdown, the $PM_{2.5}$ concentration was reduced by 21%. There were also substantial reductions in CO and $NO_2$ concentrations by 49% and 35%, respectively, but an increase in $O_3$ levels by 15% compared to the prior 17 days before the lockdown. Otmani et al. (2020) evaluated the changes in levels of some air pollutants, $PM_{10}$, $NO_2$ and $SO_2$ in Salé city, Morocco, during the lockdown measures. The obtained results showed that the difference between the concentrations recorded before and during the lockdown period were respectively 75%, 49% and 96% for $PM_{10}$, $SO_2$ and $NO_2$.

Satellite instruments afford a global view of the planet's air pollution. The Sentinel-5Precursor/Tropospheric Monitoring Instrument (TROPOMI) sensor is a part of the European Space Agency (ESA) space Program for earth monitoring; the main objectives are to provide operational space-borne observations in support to the operational monitoring of Air Quality (Borsdorff et al., 2018). Using spectral bands from the ultraviolet, visible and near-infrared wavelength range, TROPOMI measures $O_3$, $NO_2$, $SO_2$, bromate ($BrO_3^-$), formaldehyde (HCHO) and water vapor ($H_2O$) tropospheric columns from the ultraviolet, visible and near-infrared wavelength, and CO and methane ($CH_4$) tropospheric columns are measured from the short-wave infrared wavelength range (Veefkind et al., 2017). The S-5P/TROPOMI data used in several air pollution studies during outbreak of the COVID-19 pandemic around the world. Gautam, 2020 studied $NO_2$ column observations to compare the air quality data released by international agencies before and after the novel coronavirus pandemic over India, China, Spain, France and Italy. The significant reduction in the percentage of $NO_2$ in India and China by using S-5P/TROPOMI reached 70% and 20–30% $NO_2$ reduction in India and China, respectively. The $NO_2$ reduced 20–30% in European countries (i.e., Spain, Italy, and France).

Finally, in an attempt to point out the main changes in $NO_2$, $O_3$, $PM_{2.5}$, $PM_{10}$ concentrations and Air Quality Index (AQI) in Baghdad, their daily averages were calculated for the periods before the lockdown from January 16 to February 29, 2020, and during four periods of partial and total lockdown from (March 1 to July 24, 2020). The objective was to evaluate the relative variation (in %) and the difference in the mean concentration (in $\mu g/m^3$) between the five periods (before and during the lockdown). Study of $NO_2$ tropospheric column data derived from TROPOMI over Iraq from January to July 2020, and calculates reduction in the percentage of $NO_2$ before and during the lockdown. This study aims to assess the impacts of COVID-19 lockdown conditions on the air quality of Baghdad, which is one of the most polluted large cities in the Middle East.

## 2. Material and methods

### 2.1. Study area

Iraq is located in the eastern part of the Middle East and North African countries (MENA region). It is surrounded by Iran in the east, Turkey to the north, Syria, and Jordan to the west, Saudi Arabia, and Kuwait to the south and the Gulf to the southeast (Al-Ansari, 2013). Iraq has a narrow coastal strip on the Arabian Gulf with a length of about 58 km (El Raey, 2010). The climate in Iraq is mainly of the continental, subtropical semi-arid type, with the north and north-eastern mountainous regions having a Mediterranean climate (FAO, 2003). Iraq is shaped like a basin containing the great Mesopotamian plain of the Tigris and Euphrates rivers, as shown in Fig. 1A (Al-Ansari, 2013). The current population of Iraq is about 40 million, shown in Fig. 1B based on projections of the latest United Nations data. Iraq is currently growing at a rate of 2.32% per year. Nearly 70% of Iraq's population lives in urban areas, and they have several large cities that reflect that. The largest by far is the nation's capital, Baghdad, with a population of 7.5 million. The cities of Basra and Mosul both have populations exceeding 2 million derived from Iraq population data (https://worldpopulationreview.com/countries/iraq-population/). Baghdad city is located in central Iraq. The borders of the municipality of Baghdad encompass fourteen administrative units, eight in Rusafa (east of Tigris River) and six in Karkh (west of Tigris River). The area of the municipality of Baghdad reached 870 $km^2$. Advantages of the characteristics of study area are: essentially great extremism in temperature, little precipitation, low relative humidity and high brightness of the sun (Hashim and Sultan, 2010).

**Table 1**
Dates of data acquisition of S-5P/TROPOMI that covers the period from January 02, 2020, before the lockdown in Iraq until July 24, 2020 in current study.

| Situation | Dates of data acquisition from TROPOMI |
|---|---|
| Before COVID-19 pandemic (business as usual) | January 02, 2020 |
| Before COVID-19 pandemic (business as usual) | February 04, 2020 |
| During partial lockdown | March 16, 2020 |
| During total lockdown | April 02, 2020 |
| During partial lockdown | April 30, 2020 |
| During partial lockdown | May 19, 2020 |
| During total lockdown | June 05, 2020 |
| During partial lockdown | July 24, 2020 |

### 2.2. Data sources

Due to the technical damage of automatic monitoring stations for air pollutants of the Ministry of Environment in Baghdad during the previous period, air pollution data were collected from an online platform (https://air.plumelabs.com/en/) monitoring and analyzing the air quality (World Air Map, 2020). Daily concentrations of four air pollutants were measured, including $NO_2$, $O_3$, $PM_{2.5}$ and $PM_{10}$ for Baghdad before and during the lockdown, in addition to the air quality index (AQI) for the same time period. $NO_2$, $O_3$, $PM_{2.5}$ and $PM_{10}$ concentration values were not available for the previous years. In this work, used S-5P/TROPOMI global daily gridded data at $0.05° \times 0.05°$ derived from the near-real-time operational product (Van Geffen et al., 2019), obtained via the Copernicus open data access hub derived from European Space

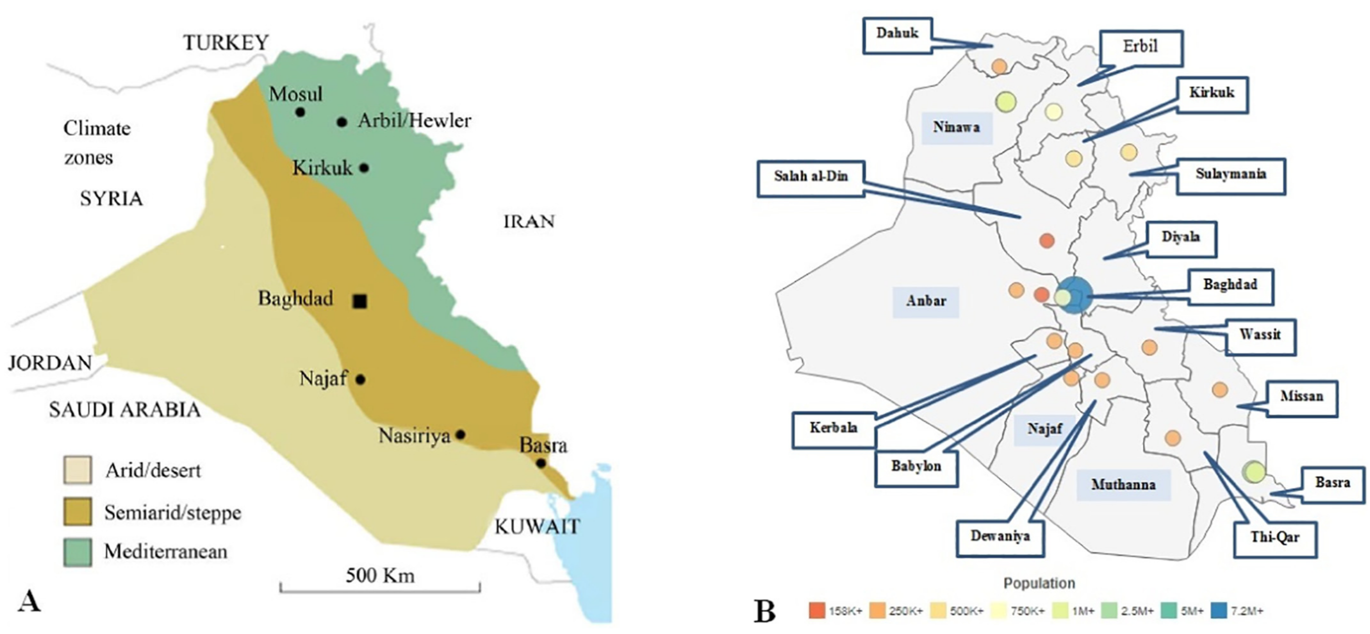


**Fig. 1.** (A) Climate zones of Iraq; (B) Iraq population in 2020.

Agency (ESA), (https://s5phub.copernicus.eu) for $NO_2$ tropospheric column data. Table 1 shows dates of data acquisition of S-5P/TROPOMI that cover the period from January 02, 2020, before the lockdown in Iraq until July 24, 2020.

### *2.3. AQI calculation*

To understand the overall improvement in air quality, AQI was detailed. AQI uses $NO_2$, $O_3$, $PM_{2.5}$ and $PM_{10}$, of which minimum concentrations three pollutants should be available. The concentrations are converted to a number on a scale of 0–500. The sub index AQI ($AQI_i$) for each pollutant (i) is calculated using Eq. (1)

$$AQI_i = \frac{IN_{HI} - IN_{LO}}{B_{HI} - B_{LO}} \times (C_i - B_{LO}) + IN_{LO} \quad (1)$$

where, $C_i$ is the concentration of pollutant 'i'; $B_{HI}$ and $B_{LO}$ are breakpoint concentrations greater and smaller to $C_i$ and $IN_{HI}$ and $IN_{LO}$ are corresponding AQI values. The overall AQI is the maximum AQIi, and the corresponding pollutant is the dominating pollutant. The AQI is divided into six categories: good, satisfactory, moderate, poor, very poor and severe depending on whether the AQI falls between 0–50, 51–100, 101–200, 201–300, 301–400 and 401–500, respectively (Sharma et al., 2020).

## 3. Results and discussion

### *3.1. Air pollution assessment during COVID-19*

Lockdown due to COVID-19 reduced transportation activities, which results in less energy consumption and lower oil demand. These changes in transport activities and oil demand exert a significant impact on the environmental quality.

#### *3.1.1. $NO_2$ concentration*

Fig. 2 represents the $NO_2$ concentrations (μg/m$^3$) in Baghdad, before and during the lockdown from January 16 to July 24, 2020. The results showed that average of $NO_2$ concentration before lockdown from January 16 to February 29 was 91 μg/m$^3$. During the 1st partial and total lockdown from March 1 to April 21; daily $NO_2$ concentrations reduced in Baghdad, due to the slowdown in transportation activity and social distancing measures, and average of $NO_2$ of this period was 86 μg/m$^3$. The $NO_2$ average continued to decline during the period of April 22 to May 23, during the 2nd partial lockdown, reached 85 μg/m$^3$. As a result of high number of confirmed cases of Covid-19 in Iraq, the total lockdown was imposed again from May 24 to June 13. The average of $NO_2$ concentration in Baghdad during this period reached 84 μg/m$^3$. The concentration of $NO_2$ continued to fluctuate with a tendency to decrease in Baghdad from June 14 to July 24 during the 3rd partial lockdown. The average of $NO_2$ concentration during this period reached 73 μg/m$^3$, that is confirms decrease $NO_2$ concentration in Baghdad during the lockdown, relative to same levels in January 2020. From Fig. 2, noted the daily concentrations and averages of $NO_2$ did not exceed the WHO limit 200 μg/m$^3$, before and after lockdown.

#### *3.1.2. $O_3$ concentration*

Fig. 3 represents daily $O_3$ concentrations (μg/m$^3$) in Baghdad from January 16 to July 24, 2020. The average of $O_3$ before the pandemic from January 16 to February 29 reached 8 μg/m$^3$. Daily $O_3$ concentrations rose during the 1st partial and total lockdown from March 1 to April 21, the average of $O_3$ recorded 9 μg/m$^3$. After the 1st total lockdown, the average of $O_3$ from April 22 to May 23 increased again to 14 μg/m$^3$. Daily $O_3$ concentrations continued to rise in Baghdad during May and early June, reaching an average from May 24 to June 13, 26 μg/m$^3$. In mid-July, the daily $O_3$ concentration exceeded WHO limit 100 μg/m$^3$ for the first time in 2020, due to high temperatures and low $NO_2$ concentrations. The average of $O_3$ from June 14 to July 24 reached 50 μg/m$^3$. The increase in $O_3$ concentrations in Baghdad was associated with a decrease in $NO_2$ concentrations, due to the inverse relationship between them.

#### *3.1.3. $PM_{2.5}$ concentration*

Fig. 4 represents the daily concentrations (μg/m$^3$) of $PM_{2.5}$ in Baghdad from January 16 to July 24, 2020. The results showed that the average of $PM_{2.5}$ concentration before the pandemic, from January 16 to

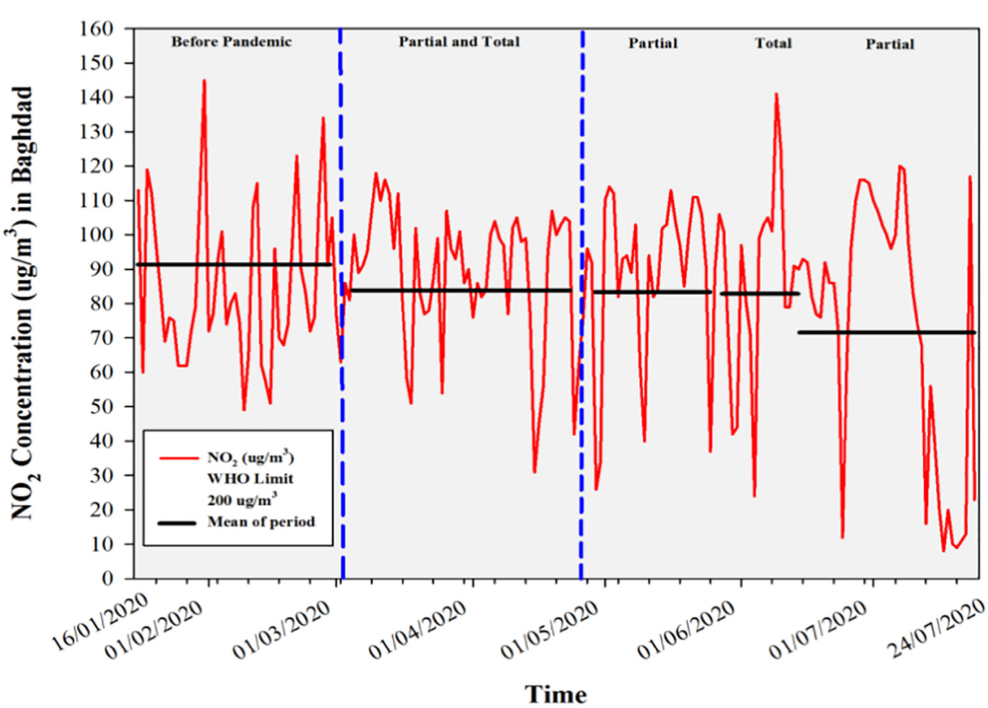


**Fig. 2.** $NO_2$ concentrations (μg/m$^3$) in Baghdad, before and during the lockdown from January 16 to July 24, 2020.

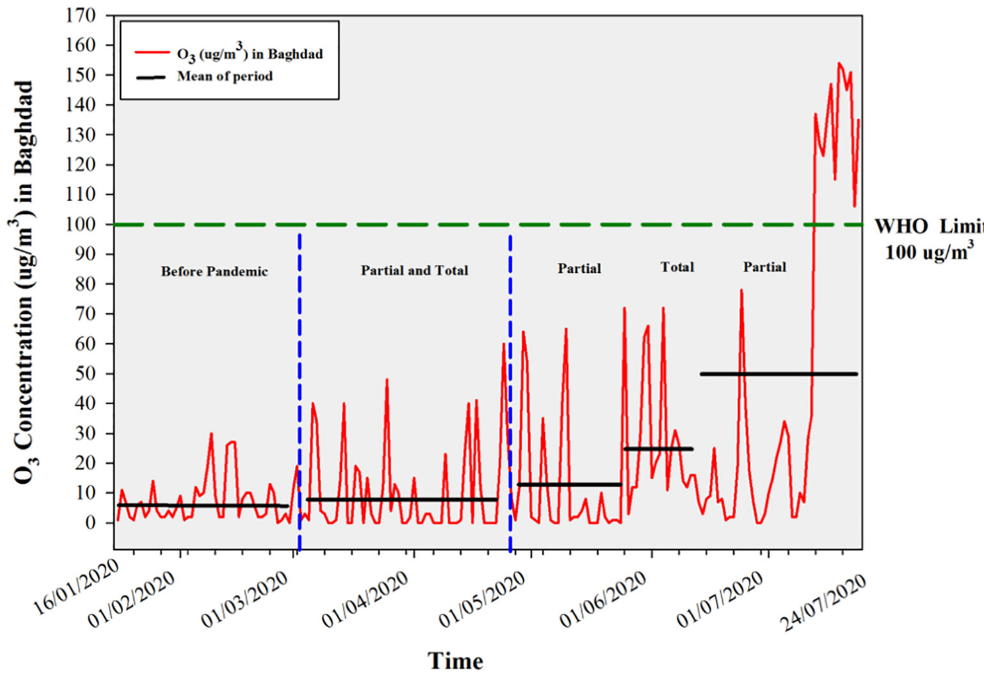


**Fig. 3.** $O_3$ concentrations ($\mu g/m^3$) in Baghdad from January 16 to July 24, 2020.

February 29, was 40 $\mu g/m^3$. During the 1st partial and total lockdown from March 1 to April 21, the average of $PM_{2.5}$ concentration dropped to 37 $\mu g/m^3$. Daily concentrations of $PM_{2.5}$ increased at the end of April and beginning of May, reaching a maximum value of 117 $\mu g/m^3$. The average of $PM_{2.5}$ from April 22 to May 23, reached 42 $\mu g/m^3$. During the 2nd total lockdown from May 25 to June 13, the average of $PM_{2.5}$ decreased slightly to 40 $\mu g/m^3$. From June 14 to July 24, the period characterized by fluctuating daily $PM_{2.5}$ concentrations during the 3rd partial lockdown, bringing the average of $PM_{2.5}$ to 39 $\mu g/m^3$. Although daily concentrations of $PM_{2.5}$ in Baghdad recorded few values less than the WHO limit 25 $\mu g/m^3$, but during the study period most of the $PM_{2.5}$ concentration exceeded this limit, especially in May and June, due to drought and high temperature.

*3.1.4. $PM_{10}$ concentration*

Fig. 5 represents the daily concentrations of $PM_{10}$ ($\mu g/m^3$) in Baghdad from January 16 to July 24, 2020. The results showed that the average of $PM_{10}$ concentration before the pandemic, from January 16 to February 29, was 119 $\mu g/m^3$. During the 1st partial and total lockdown from March 1 to April 21, the average of $PM_{10}$ concentration dropped to 101 $\mu g/m^3$. Daily concentrations of $PM_{10}$ increased at the end of April and beginning of May, reaching a maximum value of 541 $\mu g/m^3$.

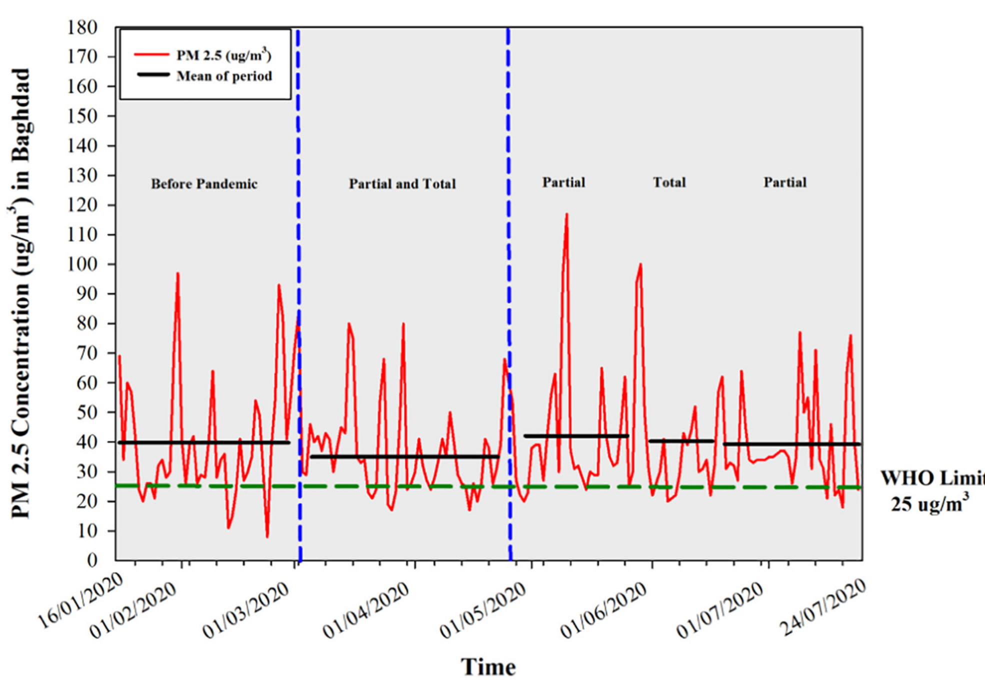


**Fig. 4.** $PM_{2.5}$ concentrations ($\mu g/m^3$) in Baghdad from January 16 to July 24, 2020.

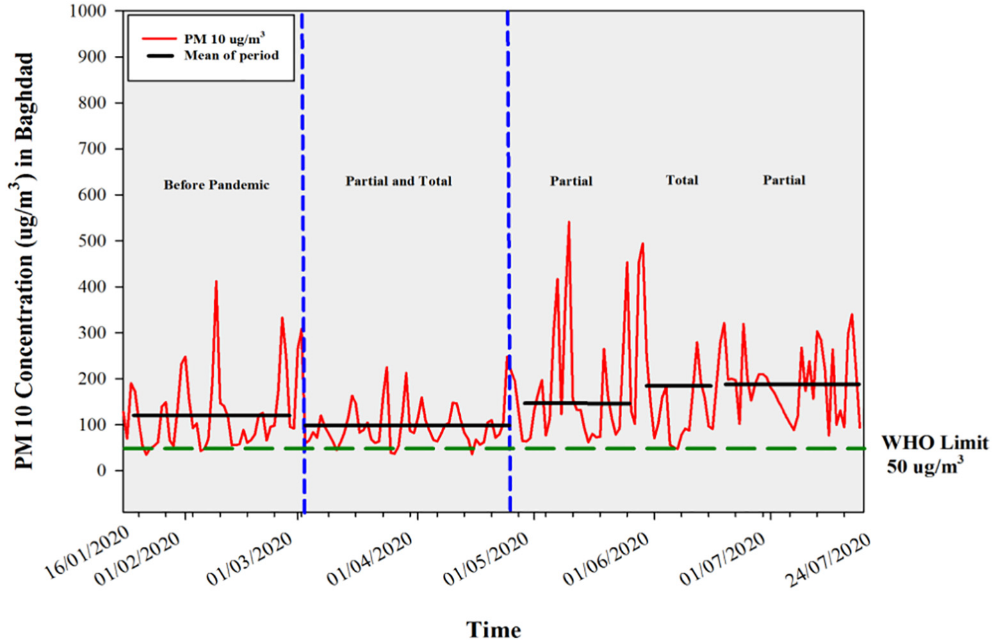


**Fig. 5.** $PM_{10}$ concentrations (μg/$m^3$) in Baghdad from January 16 to July 24, 2020.

The average of $PM_{10}$ from April 22 to May 23, reached 160 μg/$m^3$. During the 2nd total lockdown from May 25 to June 13, the average of $PM_{10}$ increased to 185 μg/$m^3$. From June 14 to July 24, the period characterized by fluctuating daily of $PM_{10}$ concentrations during the 3rd partial lockdown, the average of $PM_{10}$ increased slightly to 186 μg/$m^3$. The summer in Iraq lead to activity in the movement of wind, which raises dust, which increases the concentration of PM in Baghdad; in addition to the influence of transportation and fuel combustion activities. Almost all daily recorded concentrations of $PM_{10}$ in Baghdad exceeded the WHO limit 50 μg/$m^3$, during the study period.

### 3.2. AQI for Baghdad

For the purpose of studying the air quality of Baghdad before and during the lockdown, according to the recorded values of air pollutants, Fig. 6 represents the AQI for Baghdad from January 16 to July 24, 2020. Before the pandemic, from January 16 to February 29, AQI values ranged between 50 and 300, with an average of 120; meaning that AQI located within the third level (unhealthy for sensitive groups). From March 1 to April 21, AQI values improved in Baghdad, and the average for this period reached 105. The reduction average of AQI before and during this period reached around 13%. AQI of Baghdad declined during the 2nd partial lockdown from April 22 to May 23, with highest daily value reached 512. The average for this period increased to 151. AQI of Baghdad continued to record poor numbers. The average for the total and partial lockdown periods from May 24 to July 24, 2020 recorded 161 and 167, respectively. The above results confirm that the AQI for Baghdad recorded the lowest values during the 1st partial and total lockdown period in March and April 2020. This period represented the lowest daily concentrations of air pollutants recorded in the current

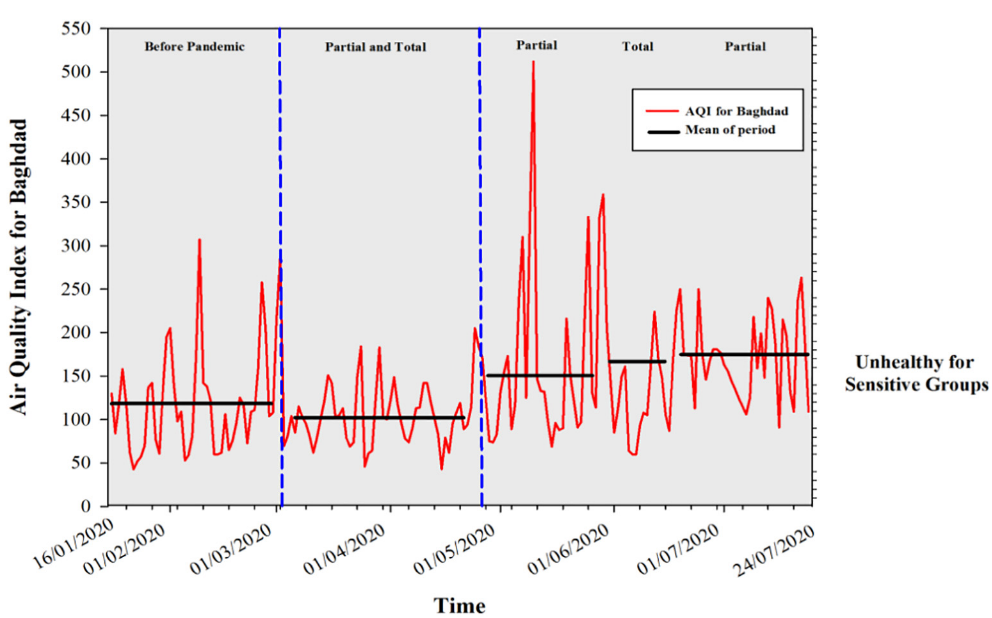


**Fig. 6.** AQI of Baghdad before and during the lockdown from January 16 to July 24, 2020.

**Table 2**
Percentage changes of average concentrations of ($NO_2$, $O_3$, $PM_{2.5}$, $PM_{10}$ Concentrations and AQI) between January 16, 2020 (before the lockdown) and during the lockdown periods.

| Time period | Average of $NO_2$ | Average of $O_3$ | Average of $PM_{2.5}$ | Average of $PM_{10}$ | Average of AQI |
|---|---|---|---|---|---|
| January 16–February 29 (before the lockdown) | 91 | 8 | 40 | 119 | 120 |
| March 1–April 21 (during the 1st partial and total lockdown) | 86 | 9 | 37 | 101 | 105 |
| Percent reduction | −6% | 13% | −8% | −15% | −13% |
| April 22–May 23 (during the 2nd partial lockdown) | 85 | 14 | 42 | 160 | 151 |
| Percent reduction | −7% | 75% | 5% | 34% | 26% |
| May 25–June 13 (during the 2nd total lockdown) | 84 | 26 | 40 | 185 | 161 |
| Percent reduction | −8% | 225% | 0% | 55% | 34% |
| June 14–July 24 (during the 3rd partial lockdown) | 73 | 50 | 39 | 186 | 167 |
| Percent reduction | −20% | 525% | −2.5% | 56% | 39% |

study. It also recorded the lowest average of pollutants compared to the pre-pandemic and post-pandemic period, due to citizen's commitment to lockdown measures, slow transportation, closures of universities and schools, and restrictions on the movement of employees. These measures contributed to a large extent to the decrease in the air pollutants emission in Baghdad during the 1st partial and total lockdown.

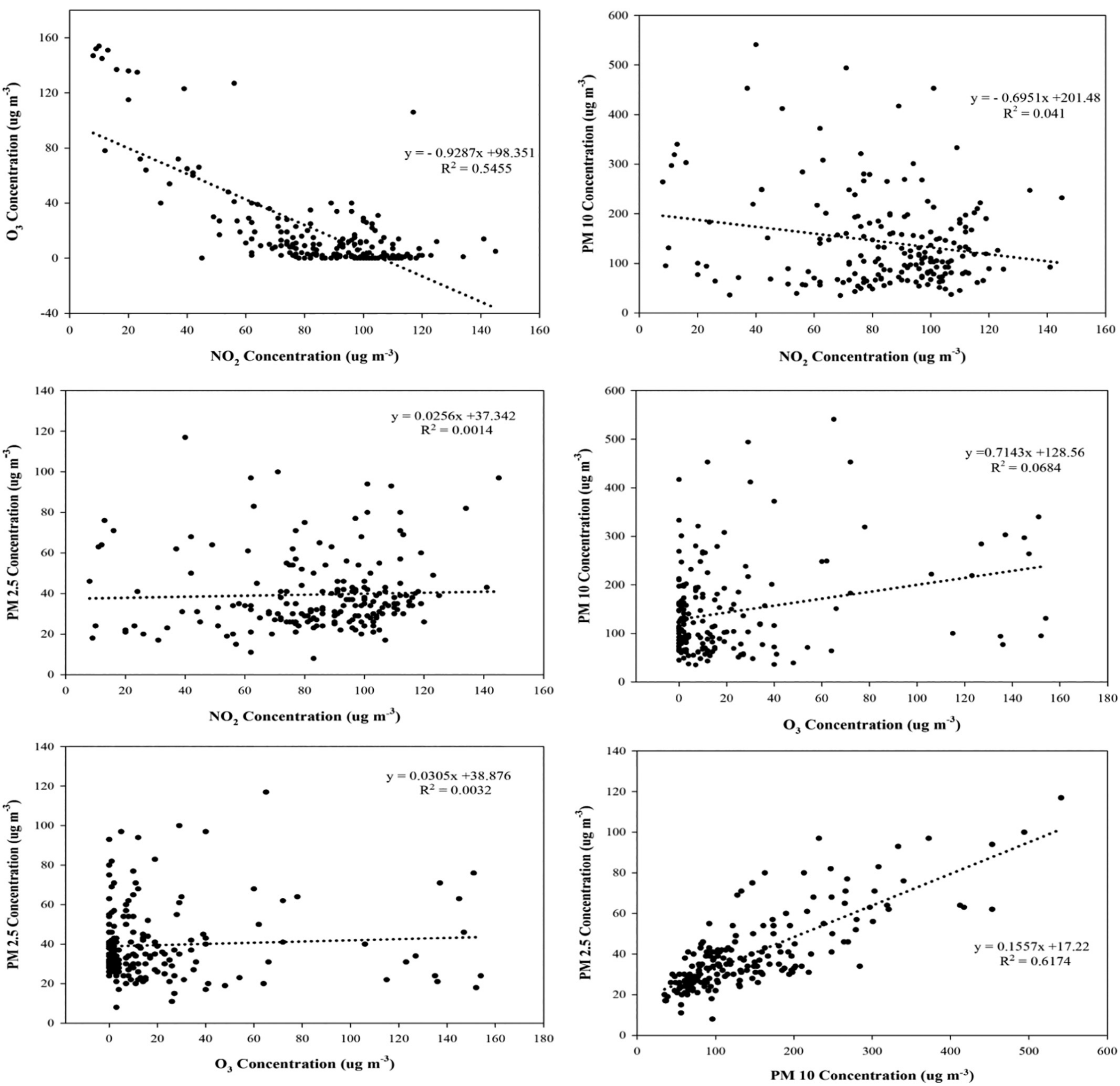


**Fig. 7.** The correlation coefficients between air pollutants ($NO_2$, $O_3$, $PM_{2.5}$ and $PM_{10}$) in air of Baghdad before and after the lockdown.

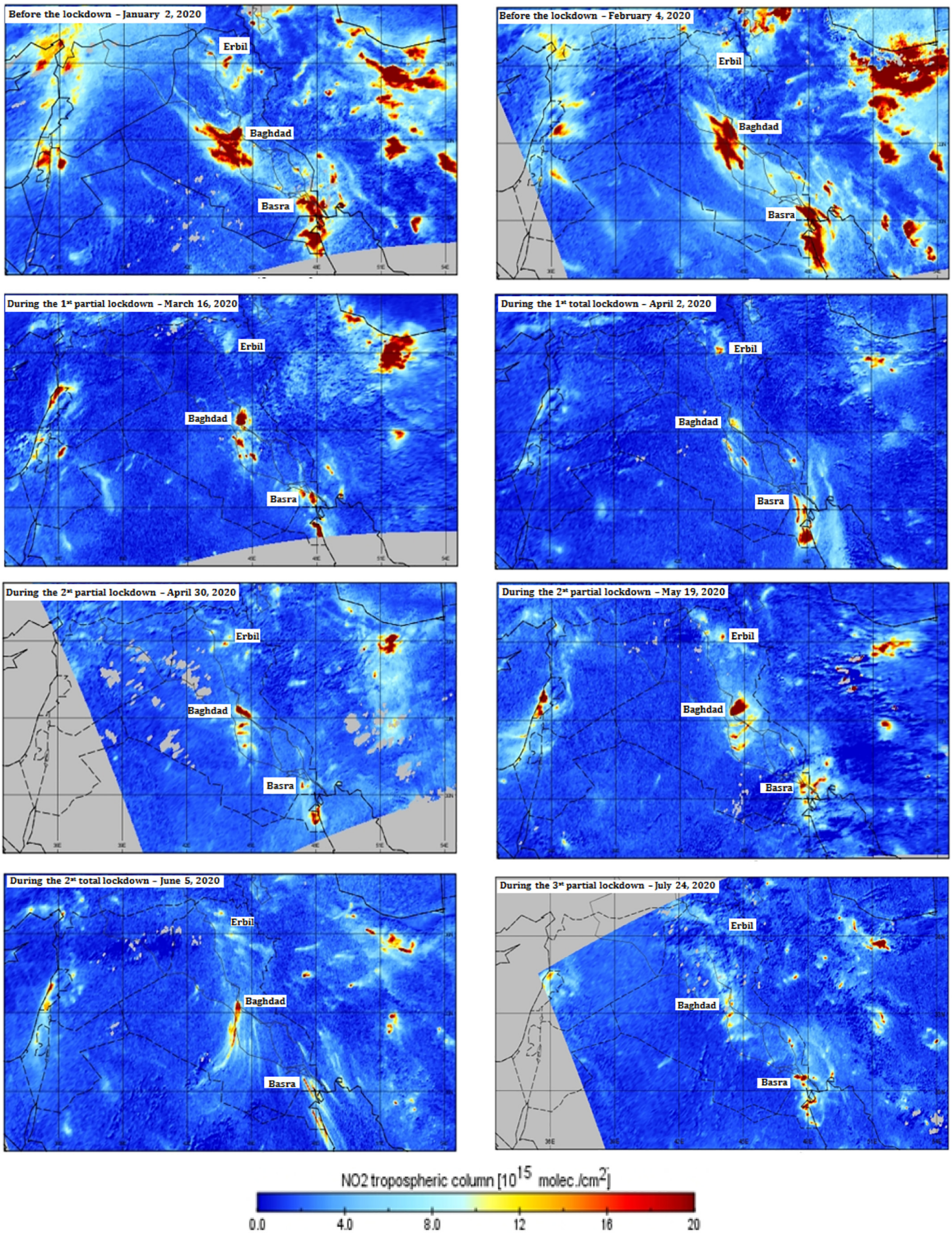


**Fig. 8.** $NO_2$ emissions in Iraq before, and during the COVID-19 lockdown, based on data acquisition derived from S-5P/TROPOMI.

### 3.3. Percentage changes of $NO_2$, $O_3$, $PM_{2.5}$, $PM_{10}$ concentrations and AQI

The concentrations of $NO_2$, $O_3$, $PM_{2.5}$ and $PM_{10}$ were not available from the used sources for the previous years; therefore, the values were compared between the periods before the lockdown (January 16, 2020) and during the lockdown (March 1 to July 24, 2020). There was a reduction average concentrations of $PM_{10}$, $PM_{2.5}$ and $NO_2$ by 15%, 8% and 6%, respectively, compared to the period before the lockdown, as shown in Table 2. There was a substantial reduction in the average concentrations of $NO_2$ in lockdown periods by 7%, 8% and 20%, respectively, compared to the period before the lockdown. There was a reduction average concentrations $PM_{2.5}$ by 2.5% during June 14 to July 24, compared to the period before the lockdown. There was an increase in $PM_{10}$ by 34%, 55% and 56%, respectively, during the periods of lockdown. The natural sources of suspended particles in Iraq are dust and suspended in the air. This phenomenon reaches its top activity in spring and summer, due to the arrival of depressions coming from north of the Arabian Gulf and from central Asia causing northwesterly winds with a varying severity according to the depression's severity (1st National Communication, Ministry of Health and Environment (MoHE), 2016). As for the industrial sources, represented by power plants and transportation, as well as the spread of different kinds of generators of various sizes servicing homes, farms, factories, and various governmental and non-governmental. This leads to increased air pollutants in the atmosphere, and environmental pollution (Hashim et al., 2020). On the other hand, there was an increase in $O_3$ by 13%, 75%, 225% and 525%, between the periods before the lockdown (January 16 to February 29, 2020) and during the lockdown (March 1 to July 24, 2020). That's can be explained by the higher levels of solar activity during the period of the lockdown, especially in June and July. The AQI improved in Baghdad during the 1st lockdown, compared to its pre-lockdown average of −13%. However, this temporary improvement diminished in the subsequent periods, reaching 39% during the June and July. The poor air quality of Baghdad is due to the presence of most industrial and commercial activities there, in addition to high population density and traffic pollution. Also, the climate of Iraq in general is dry and hot in summer, which led to increase the concentration of pollutants and deteriorate the air quality (Ministry of Environment, 2016).

Fig. 7 presents the correlation coefficients between air pollutants ($NO_2$, $O_3$, $PM_{2.5}$ and $PM_{10}$) in air of Baghdad before and after the lockdown. Air pollutants had significant correlations with each other. The $PM_{2.5}$ and $PM_{10}$ concentrations correlated well ($R^2 = 0.6174$), which could indicate that $PM_{2.5}$ and $PM_{10}$ originated from common sources. On the other hand, $NO_2$ had negatively correlated with $O_3$ and $PM_{10}$. The concentration of surface $O_3$ decreases substantially with increased concentration of $NO_2$. When the nitric oxide (NO) emissions are sufficiently large, NO released in the atmosphere converts a large fraction of $O_3$ into $NO_2$ (Monks et al., 2015).

### 3.4. $NO_2$ tropospheric column from S-5P/TROPOMI

Fig. 8 represents $NO_2$ emission in Iraq before, and during the COVID-19, based on dates of data acquisition derived from S-5P/TROPOMI, as shown in Table 1. According to these data, the $NO_2$ emissions reduced up to 35 to 40% across Iraq due to lockdown, between January and July 2020, especially across the major cities such as Baghdad, Basra, Najaf, and Erbil. Fig. 8 showed that Baghdad recorded the highest $NO_2$ emission before the lockdown, compared to other cities, due to high population density, traffic pollution and industrial activities. The region located southern Baghdad, such as Babylon, Najaf and Karbala, contained high $NO_2$ emissions, due to industrial activities and power plants. Basra in southern Iraq has hotspots of $NO_2$, because it is the largest city in the south of Iraq contains oil fields and associated gas burning activities. The effect of the lockdown is apparent on the reduction of $NO_2$ emission in Baghdad, Basra and Erbil. Transportation restriction, industry emission slowdown, led to a clear decrease in $NO_2$ emission, compared to previous periods, before and during the COVID-19 lockdown. Due to the high incidence of confirmed cases of COVID-19, the Iraqi government announced the 2nd total lockdown again on May 24, 2020, to control the spread of the pandemic. As a result, $NO_2$ emission decline almost to the lowest levels on June 5, 2020 in all parts of Iraq. On June 14, up to July 24, 2020 Iraq has returned and announced the partial lockdown for the third time. $NO_2$ emission decline slightly, especially in Baghdad, Basra and Erbil, compared to the levels in the beginning of April. The results showed that the $NO_2$ tropospheric column over Iraq revealed a major hotspot of high concentration, especially in the Baghdad and Basra before the lockdown, and these hotspots receded significantly during the lockdown on April, June and July 2020.

## 4. Conclusions

In this study, the influences of emission reductions due to reduced anthropogenic activities, mainly on transportation and industry during the COVID-19 lockdown in Iraq on air pollution were investigated. There was a substantial reduction in the $NO_2$ concentration by 6, 7, 8 and 20% in Baghdad during four periods of partial and total lockdown, compared to the period before the lockdown. There was 8 and 15% reduction in $PM_{2.5}$ and $PM_{10}$ concentrations, respectively, in Baghdad, during the 1st partial and total lockdown. Even under the low-traffic pollution in Baghdad, the $PM_{2.5}$ and $PM_{10}$ concentrations before and during the lockdown period exceeded the WHO daily limit values, providing evidence of the high contribution from non-traffic related sources, such as natural sources and local dust. On the other hand, there was an increase in $O_3$ by 13%, 75%, 225% and 525%, between the periods before the lockdown (January 16 to February 29, 2020) and during the lockdown (March 1 to July 24, 2020), which could be due to the decrease in $NO_2$ and increase $PM_{10}$ concentrations. The AQI improved in Baghdad during the 1st lockdown, average of 13%, compared to its pre-lockdown. However, this temporary improvement diminished in the subsequent periods, during the June and July. Data of $NO_2$ tropospheric column derived from Sentinel-5P/TROPOMI shown clearly reduction up to 35 to 40% across Iraq, during the lockdown; due to transportation restriction and industry emission slowdown. Transportation and industrial activities have significantly been affected due to COVID-19 lockdowns, as there are less energy consumption and less oil demand. The outcomes of the lockdown can be easily identified as an improvement of the environmental and air quality; despite the economic and social consequences associated with the lockdown.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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