On the investigation of COVID-19 lockdown influence on air pollution concentration: regional investigation over eighteen provinces in Iraq

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Abstract

At the end of 2019, a novel coronavirus COVID-19 emerged in Wuhan, China, and later spread throughout the world, including Iraq. To control the rapid dispersion of the virus, Iraq, like other countries, has imposed national lockdown measures, such as social distancing, restriction of automobile traffic, and industrial enterprises. This has led to reduced human activities and air pollutant emissions, which caused improvement in air quality. This study focused on the analysis of the impact of the six partial, total, and post-lockdown periods (1st partial lockdown from March 1 to 16, 2020, 1st total lockdown from March 17 to April 21, 2nd partial lockdown from April 22 to May 23, 2nd total lockdown from May 24 to June 13, 3rd partial lockdown from June 14 to August 19, and end partial lockdown from August 20 to 31) on the average of daily NO₂, O₃, PM_{2.5}, and PM₁₀ concentrations, as well as air quality index (AQI) in 18 Iraqi provinces during these periods (from March 1st to August 31st, 2020). The analysis showed a decline in the average of daily PM_{2.5}, PM₁₀, and NO₂ concentrations by 24%, 15%, and 8%, respectively from March 17 to April 21, 2020 (first phase of total lockdown) in comparison to the 1st phase of partial lockdown (March 1 to March 16, 2020). Furthermore, the O₃ increased by 10% over the same period. The 2nd phase of total lockdown, the 3rd partial lockdown, and the post-lockdown periods witnessed declines in PM_{2.5} by 8%, 11%, and 21%, respectively, while the PM₁₀ increases over the same period. Iraqi also witnessed improvement in the AQI by 8% during the 1st phase of total lockdown compared to the 1st phase of partial lockdown. The level of air pollutants in Iraq declined significantly during the six lockdown periods as a result of reduced human activities. This study gives confidence that when strict measures are implemented, air quality can improve.

Keywords Air pollution · Iraqi provinces · COVID-19 · Lockdown · Air quality index

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Introduction

On December 31, 2019, a novel coronavirus was reported in the Wuhan region of Central Hubei Province, China (Shi et al. 2020). Subsequently, the World Health Organization (WHO) named the novel coronavirus as COVID-19 and classified it as a novel group of coronaviridae that is also called severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (Hassan et al. 2020) owing to its close similarity to the earlier virus that caused the 2002–2003 epidemic called severe acute respiratory syndrome (SARS) (Xu et al. 2020a). More than 8000 people from various countries were infected with SARS-CoV while more than 774 persons died. In 2012, another coronavirus called MERS coronavirus (MERS-CoV) emerged in the Middle East, infecting about 2494 with a disease called “Middle East respiratory syndrome” whereas about 860 persons died from it (Munster et al. 2020). It was initially thought that COVID-19 has a zoonotic origin (Lu et al. 2020) as the earlier two coronavirus-related diseases (MERS and SARS) originated from human interaction with animals. Since the emergence of COVID-19 in Wuhan, China, it has spread to almost all the countries of the world (Li et al. 2020), causing different degrees of respiratory illness. Owing to the rate of its spread throughout the world, it was subsequently declared a pandemic by the WHO on January 30, 2020 (Lu et al. 2020). Since then, it has been reported in almost all regions of the world (WHO 2020). The pandemic has been felt in at least 190 countries; as of August 31, 2020, more than 25,154,771 infections have been confirmed while 844,605 deaths were reported (<https://covid19.who.int/>).

According to the WHO, COVID-19 is contracted via direct contact with a person that has been infected by the virus, or through touching surfaces that carry the virus. One major source of worry regarding this virus is that it presents similar symptoms as other mild viral diseases, including dry cough, flu, fever, and sore throat (Huang et al. 2020). Some measures have been put in place to reduce the spread of the virus; these include personal hygiene, maintaining proper social distance, avoiding large gatherings, and staying home when there is no need of going outside to reduce the risk of contracting the virus (Bherwani et al. 2020; Gautam and Hens 2020). With these measures in place, human activities have been greatly impacted and both local and global economies have been adversely impacted (Chu et al. 2020; Long and Feng 2020; Sharifi and Khavarian-Garmsir 2020).

Iraq confirmed the COVID-19 index case in Najaf, southern Baghdad on the 24th day of February 2020 (WHO, situation report-36). In a bid to ensure appropriate

control of the virus, series of lockdown measures (partial and total) were announced by the Iraqi government on March 1, 2020; this included the closing of schools, airports, railways, and restriction of all forms of movement between provinces (Jebril 2020). As of August 31, 2020, Iraq has already confirmed more than 234,934 cases of COVID-19 and more than 7042 deaths (Ministry of Health 2020).

Being a pandemic, the lockdown measures that were announced to prevent the spread of the pandemic (Wu and McGoogan 2020) have negatively affected human activities in the form of restricted vehicle use, public transportation, and other economic activities (Gautam and Trivedi 2020; Pata 2020; Bashir et al. 2020; Shehzad et al. 2020). But one good aspect of the restrictions is that air quality has greatly improved during the lockdown periods owing to reduced human activities and low emission of air pollutants. One major problem of the twenty-first century has been the continuous deterioration of air quality due to different kinds of human activities (Motesaddi et al. 2017; He et al. 2020). Air pollution remains a major public health threat globally (Begum et al. 2013; Tung et al. 2014; Tusher et al. 2019) and being that more than 55% of the global population lives in the industrialized areas (United Nations 2019), air pollution due to various industrial activities remains a global threat (Lelieveld et al. 2015). In 2016, more than 4.2 million people died prematurely due to pollution-related illnesses globally (WHO 2019).

Air pollution is defined as the suspension of particulate materials (< 2.5 or $10 \mu\text{m}$; $\text{PM}_{2.5}$ and PM_{10}) in the air; there is also increased concentrations of different gases in the air, such as nitrogen dioxide (NO_2), volatile organic compounds (VOCs), ozone (O_3), and carbon monoxide (CO) released from vehicle exhaust pipes and industrial activities (Cohen et al. 2017). NO_2 is one of the highly reactive gases identified as nitrogen oxides (NO_x); it irritates the human respiratory system and can endanger the ecosystem via the formation of acid rain and nitric acid (EPA 2020a). Particulate materials (PM) are the major component of air pollutants (Burke 2020) as they are a mixture of different materials suspended in the air. They are a threat to human health as they enter the bloodstream and the human lungs. Most cases of poor visibility are associated with a high concentration of $\text{PM}_{2.5}$ in the air (EPA 2020b). Owing to the effect of ground-level O_3 on human health, it is considered the most harmful air pollutants (Sicard et al. 2016, 2019; Nuvolone et al. 2017).

The Iraqi economy relies mainly on the energy sector as it is the main source of foreign exchange. Fossil fuels are mainly used for energy production in Iraq and due to population growth, the demand for local consumption has increased tremendously (Hashim et al.

2020b). The activities involved in gas flaring, oil refining, and generation of electricity, as well as the increase in people movement, have all contributed to air contamination in Iraq (IEA 2012). Despite the abundance of fossil fuel for energy production in Iraq, the national electric power grid has not lived up to expectation and people have resorted to various sizes of power generators to meet their energy needs; these are contributors to the deteriorating quality of air in Iraq, especially in the big cities like Basra and Baghdad (Ministry of Environment 2016). As Iraq is notorious for various high-density traffic areas, high levels of emission of different pollutants are expected and the impact on the environment and the economy is expected to be on the increase (Jassim et al. 2014).

Most studies in many countries have recently focused on changes in air quality (Das et al. 2020; Sulaymon et al. 2021; Vulichi et al. 2021) and water quality (Khan et al. 2021) during this era of COVID-19. There are no studies so far that have dealt with studying air pollution during the Covid-19 pandemic at the level of Iraq. As a result of this knowledge gap, few studies have addressed the issue of air pollution during the pandemic. For instance, the effect of COVID-19-related lockdown measures on the levels of air pollutants in Baghdad, Iraq, has been studied by Hashim et al. (2020a) from February 24 to July 24, 2020. The study focused on the analysis of the daily $PM_{2.5}$, PM_{10} , NO_2 , and O_3 concentrations pre-and during the national lockdown periods in Baghdad. During these periods, Baghdad witnessed decreases in NO_2 , $PM_{2.5}$, and PM_{10} levels by 6%, 8%, and 15%, respectively from the 1st March to 21st April 2020 (covering the 1st phase of partial and complete lockdown) in comparison to the pre-lockdown period. A 13% increase was also observed in O_3 concentration over the same period. From 14th June to 24th July (2nd phase of partial lockdown), there was a 20% decrease in NO_2 level and 2.5% decrease in $PM_{2.5}$ level while O_3 level decreased by 52% and PM_{10} level increased by 56% within the same period. Baghdad also witnessed a 13% improvement in air quality index (AQI) from March 1 to April 21, 2020 (1st partial lockdown) in comparison to the pre-lockdown period.

The decline in the levels of air pollution as a result of the measures to contain the novel coronavirus has been the focus of many studies, especially in China where the virus emerged in 2019 (Shakil et al. 2020). For instance, the study by Xu et al. (2020b) reported a 30% and 40% decline in $PM_{2.5}$, and PM_{10} concentration while SO_2 , NO_2 , and CO concentrations decreased by 61%, 33%, and 28%, respectively over three Central China cities in February 2020. Another study by Bao and Zhang (2020) reported an average decline of 7.8% in AQI over 44 northern China cities. In the same

manner, a significant reduction in air pollutant levels ($PM_{2.5}$, PM_{10} , CO , SO_2 , and NO_2) have been reported across different regions of the world during the period of the COVID-19 pandemic (Wang and Su 2020; Collivignarelli et al. 2020; Dantas et al. 2020; Kerimray et al. 2020; Nakada and Urban 2020; Cárcel-Carrasco et al. 2021; Bhat et al. 2021).

In Iraq, the changes in daily average O_3 , NO_2 , $PM_{2.5}$, PM_{10} , and AQI were calculated over the six phases of partial and total lockdown (March 1 to August 20, 2020), as well as during the post-lockdown period (August 21 to 31, 2020). The study mainly aimed at evaluating the differences in the average daily concentrations (in $\mu g/m^3$) and relative variation (in %) between the six periods of partial, total, and post-lockdowns. Also, the daily concentrations of different air pollutants and AQI in 18 Iraqi provinces. In this study, the focus is on the impacts of the COVID-19-related lockdown periods on air quality in all provinces in Iraq; it should be noted that Baghdad and Basra are among the places with high levels of air pollution in the Middle East due to high human activities (Ministry of Health and Environment 2016).

Material and methods

Study area

Being a Middle Eastern country, Iraq is located approximately on 33° 00' N latitude (between 29° 02' N and 37° 23' N) and 44° 00' E longitude (between 38° 47' E and 48° 35' E). Iraq has a total area of 438,317 km², with the residents mostly settled along the Tigris and Euphrates Rivers in the eastern, northern, and central regions of the country. Due to harsh weather and lack of basic facilities, most of the western and southern regions are partly inhabited; hence, both regions are mostly desert areas (Chabuk et al. 2020). The middle and southern regions of Iraq have varying climates, ranging from continental and subtropical to arid and semi-arid, while the mountainous northern and north-eastern regions have a Mediterranean climate, as shown in Fig. 1 (Al-Ansari et al. 2018; Salman et al. 2020). Rainfall is mainly experienced during December to February but can extend to 6 months (November–April) in the northern and north-eastern regions. The average winter temperature is about 16 °C, with the day temperature dropping to about 2 °C while the night temperature reaches sub-zero. During the summer periods, the weather is extremely hot, with day temperature reaching over 43 °C in July and August and drops to around 26 °C at night (The World Bank 2006; Frenken 2009).

Fig. 1 Topographic and climatic zones of Iraq (Salman et al. 2020)

Data sources

The research methodology is based on studying the daily concentrations of four air pollutants in the provinces of Iraq during the period of partial and total lockdown. Because data on these pollutants were not available from the official Iraqi authorities during or before the aforementioned period, due to technical and administrative problems. The air pollution data used in this study was captured from an online monitoring system (<https://air.plumelabs.com/en/>) that captures and analyses the quality of air over a region (World Air Map 2020). The daily NO₂, O₃, PM_{2.5}, and PM₁₀ levels were measured for all the 18 Iraqi provinces during and after the lockdown periods (March 1 to August 31, 2020); the AQI was also measured for the same period. There were no records of the NO₂, O₃, PM_{2.5}, and PM₁₀ concentrations for the previous years. On the other hand, the mentioned pollutants are the most air pollutants in Iraq, due to the spread of power generation and the oil industry in many places in Iraq, in addition to the increasing number of vehicles (Ministry of Environment 2016). The partial, total, and post-lockdown periods in Iraq (March 1 to August 31, 2020) considered in this study are shown in Table 1.

AQI calculations

The AQI of the provinces during the considered period of study was calculated to understand the overall changes in air

quality. To calculate the AQI values, the concentrations of a minimum of three air pollutants (such as NO₂, O₃, PM_{2.5}, and PM₁₀) must be available as these concentrations are to be transformed into numbers on a scale of 0–500. Equation 1 is used for the sub-index AQI (AQI_{*i*}) calculation for each pollutant (i).

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

where C_i is the air concentration of pollutant “i”; IN_{HI} and IN_{LO} are the related AQI values; and B_{HI} and B_{LO} are the breakpoint pollutant concentrations (greater than and less than C_i). The overall AQI represents the max. AQI_{*i*} while the related pollutant is the leading pollutant. AQI values can be

Table 1 Partial, total, and post-lockdown periods in Iraqi provinces from March 1 to August 31, 2020, for the current study

Situation	Partial and total lockdown periods
During 1st partial lockdown	March 1 to 16, 2020
During 1st total lockdown	March 17 to April 21, 2020
During 2nd partial lockdown	April 22 to May 23, 2020
During 2nd total lockdown	May 24 to June 13, 2020
During 3rd partial lockdown	June 14 to August 19, 2020
End partial lockdown	August 20 to 31, 2020

classified into 6 categories as follows: good (0–50), satisfactory (51–100), moderate (101–200), poor (201–300), very poor (301–400), and severe (401–500) (Sharma et al. 2020).

Results and discussion

Assessment of air pollution levels during COVID-19

Various human activities were restricted during the lockdown measures to contain the spread of COVID-19. As a result, there were significant declines in energy demand and consumption. These declines in energy demand impacted the transportation sector severely and consequently reduced the rate of air pollutant emission; hence, air quality was significantly improved during these periods of lockdown.

NO₂ concentration

The observed daily average concentrations of NO₂ (µg/m³) in the Iraqi provinces during and after the lockdown periods (March 1 to August 31, 2020) are shown in Fig. 2a. From March 1 to March 16 (the 1st partial lockdown period), the daily average concentration of NO₂ significantly reduced in Iraq as transportation activities were significantly restricted due to the implementation of the rules on social distancing; on average, the NO₂ concentration was 42 µg/m³ during this period. The 1st period of total lockdown (17th March 2020 to 21st April 2020) witnessed a decline in daily NO₂ concentration, reaching 39 µg/m³. To ease the restriction measures on citizens, a 2nd partial lockdown period was imposed from April 22 to May 23 and during this period, there was a significant increase in the average daily NO₂ concentrations in Iraq, reaching 42 µg/m³. As the number of confirmed COVID-19 cases increased in Iraq, the 2nd phase of total lockdown was implemented from 24th May 2020 to 13th June 2020, and during this period, the daily average NO₂ concentrations reduced to 38 µg/m³. However, the relaxation of the 2nd total lockdown and introduction of the 3rd partial lockdown phase (from June 14 to August 20, 2020) brought about an increase in the daily average NO₂ concentration in Iraq, reaching 40 µg/m³. Relaxation of the 3rd partial lockdown from August 21, 2020, caused an increase in the average daily NO₂ concentration as it reached 46 µg/m³ throughout Iraq. The daily average concentration of NO₂ in Iraq during the post-lockdown phases in Iraqi provinces is presented in Fig. 2a; observably, the values were still within the limit recommended by WHO which is 200 µg/m³ (World Health Organization 2006). Figure 2b shows the spatial

distribution of the average daily concentrations of NO₂ for Iraqi provinces from March 1 to August 31, 2020. The highest levels of NO₂ were observed in Baghdad and Babylon during the study periods. The average daily NO₂ concentrations for all provinces of Iraq are provided as supplementary material (Fig. 3).

Concentration of O₃

The average daily concentration of O₃ during and after the lockdown periods (March 1 to August 31, 2020) is shown in Fig. 4a. The 1st phase of partial lockdown (March 1 to 16, 2020), witnessed an average daily O₃ concentration of 40 µg/m³. The announcement of the 1st total lockdown phase (March 17 to April 21, 2020) brought about an increase in the average daily concentration of O₃, reaching 44 µg/m³. The 2nd partial lockdown period (April 22 to May 23, 2020) was graced with a slight decrease in daily O₃ concentrations, reaching 43 µg/m³. The reintroduction of a 2nd total lockdown period in Iraq (May 24 to June 13, 2020) brought about the highest increase in the daily average concentration of O₃ as it reached 58 µg/m³ due to low NO₂ concentration and high temperatures. The observed daily average concentration of O₃ in Iraq decreased to 57 µg/m³ from June 14 to August 20, 2020 (3rd partial lockdown). From August 21 to 31, 2020 (the end of the 3rd partial lockdown in Iraq), the average daily O₃ concentrations were reduced to 49 µg/m³. The spatial distribution of the average daily O₃ concentrations for Iraqi provinces from March 1 to August 31, 2020, was shown in Fig. 4b. The highest levels of O₃ were recorded in the Wassit, Missan, and Thi-Qar provinces during the study periods. A supplementary file illustrating the average of the daily O₃ concentrations for all the provinces of Iraq is provided in Fig. 5.

PM_{2.5} concentration

The daily average concentrations of PM_{2.5} (µg/m³) in Iraqi provinces are shown in Fig. 6a (from March 1 to August 31, 2020). Observably, the average daily PM_{2.5} concentration in Iraq was 38 µg/m³ from March 1 to 16, 2020 (1st partial lockdown). From March 17 to April 21, 2020 (1st period of total lockdown), the daily average PM_{2.5} concentration significantly reduced to 29 µg/m³ but from 22nd April to 23rd May 2020 (2nd partial lockdown), there was an increase in the PM_{2.5} concentrations, reaching 38 µg/m³ following the partial reopening of the economy. The 2nd total lockdown period (May 25 to June 13, 2020) saw a slight decrease in the average PM_{2.5} concentration to 35 µg/m³. There were variations in the average daily concentration of PM_{2.5} during the 3rd partial lockdown (June 14 to August 20, 2020) as the

Fig. 2 **a** The average of daily NO_2 concentrations ($\mu\text{g}/\text{m}^3$) in provinces of Iraq, during and post the lockdown from the 1st of March to August 31, 2020. **b** The spatial distribution of the averages of daily NO_2 concentrations for 18 Iraqi provinces from the 1st of March to August 31, 2020

(b)

Fig. 3 The average of daily NO₂ concentrations for provinces of Iraq from March 1 to August 31, 2020

average value was around $34 \mu\text{g}/\text{m}^3$. Upon lifting of restriction at the end of the 3rd partial lockdown (from August 21 to 31, 2020), Iraq witnessed a clear increase in the average daily PM_{2.5} concentrations as it reached $30 \mu\text{g}/\text{m}^3$ throughout the country. Although the observed daily PM_{2.5} concentration in the Iraqi provinces exceeded the recommended WHO limits ($25 \mu\text{g}/\text{m}^3$) (World Health Organization 2006), especially during the 1st total lockdown period, however, most of the observed excesses in PM_{2.5} concentrations during the study period were only during May and June as a result of drought and extreme temperatures in different Iraqi cities. The spatial distribution of the averages of daily PM_{2.5} concentrations for Iraqi provinces from March 1 to August 31, 2020, is shown in Fig. 6b. Observably, Salah al-din and Dahuk provinces recorded the highest PM_{2.5} concentrations during the study periods. A supplementary file detailing the averages of the daily PM_{2.5} concentrations for all the studied Iraqi provinces is presented in Fig. 7.

Concentration of PM₁₀

The observed daily average concentration of PM₁₀ in the Iraqi provinces from March 1 to August 31, 2020, was presented in Fig. 8a. The period from March 1 to March 16, 2020 (1st partial lockdown period) recorded an average daily PM₁₀ concentration of $132 \mu\text{g}/\text{m}^3$ which later declined during 1st total lockdown period (March 17 to April 21, 2020), reaching $112 \mu\text{g}/\text{m}^3$ throughout the studied Iraqi provinces. The period of April 22 to May 23, 2020 (the 2nd partial lockdown) recorded the maximum daily PM₁₀ concentration ($432 \mu\text{g}/\text{m}^3$)

with an average value of $173 \mu\text{g}/\text{m}^3$ for this period. From May 25 to June 13, 2020, there was an increase in the average daily concentration of PM₁₀ (increased to $177 \mu\text{g}/\text{m}^3$) due to the implementation of the 2nd total lockdown. From June 14 2020 to August 20, 2020, there were fluctuations in the daily average concentration of PM₁₀ as the 3rd partial lockdown was in place, with the average value decreasing to $166 \mu\text{g}/\text{m}^3$. However, the end of August witnessed clear declines in the daily average concentration of PM₁₀ (decreased to $125 \mu\text{g}/\text{m}^3$) as a result of the increased movement of wind and dust particles during the summer period. All the observed daily concentrations of PM₁₀ as recorded in Fig. 8a exceeded the recommended limit of $50 \mu\text{g}/\text{m}^3$ by the WHO. The spatial distribution of the average daily concentrations of PM₁₀ for the studied Iraqi provinces from March 1 to August 31, 2020, is shown in Fig. 8b; observably, the highest level of PM₁₀ was recorded in Salah al-din province during the study period. A supplementary file that detailed the average daily PM₁₀ concentrations for all the Iraqi provinces is provided in Fig. 9.

AQI for 18 provinces in Iraq

To study the air quality in all the 18 provinces in Iraq during the different phases of lockdown, the levels of different air pollutants were recorded and presented as the AQI for the regions during the studied periods (see Fig. 10a). The period from March 1 to March 16, 2020 (1st partial lockdown period) saw the average AQI values ranging from 88 to 175 and averaged at 120;

Fig. 4 **a** The average of daily O_3 concentrations ($\mu g/m^3$) in provinces of Iraq, during and post the lockdown from the 1st of March to August 31, 2020. **b** The spatial distribution of the averages of daily O_3 concentrations for 18 Iraqi provinces from the 1st of March to August 31, 2020

Fig. 5 The average of daily O_3 concentrations for provinces of Iraq from March 1 to August 31, 2020

this implies that the AQI level was within the unhealthy level for sensitive persons (3rd level). The 1st total lockdown period (March 17 to April 21, 2020) witnessed improvements in the AQI values in Iraq, with the average value reaching 111 (8% decline in AQI value between the 1st partial lockdown and 1st total lockdown periods). Iraq witnessed a decline in AQI from April 22 to May 23, 2020 (2nd partial lockdown period); the maximum daily value during this period was 320, with an average value of 153. Average values of 157 and 151 were recorded during the 2nd total lockdown and 3rd partial lockdown, respectively (from May 24 to August 20, 2020). The month of August witnessed improvement in the AQI for Iraq as the average value was recorded as 122. Observably, the period of March–April 2020 (1st total lockdown period) recorded the lowest AQI for Iraq due to the commitment of the citizens to the implemented lockdown measures by the government. These lockdown measures helped to reduce the level of emission of air pollutants into the Iraqi cities as human activities were significantly curtailed. Figure 10b shows the spatial distribution of the average AQI levels for Iraqi provinces from March 1 to August 31, 2020. Among the studied provinces, Basra and Sulaymania provinces recorded the best AQI during the study period. Figure 11 is a supplementary file detailing the average levels of AQI for all the studied Iraqi provinces.

Level of changes in the pollutant concentrations and AQI

Being that there were no records of the NO_2 , O_3 , $PM_{2.5}$, and PM_{10} concentrations for the preceding

years, the obtained values in this study were matched against the values from the lockdown and post-lockdown periods. The daily $PM_{2.5}$, PM_{10} , and NO_2 concentrations were significantly reduced by 24%, 15%, and 8%, respectively during the 1st total lockdown period compared to the 1st partial lockdown period (see Table 2). Similarly, the average NO_2 concentration was significantly reduced during the 2nd total lockdown period and 3rd partial lockdown period by 10% and 5%, respectively in comparison to the 1st period of partial lockdown. The average concentration of $PM_{2.5}$ continued to reduce by 8%, 11%, and 21% during the 2nd total lockdown period, 3rd partial lockdown period, and post-partial lockdown period respectively, when compared to the 1st period of partial lockdown. The concentration of PM_{10} increased by 31%, 34%, and 26%, respectively, during the 2nd partial lockdown period, 2nd total lockdown period, and 3rd partial lockdown period. From August 20 to 31 (end of lockdown periods), the PM_{10} concentration was reduced by 5% in comparison to the 1st partial lockdown period. Dust particles are the major natural source of suspended air particles in Iraq, due to the prevalence of desert regions in the country. The level of suspended dust particles normally reaches the maximum during the summer and spring periods, due to the influence of the arriving depressions from central Asia and the northern Arabian Gulf (1st National Communication, 2016). On the other hand, transportation activities and emissions from power plants, coupled with the availability of different sizes of generating sets, contribute to the suspended air particles in Iraq (Hashim et al. 2020a). The concentration of O_3 showed some levels of fluctuation during the 1st

Fig. 6 **a** The average of daily $PM_{2.5}$ concentrations ($\mu g/m^3$) in provinces of Iraq, during and post the lockdown from the 1st of March to August 31, 2020. **b** The spatial distribution of the averages of daily $PM_{2.5}$ concentrations for 18 Iraqi provinces from the 1st of March to August 31, 2020

Fig. 7 The average of daily PM_{2.5} concentrations for provinces of Iraq from March 1 to August 31, 2020

partial lockdown, total, and post-lockdown periods possibly due to increased solar activities during the lockdown periods in Iraq, especially in June and July. On average, the AQI levels in the Iraqi provinces improved by 8% during the 1st total lockdown period compared to the pre-lockdown period. But this gain was lost during the months of summer in Iraq, reaching 28%, 31%, and 26% in May, June, and July, respectively. The end of August saw a 2% improvement in the AQI of the studied Iraqi provinces. Commercial and industrial activities in the large cities of Baghdad, Basra, Mosul, and Erbil contributed to the poor air quality in the whole of Iraq; a high population and vehicular traffic also contributed to the pollution level in Iraq. The dryness and hotness of the country during the summer season also increase the level of suspended particles in the air, thereby deteriorating the quality of air (Ministry of Environment 2016).

The correlation coefficients between the levels of different air pollutants in the studied Iraqi provinces during the lockdown periods and after the suspension of the lockdown measures are presented in Fig. 12 as supplementary material. Observable, there is a significant correlation between the air pollutants; for instance, the PM_{2.5} and PM₁₀ concentrations showed a high correlation ($R^2 = 0.7247$), implying that both are of a common source. Contrarily, a negative correlation existed between NO₂ and O₃, PM_{2.5} and PM₁₀. A significant decrease was observed in the surface O₃ concentration as the NO₂ increases. At a higher atmospheric NO₂

concentration, most of the NO₂ reacts with O₃ to form NO₂ (Monks et al. 2015).

Summary of outcomes

The modeling results of the current study showed that the daily concentration of NO₂ in the 18 provinces of Iraq has decreased during periods of total lockdown, relative to periods of partial lockdown. Baghdad and Babylon recorded the highest concentration of daily levels among the Iraqi provinces. However, these concentrations are within the limit recommended by the WHO which is 200 µg/m³. On the contrary, daily O₃ concentrations rose to record the highest values in Missan, Wassit, and Thi-Qar. While the lowest values in Baghdad, Babylon, and Erbil. The daily concentrations of PM_{2.5} exceeded the WHO limit (25 µg/m³) during the study period. Salah al-Din and Dahuk topped the provinces of Iraq with the highest daily PM_{2.5} concentration, while the PM₁₀ concentrations were significantly exceeded the WHO limit (50 µg/m³) during periods of partial and total lockdown. Salah al-Din also recorded the highest concentration rate among other provinces. The AQI improved during the 1st total lockdown from March 17 to April 21, in the 18 provinces of Iraq. However, this improvement retreated during the subsequent partial and total lockdown periods, due to the great laxity in applying the measures of the lockdown and social distancing in Iraq.

Fig. 8 **a** The average of daily PM_{10} concentrations ($\mu g/m^3$) in provinces of Iraq, during and post the lockdown from the 1st of March to August 31, 2020. **b** The spatial distribution of the averages of daily PM_{10} concentrations for 18 Iraqi provinces from the 1st of March to August 31, 2020

Fig. 9 The average of daily PM_{10} concentrations for provinces of Iraq from March 1 to August 31, 2020

Importance of research

In addition to the need for an integrated health system and permanent preparedness for emergency crises, the COVID-19 crisis demonstrated the urgent need for a monitoring system for pollutants and air quality. Although Iraq has a number of air pollution monitoring stations deployed in Baghdad and some of the provinces, it does not cover all regions of Iraq; because the pollution control system in Iraq is modern and the operating requirements are not completed in a typical manner. As for the other stations, they will be under maintenance or trial operation (Ministry of Environment 2016).

The most important results of the current study with regard to the study of air pollution in Iraq during partial, total, and post-lockdown periods of COVID-19 are as follows:

- The current study is the first in Iraq to study pollutants and air quality during partial and total lockdown measures due to the COVID-19.
- The need to establish an advanced system for monitoring air pollution in Iraq, at least similar to regional countries.
- Preparing a national database of air pollutants available to citizens and researchers on the Internet.
- The necessity of measuring the concentration of air pollutants on a routine and continuous basis in the provinces of Iraq.
- Focusing on hot spots for air pollutants such as province centers, especially Baghdad and Basra, because they are

among the largest industrial, residential, and commercial areas.

Conclusion

The impact of the reduction in human activities on air quality in Iraq during the COVID-19 lockdown and post-lockdown periods was investigated in this study. A substantial decrease (8%, 10%, and 5%) was observed in the concentration of NO_2 during the 3 phases of complete and partial lockdowns in comparison to the period of 1st partial lockdown. Furthermore, the average $PM_{2.5}$ and PM_{10} concentrations reduced by 24% and 15%, respectively in the studied provinces of Iraq during the period of 1st total lockdown. It was observed that Iraq consistently records higher levels of $PM_{2.5}$ and PM_{10} even before the lockdown period as the observed daily periods pre-COVID-19 normally exceed the recommended limit by the WHO. This is evidence of the contribution of natural elements to the poor air quality in Iraq. The O_3 concentration was improved by 10%, 8%, 45%, 43%, and 23% during the 1st partial lockdown, the partial lockdown, total lockdown, and post-lockdown periods as a result of the reduction in the concentrations of NO_2 and PM_{10} . The 1st total lockdown period in Iraq witnessed an average of an 8% increase in AQI in comparison to the 1st partial lockdown period. However, this improvement was lost during May, June, and July due to the increased suspension

Fig. 10 **a** AQI for Iraq from the 1st of March to August 31, 2020. **b** The spatial distribution of the AQI average levels for 18 Iraqi provinces from the 1st of March to August 31, 2020

Fig. 11 The average of AQI levels for all provinces of Iraq from March 1 to August 31, 2020

of dust particles during the summer months. The lockdown measures aimed at containing the spread of COVID-19 but the impact was greatly felt in the industrial and transport sectors, causing reductions in oil demand and energy consumption. Despite the economic hardships associated with the COVID-19 lockdown measures, one significant benefit of the implemented measures is the improvement in air quality throughout the globe.

This research limited with focus to known the percent variation in air pollution concentration and air

quality index during the COVID-19 partial, total, and post-lockdown in 18 provinces of Iraq. But future studies will consider the relationship between the air pollutants and meteorological variables as well as the effect of the COVID-19 on surface water quality during pre-lockdown, lockdown, and post-lockdown periods over the study area with the help of statistical and geospatial techniques. Likewise, future research will investigate the prediction of air pollutants, AQI, and water quality index by employing the stochastic and machine learning models in the study region.

Table 2 Percentage changes of average NO_2 , O_3 , $\text{PM}_{2.5}$, PM_{10} concentrations, and AQI in Iraqi provinces, between March 1 to August 31, 2020, during the partial, total, and post-lockdown periods

Period	Average of NO_2	Average of O_3	Average of $\text{PM}_{2.5}$	Average of PM_{10}	Average of AQI
March 1 to 16 (during the 1st partial lockdown)	42	40	38	132	120
March 17 to April 21 (during 1st total lockdown)	39	44	29	112	111
Percent reduction	−8%	10%	−24%	−15%	−8%
April 22–May 23 (during the 2nd partial lockdown)	42	43	38	173	153
Percent reduction	0%	8%	0%	31%	28%
May 24 to June 13 (during 2nd total lockdown)	38	58	35	177	157
Percent reduction	−10%	45%	−8%	34%	31%
June 14 to August 20 (during 3rd partial lockdown)	40	57	34	166	151
Percent reduction	−5%	43%	−11%	26%	26%
August 21 to 31 (end partial lockdown)	46	49	30	125	122
Percent reduction	10%	23%	−21%	−5%	2%

Fig. 12 The correlation coefficients between air pollutants (NO_2 , O_3 , $\text{PM}_{2.5}$, and PM_{10}) in air of Iraqi provinces, during and post the lockdown from March 1 to August 31, 2020

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Availability of data and materials Data were obtained from an open-source website and presented in the manuscript itself.

Declarations

Ethical approval The manuscript is conducted within the ethical manner advised by the Environmental Science and Pollution Research.

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