



Assessing the air quality of megacities during the COVID-19 pandemic lockdown: a case study from Makkah City, Saudi Arabia

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Abstract

Many countries are concerned about how concentrations of outdoor air pollutants have decreased due to control measures aftermath of the COVID-19 outbreak. In Saudi Arabia, the measures started with suspending entry to Saudi Arabia on February 27, 2020, and ended with full prevention of Saudis for outdoor movement on April 2, 2020, until the back return to normal life by the start of September 2020. These measures are expected to impact air quality levels during this period by decreasing the concentrations of air pollutants. This paper investigates the major trends of ambient air pollution (SO₂, NO₂, CO, O₃, and PM₁₀), and maps the spatiotemporal variability of air pollutants in Makkah city, using a continuous air quality monitoring network (6 sites) during the pre-pandemic period. Findings indicate the presence of a significant decrease of concentration rates during the lockdown period, compared with the pre-pandemic period, by 26.34% for SO₂, 28.99% for NO₂, 26.24% for CO, 11.62% for O₃, and 30.03% for PM₁₀. Therefore, the vehicular traffic activities represent 25–30% of the total air pollution load in Makkah city. The COVID-19 lockdown conditions in Makkah provide a unique opportunity to evaluate the impact of the reduction of vehicular traffic activities on the air quality levels of Makkah city and similar mega-cities and introduce credible solutions to improve the conditions of the ambient environment and air quality in such settings.

Keywords COVID-19; Air quality · Pollution · Environmental assessment · Traffic · Saudi Arabia

Introduction

It is particularly important, and valuable from an air quality point of view, to evaluate the background concentrations of air pollutants during the coronavirus COVID-19 pandemic and the associated control measures in the action of nationwide lockdown in Saudi Arabia. Makkah city, which is located in

the southwest of the Kingdom of Saudi Arabia (KSA), is considered the holiest city in the Muslim world and is a dense-populated city located about 70 km inland from the Red Sea with millions of Muslims gathered to perform Umrah (fasting month) and pilgrimage (Hajj) every year (Abdou 2014; Munir et al. 2018). KSA exerts tremendous efforts to provide all the required services and to ensure a comforting and sustainable living environment. The atmospheric environment is one of the most critical issues in Makkah, especially during Hajj and Ramadan (fasting month).

More than 10 million Muslims are gathered annually in Makkah to perform Umrah. The Umrah performers are distributed over all the year but densely concentrated during the fasting month of Ramadan in the central part of Makkah city around the Holy Mosque, and Hajj (pilgrimage) performers by about three million are visiting Makkah during the Hajj month (nearly between August and October for the last decade). All these performers of Umrah and Hajj in addition to residents of Makkah contribute to the increasing use of traffic activities that may lead to air pollution (General Authority for Statistics (GAS) 2019).

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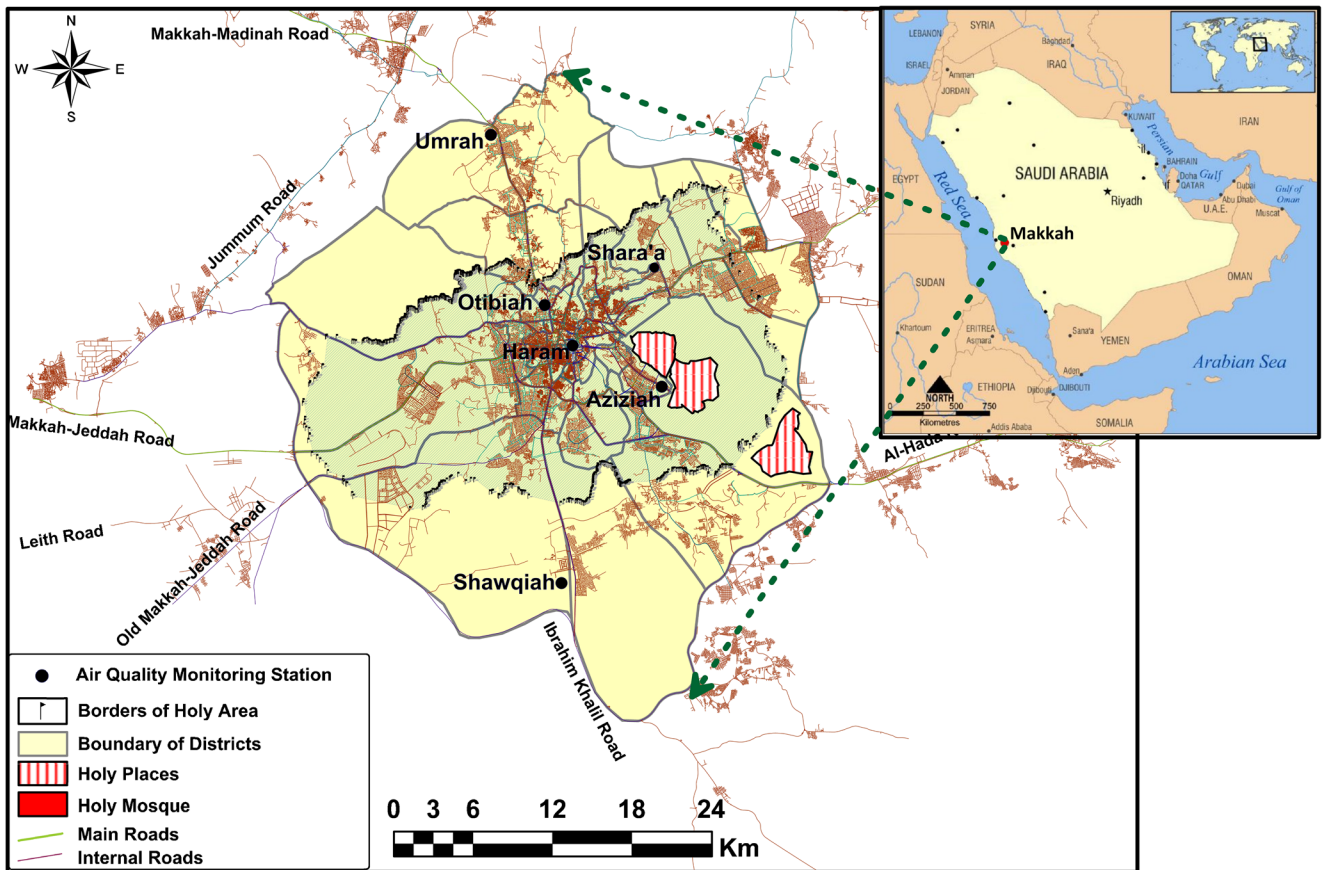


Fig. 1 The location of six air quality monitoring stations in Makkah

Numerous researchers have studied the pollution levels of atmospheric pollutants in Makkah (e.g., Munir et al. 2013a, b; Habeebullah 2013a, b; Seroji 2011; Munir and Habeebullah 2018). However, most of these studied concentrated on the particulate matter concentration (PM10), which is considered the main vital pollutant of concern in Makkah city, in addition to some studies that focused on Ozone (O₃). Therefore, it is an interesting subject to investigate the background levels of air pollutants during the COVID-19 lockdown (March 11 to August 31, 2020) in Makkah city.

During the COVID-19 outbreak in Saudi Arabia, the first confirmed case was detected on March 2, 2020. In order to control the rapid spread of the COVID-19, the epidemic center, which belong to the Ministry of Health (MoH) in KSA and in Makkah city specifically, more than 1.7 million residents have been placed on effective lockdown on March 23 and the lockdown measures were shortly after implemented in the entire KSA. Holy sites were closed across the nation, public gatherings were cancelled, and people were encouraged to stay at home. All school activities were suspended and were

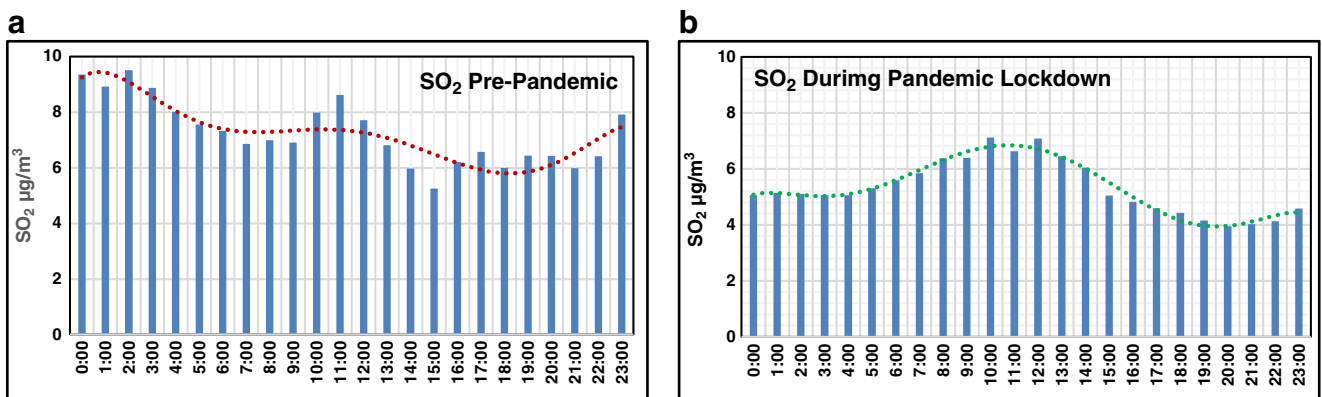


Fig. 2 Diurnal variation of SO₂ in Makkah at a pre-pandemic period and b during pandemic lockdown period

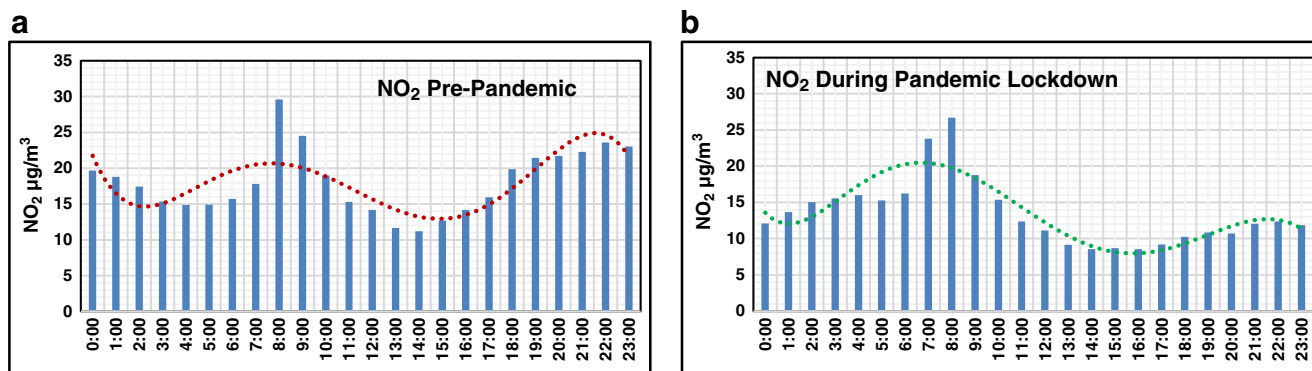


Fig. 3 Diurnal variation of NO₂ in Makkah at a pre-pandemic period and b during pandemic lockdown period

replaced by online teaching platforms. The implementation of lockdown policies has effectively limited inbound and outbound transportation to Makkah except for vital purposes, together with the mobility of people within the entire country has been largely reduced. This has led to a direct impact on the atmospheric environment (MoH 2020).

COVID-19 pandemic has changed the lifestyle completely, due to the exceptional lockdown and the implemented actions including a complete suspension of Holy places, schools, universities, and governmental entities. All these factors encouraged us to investigate the tempo-spatial air quality levels in Makkah to be correlated with the pre-pandemic period (January 1 to March 10, 2020).

The expected enhancement in the levels of air pollutants does not indicate any novelty. Still, the important task is quantifying the rate of decrease in air pollutants levels due to the implemented measures of a sharp reduction in traffic activities and suspending the visitors in the holy places, in addition to all the related issues of public gathering in Makkah, which can be indicative of the limits of measures that can be applied for enhancing the air quality levels in Makkah. The recent research activities that focused on enhancing air pollutants during the COVID-19 lockdown period were related to reducing traffic and industrial activities (Mahato et al. 2020; Tobias et al. 2020; Nakada and Urban 2020; Zambrano-Monserrate

et al. 2020; Selvam et al. 2020). These reports indicated the decrease of air pollutants concentrations by 20–60% in the main cities of Brazil, China, and Spain.

Air contamination that is related to human and traffic activities is a global reality, which leads to several health-associated problems (Chen et al. 2008; Pope III 2007; Dominici et al. 2006; Brook et al. 2004; Hosseini and Shahbazi 2016; Seifi et al. 2019). The COVID-19 pandemic event makes it possible to determine the pollution levels that may be associated with the traffic component in Makkah that will be a useful issue for the researchers to evaluate the rate of this contamination source, then optimizing the most suitable alternatives and solutions for enhancing air quality in Makkah. This research presents a general overview and the major trend of ambient air pollution and mapping the spatiotemporal variability of air pollutants in Makkah city, using a continuous air quality monitoring network (6 sites) during the pre-pandemic (January 1 to March 10, 2020) and during the COVID-19 pandemic lockdown (March 11 to August 31, 2020), throughout the major air quality indicators (SO₂, NO₂, CO, O₃, and PM₁₀) with meteorological parameters (wind speed, wind direction, relative humidity, temperature, and rainfall), in addition to the average rate of decrease of ambient air quality parameters in Makkah resulting from COVID-19 lockdown.

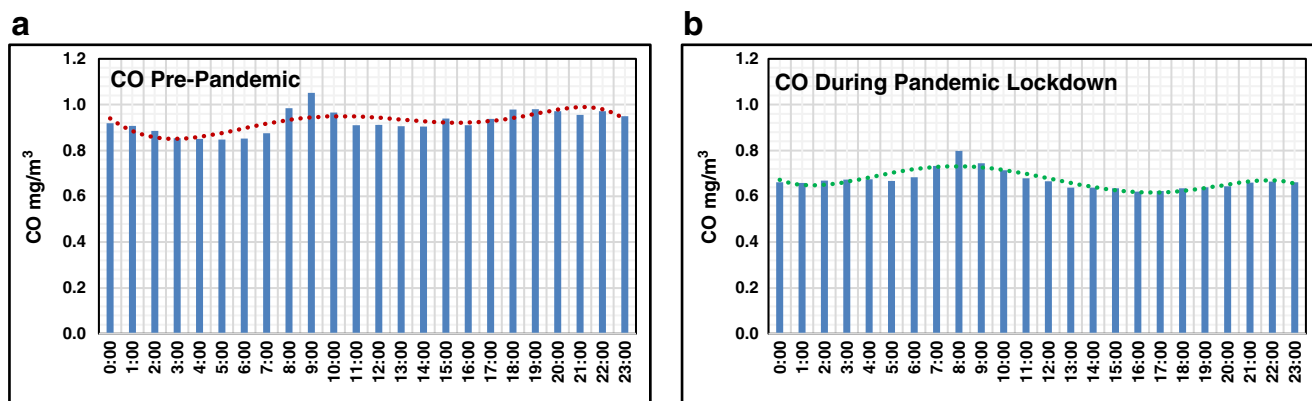


Fig. 4 Diurnal variation of CO in Makkah at a pre-pandemic period and b during pandemic lockdown period

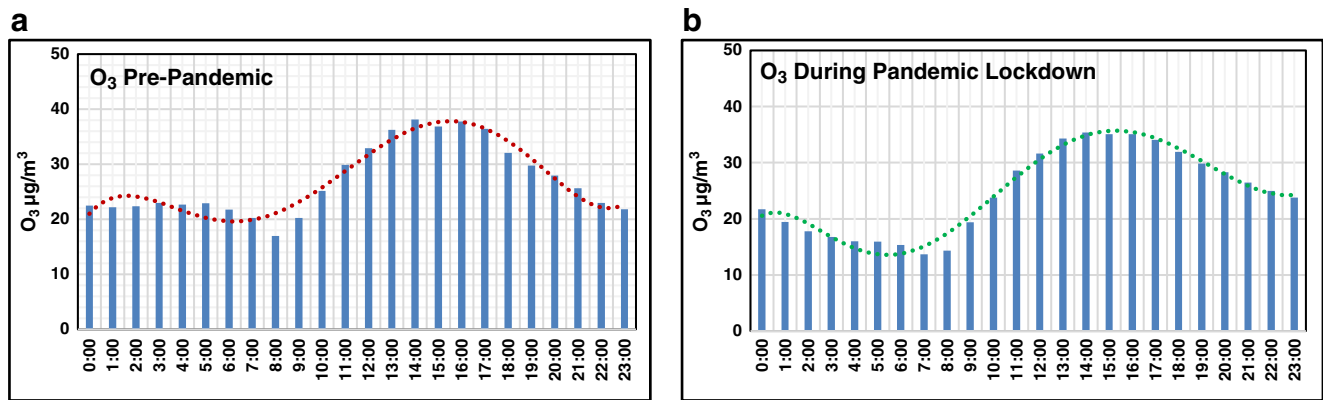


Fig. 5 Diurnal variation of O₃ in Makkah at **a** pre-pandemic period and **b** during pandemic lockdown period

Materials and methods

Makkah is situated within the southern part of the Hijaz region on the west-central part of the Arabian Shield, mainly composed of different types of igneous, metamorphic, and sedimentary rocks of Precambrian and lower Paleozoic age (Greenwood et al. 1976). In addition, there are subordinate sedimentary rocks and basaltic lava flow of Tertiary and Quaternary age (Sonbbl 1995). Topographically, Makkah has been subject to continuous uplift since the Red Sea rifting during the Oligocene time, leading to rough terrain with a varying topography between 300 and 980 m concerning sea level. The ranges of mountains in Makkah are controlled by the Red Sea dominant geological structural elements (Abotalib et al. 2019; Othman and Abotalib 2019) with dominant northwest-southeast (e.g., Mena Mountains) and east-west trends (e.g., El Tarqi Mountains). However, few mountains are isolated and conform semi-circular shape such as Thawr Mountain (755 m) and El Nour Mountain (642 m) (El Bastawesy et al. 2012; Othman et al. 2020).

Globally, networks of air quality monitoring stations can be utilized on the local, national, and worldwide scales (Elkadiri et al. 2016), due to the cumulative observations of the collected data on long-term periods: (a) a full understanding of dominant trends of pollution on the studied sites, (b) evaluation of the abrupt episodes of air pollution, (c) informing the public

by the levels of local air quality, and (d) providing the decision-makers and policymakers with the accumulated levels of air quality to optimize the most compatible strategies for controlling the pollution levels (Cyrys et al. 2012).

Instrumentation and analytical methodologies of air quality analyzers vary depending on the detection and trace species techniques: NO and NO₂ (APNA370: chemiluminescence); O₃ (APOA370: UV photometric); SO₂ (APSA370: UV fluorescence); CO (APMA370: IR Absorption); PM₁₀ (BAM1020: bray). Controlling the quality and assurance of air quality data was based on the standard operation procedure (SOP) published by PME.

In the current research, the utilized air quality data were derived from a total of six fixed continuous air quality monitoring stations (AQMS), which belong to the Presidency of Meteorology and Environment (PME). These AQMS stations are distributed in Makkah city to cover the most dominant activities such as (1) Haram AQMS (21.42464, 39.82917) that located in the eastern yard of the Holy Mosque and representing the traffic and visitors activities, (2) Taneem AQNS (21.50847, 39.79339) situated on the northwest of Makkah city which represents the industrial activities and the already-existing power plants; (3) Otebiah AQMS (21.44222, 39.81189), which is located around Holy Mosque and represent the mixed activities of traffic and

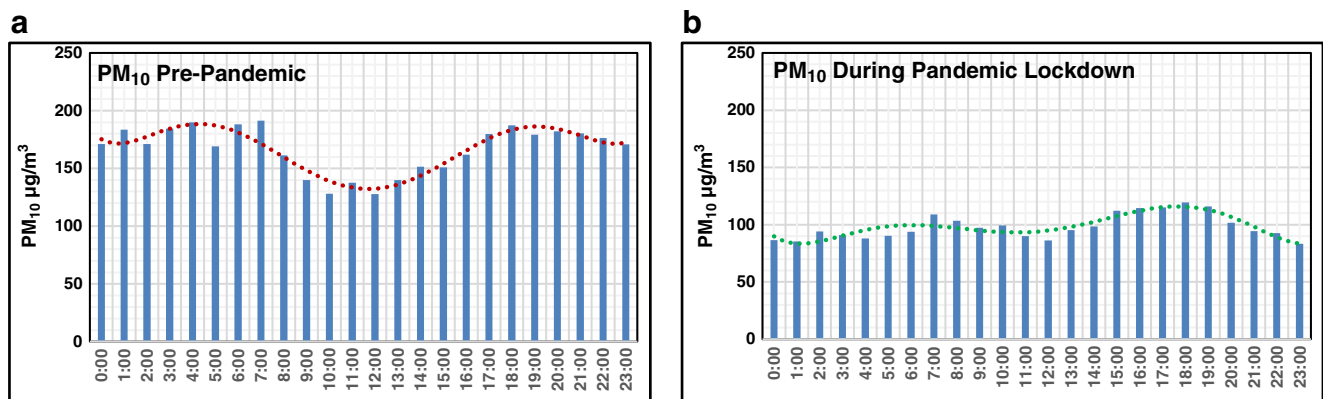


Fig. 6 Diurnal variation of PM₁₀ in Makkah at **a** pre-pandemic period and **b** during pandemic lockdown period

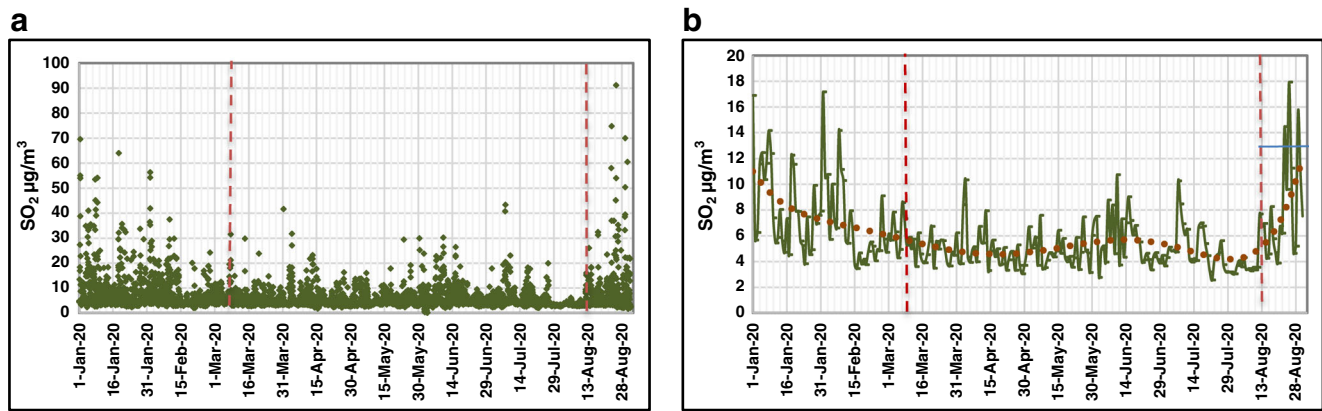


Fig. 7 Concentration of SO₂ at Makkah **a** hourly average, **b** daily average

housing; (4) Shawqia AQMS (21.36589, 39.80747) situated southwest of Makkah and equivalent to residential activities; (5) Aziziah AQMS (21.40377, 39.87837) located close to Holy Mosque and contains a large number of hotels; and (6) Shara’a AQMS (21.46472, 39.93919), which represents a major residential area and is located in the east of Makkah (Fig. 1).

The statistical treatment of air quality data through the current study using the Microsoft Excel and the “Grapher” software packages was utilized to investigate the temporal variations and the “SURFER” packages was applied to represent the spatial variations of the air quality data in the form of contour maps.

The average percent reduction of ambient air quality parameters in Makkah as a result of COVID-19 lockdown was computed using the following equation:

$$APR = \left(\frac{(DAQP_{1Jan-10 Mar.} - DAQP_{11 Mar.-31 August})}{DAQP_{1Jan-10 Mar.}} \right) \times 100 \quad (1)$$

where

APR average percent reduction of air quality parameter,

DAQP_{1Jan-10 Mar.} daily average of air quality parameter during pre-pandemic period (January 1 to March 10, 2020), and

DAQP_{11 Mar.-31 August} daily average of air quality parameter during pandemic period (March 11 to August 31, 2020).

Results and discussion

Overview and major trend of air pollution concentrations in Makkah

In Makkah, it is interesting to indicate that the daily pattern (diurnal variation) of SO₂ concentration in our study is exactly similar to day-to-day variations of vehicular traffic activities. The morning peak is only likely due to vehicular traffic in the morning (10:00 and 11:00), whereas another peak can be related to the traffic of light-duty vehicles in the late afternoon and early evening accompanied by increasing heavy-duty vehicle-related traffic during night-time (after 23:00) as a traffic restriction, construction/demolition activities, and their related-waste transfer and management, open burning of solid waste, switching of the air pollution control equipment at night (Fig. 2a), whereas during the pandemic lockdown period (March 11 to August 31, 2020), the peaks are not well marked that can be interpreted by the commitment of Makkah residents to the precautionary measures of COVID-19 (Fig. 2b).

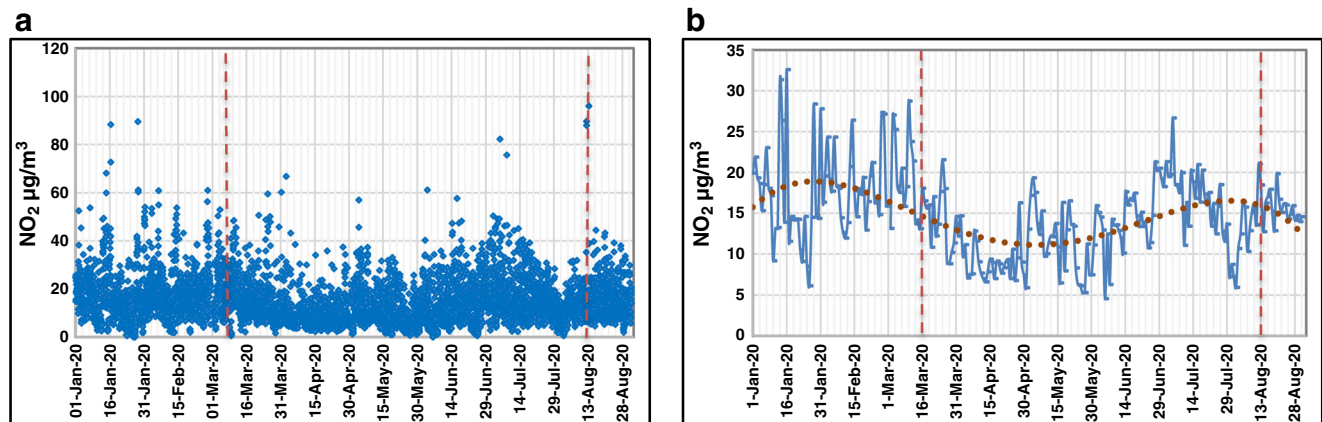


Fig. 8 Concentration of NO₂ at Makkah **a** hourly average, **b** daily average

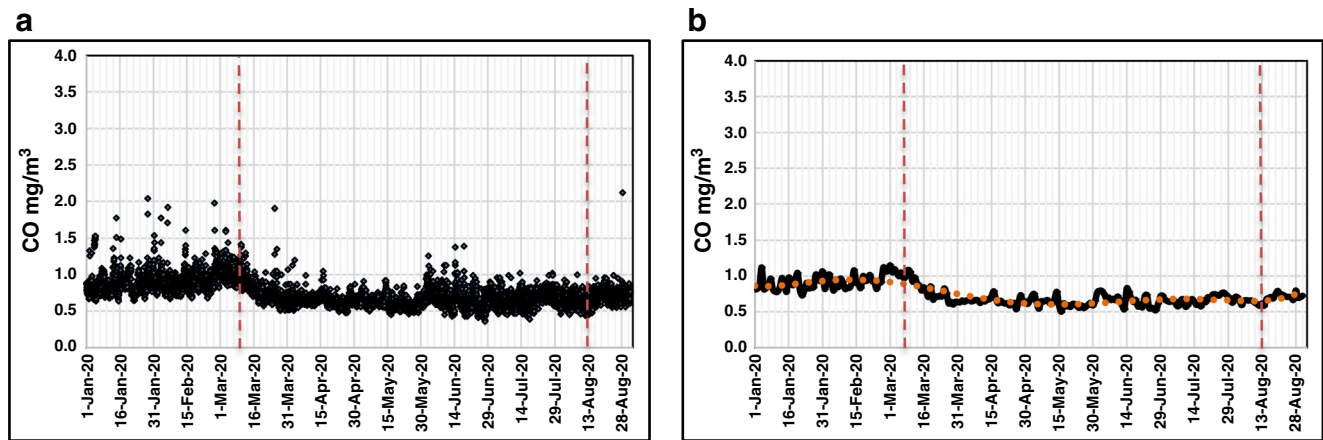


Fig. 9 Concentration of CO at Makkah **a** hourly average, **b** daily average

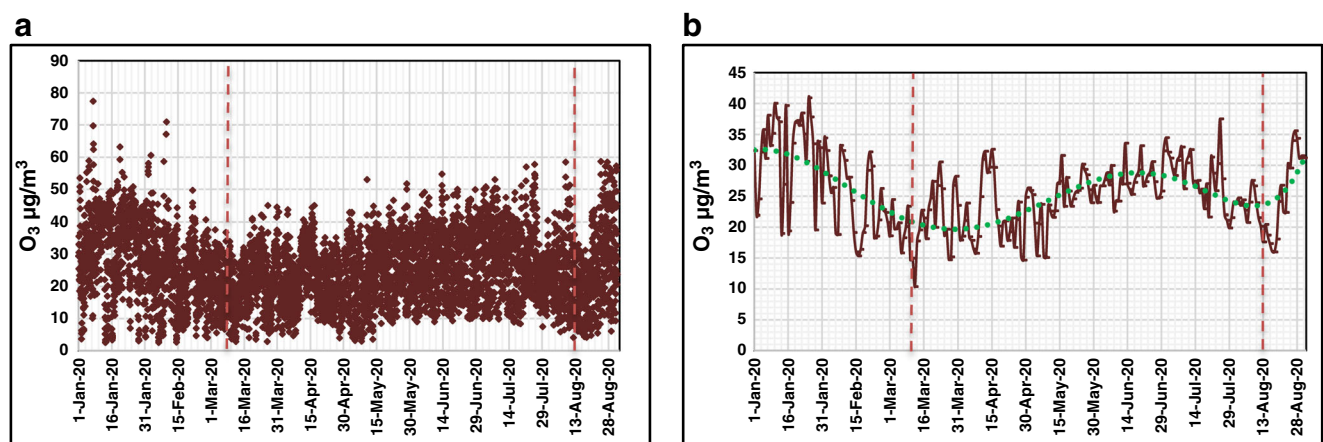


Fig. 10 Concentration of O₃ at Makkah **a** hourly average, **b** daily average

Similar to ambient diurnal variation of SO₂ concentration in Makkah on pre-pandemic conditions (January 1 to March 10, 2020), NO₂, and CO hourly diurnal variation are clearly exhibited two peaks and two troughs, mainly reflecting the effect of traffic emissions and meteorological conditions (Figs. 3 and 4). After the observed peaks at 7:00 and 8:00, the concentrations of NO₂, and CO started to decrease and reached their lowest

concentrations at 14:00 and 15:00 due to a combination of increasing boundary layer height, wind speed (WS), solar radiation (SR), and photochemical reactions in order to produce O₃ coupled with decreasing vehicle traffic emissions as evident by decreased ambient NO₂. The night-time concentrations of NO₂ and CO were significantly lower than those observed during the daytime, mainly because of the above-mentioned reasons, as well

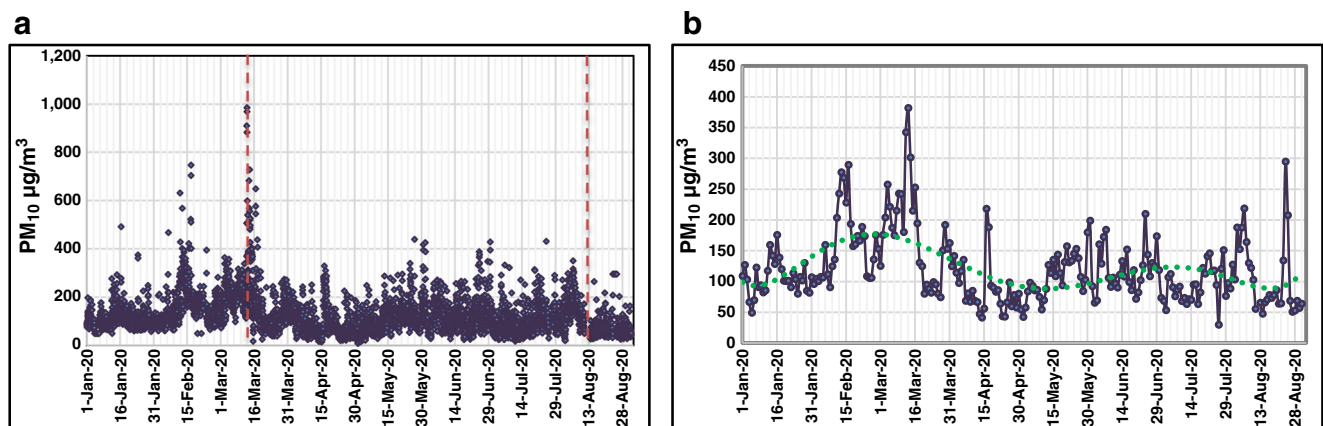


Fig. 11 Concentration of PM₁₀ at Makkah **a** hourly average, **b** daily average

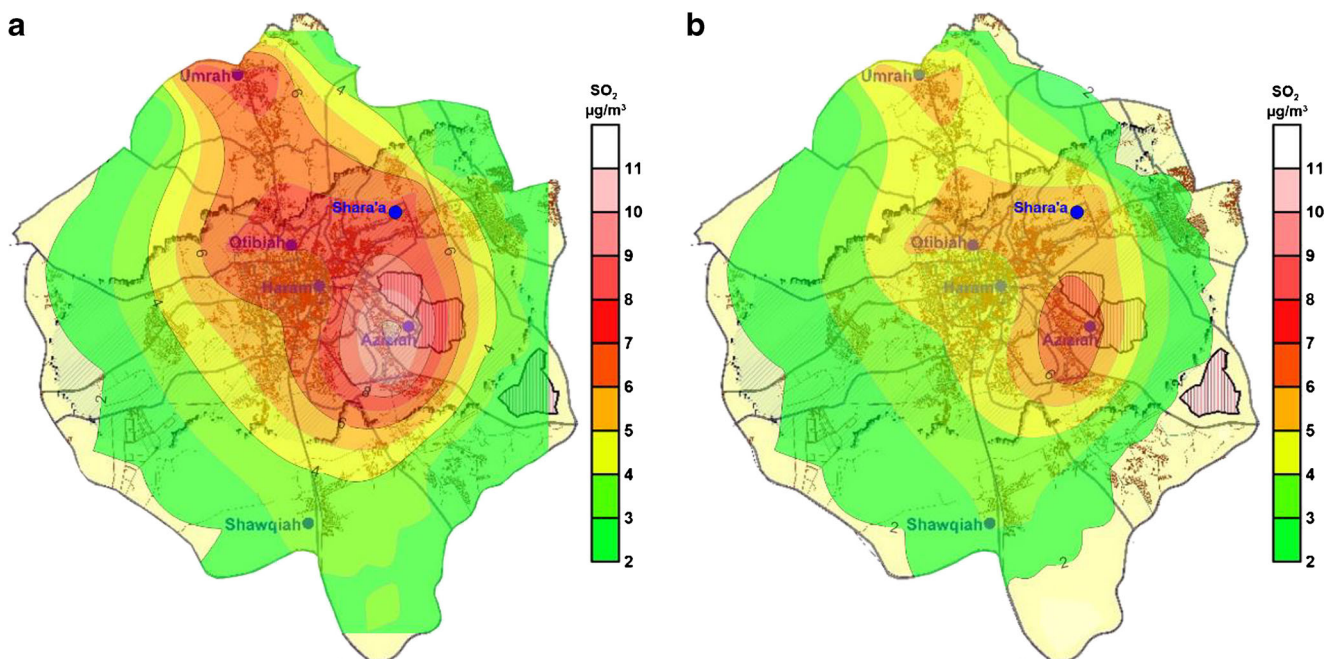


Fig. 12 Contour map of daily average SO₂ concentration in Makkah at a pre-pandemic period and b during pandemic period

as the lack of photochemical reactions for their destruction and consumption to produce ambient O₃ (Hu et al. 2014; Heger and Sarraf 2018; Taghvaei et al. 2018a, b; Henschel et al. 2015; Askariyeh and Arhami 2013; Song et al. 2017; Ezimand and Kakroodi 2019; Zuberi et al. 2015).

Furthermore, diurnal variation of O₃ revealed a sharp mountain-peak-shaped pattern after midday (15:00 and 16:00) owing to higher SR and photochemical reactions in the early afternoon (Fig. 5). Unlike other air pollutants, SO₂

revealed no specific hourly pattern, though its hourly variation and its concentration was statistically significant in the vast majority of hours. O₃ formation was also affected by solar radiation's intensity (MEE 2016, 2017 and 2018; Henschel et al. 2015; Tonse et al. 2008).

According to the diurnal variation of PM₁₀, two peaks were observed; one in the morning (07:00) and another in the night (18:00) (Fig. 6a), with concentrations of 191.3 and 187.3 µg/m³ respectively during the pre-pandemic. Moreover, as shown

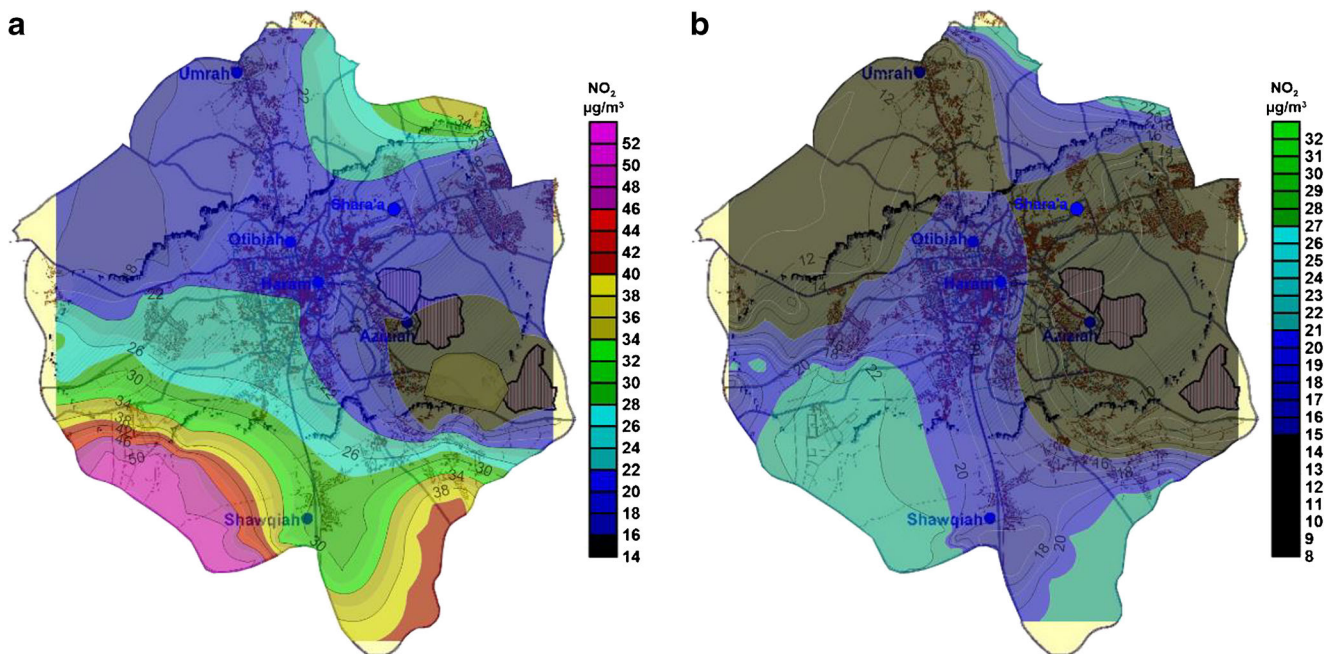


Fig. 13 Contour map of daily average NO₂ concentration in Makkah at a pre-pandemic period and b during pandemic period

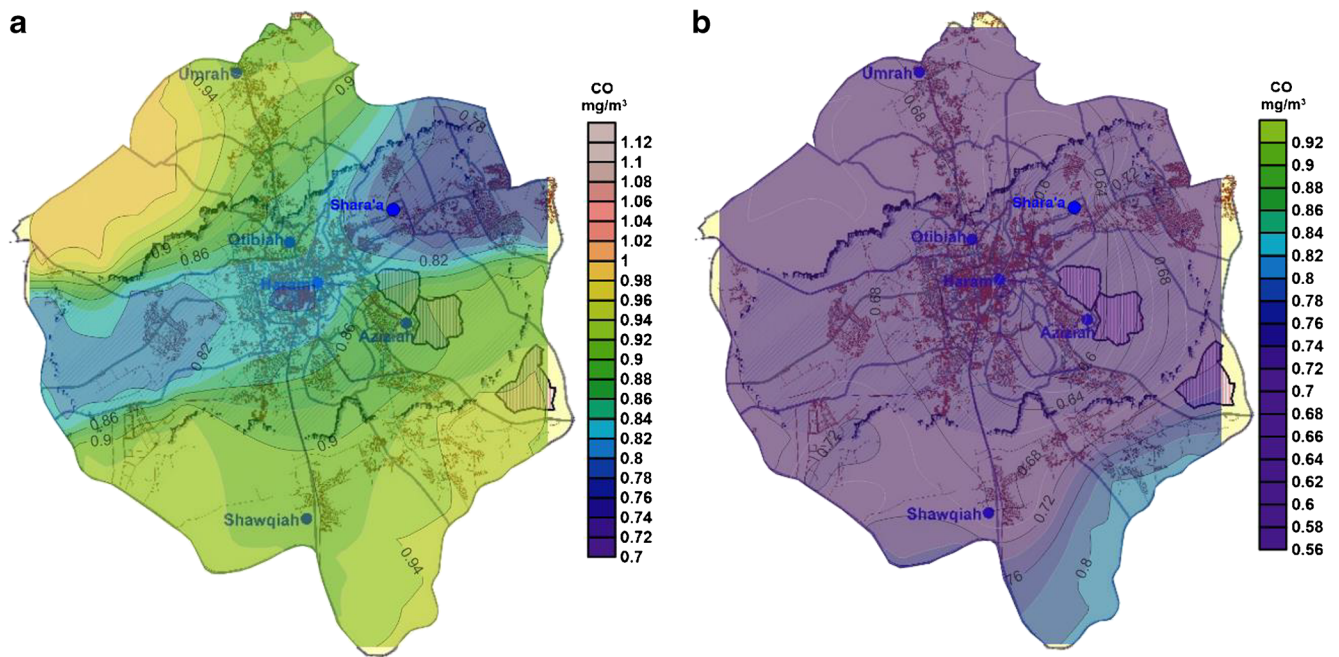


Fig. 14 Contour map of daily average CO concentration in Makkah at a pre-pandemic period and b during pandemic period

in Fig. 6b, the PM₁₀ concentrations were flat throughout the daytime during the pandemic lockdown period (March 11 to August 31, 2020) and the peaks are not well marked that can be interpreted by commitment of Makkah residents to the precautionary measures of COVID-19. It is worth noting that hourly patterns of PM₁₀ are commonly used as a notable marker of combustion emissions from road traffic and traffic-related emissions and meteorological conditions (Geng et al. 2015; Xu et al. 2016; Faridi et al. 2018;

Taghvaei et al. 2018a, b; Squizzato et al. 2018; Alizadeh-Choobari et al. 2016; Ahmed et al. 2015; Hu et al. 2014).

Temporal variation of air pollutants in Makkah

By correlating the hourly average concentrations of five criteria of air pollutants in Makkah for the six AQMS distributed all-over Makkah, during the emphasized period from January 1 to August 31, 2020, the hourly average

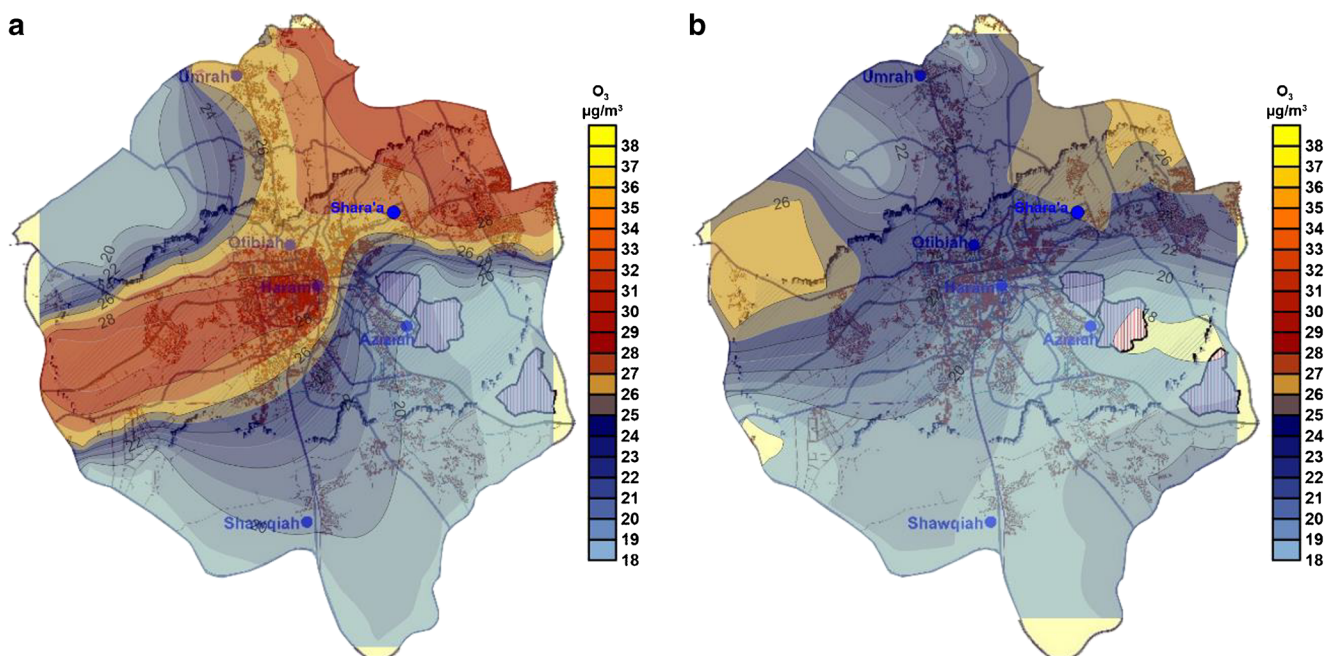


Fig. 15 Contour map of daily average O₃ concentration in Makkah at a pre-pandemic period and b during pandemic period

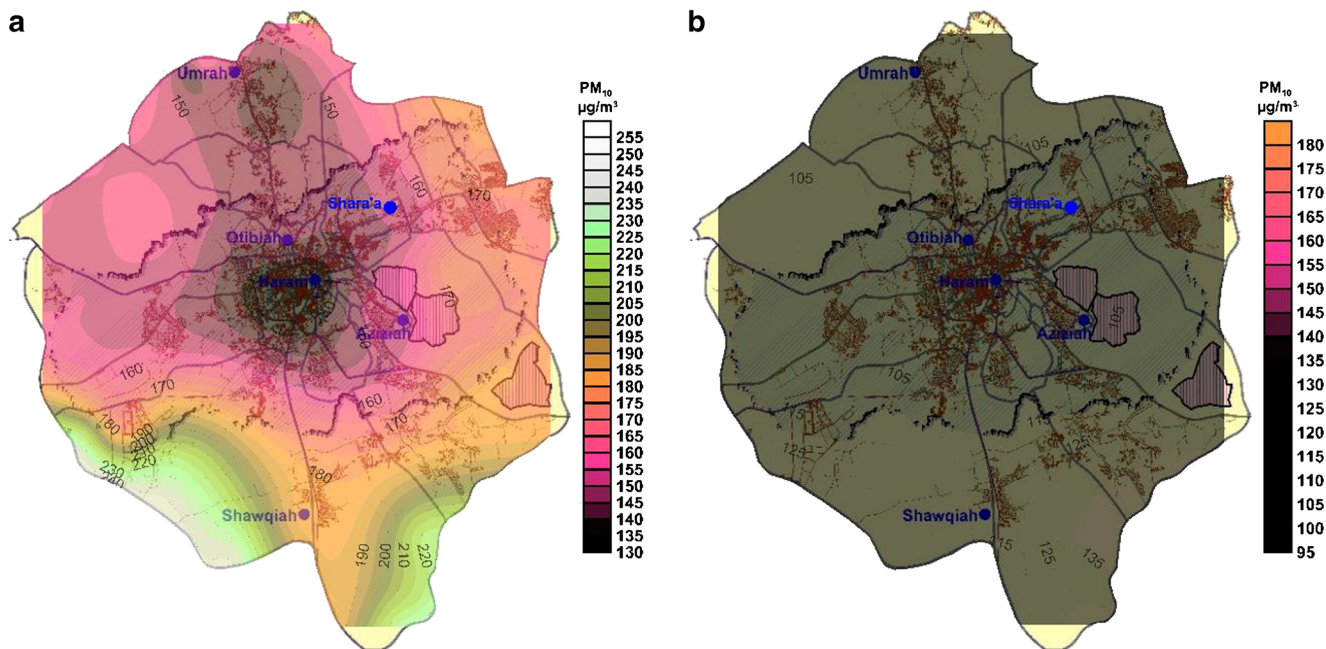


Fig. 16 Contour map of daily average PM₁₀ concentration in Makkah at **a** pre-pandemic period and **b** during pandemic period

concentration for SO₂, NO₂, CO, O₃, and PM₁₀ was registered during the pre-pandemic period (January 1 to March 10, 2020) as mean for all six AQMS stations with approximately 7.27, 18.10, 0.93, 26.98, and 142.0 µg/m³ respectively, whereas the daily average concentration of SO₂ (7.22 µg/m³), NO₂ (18.13 µg/m³), CO (0.93 mg/m³), O₃ (26.76 µg/m³), and PM₁₀ (143 µg/m³) (Figs. 7, 8, 9, 10, and 11), while during the period from March 11 to August 31, 2020 (that equivalent to COVID-19 lockdown), the hourly average concentration for SO₂, NO₂, CO, O₃, and PM₁₀ was registered as mean for all six AQMS stations with approximately 5.31, 13.48, 0.67, 24.77, and 112.0 µg/m³ respectively, whereas the daily average concentration of SO₂ (5.31 µg/m³), NO₂ (13.38 µg/m³), CO (0.67 mg/m³), O₃ (24.90 µg/m³), and PM₁₀ (111 µg/m³) (Figs. 7, 8, 9, 10, and 11).

The average hourly concentration of SO₂, NO₂, CO, O₃, and PM₁₀ was lower than the PME (General Presidency of Meteorology and Environment) air quality guidelines during

the entire study period. Hourly average concentrations of all ambient air quality parameters were investigated during the period January 1 to August 31, 2020. Ambient SO₂, NO₂, CO, O₃, and PM₁₀ revealed out significantly higher mean concentrations during COVID-19 pre-pandemic period (January 1 to March 10, 2020) according to the implemented precautionary actions of Saudi government (MoH 2020) compared with the COVID-19 pandemic period (March 11 to August 31, 2020), in all the six AQMS in Makkah (Figs. 7, 8, 9, 10, and 11).

Spatial variation of air pollutants

For studying the spatial variation of ambient air pollutants in Makkah on pre-pandemic and during the pandemic lockdown, a total of ten contour maps were constructed to follow-up the dispersion of pollutants and the most general trend of pollutants in Makkah.

Fig. 17 Comparison between average rates of percent reduction of ambient air pollutants in Makkah between pre-pandemic and during pandemic periods (all parameters in µg/m³ except CO in mg/m³)

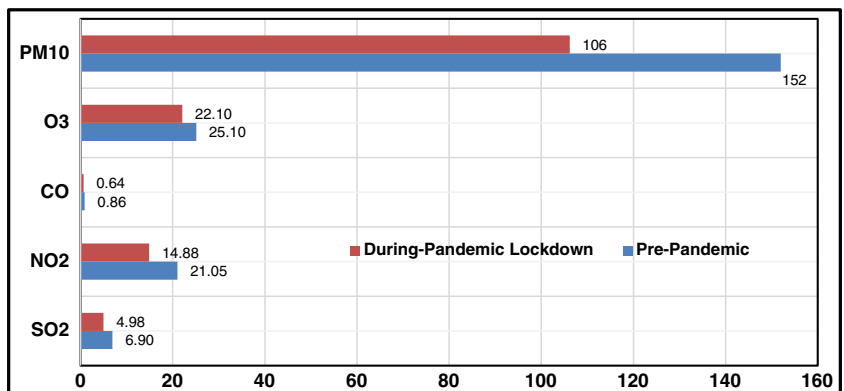
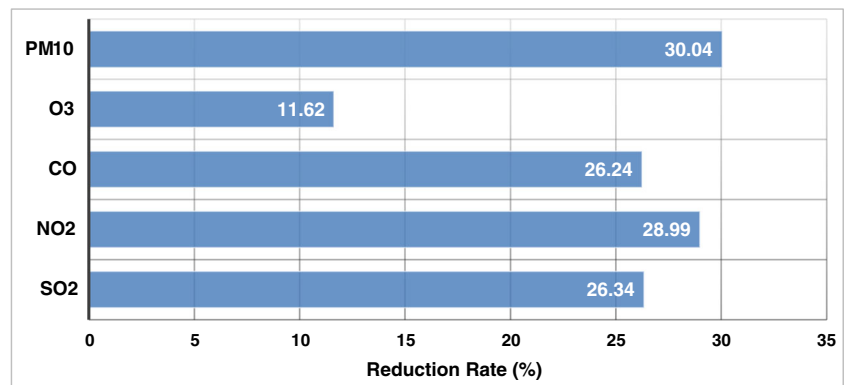


Fig. 18 Average rates of percent reduction of ambient air pollutants in Makkah during pandemic compared with pre-pandemic period (all parameters in $\mu\text{g}/\text{m}^3$ except CO in mg/m^3)



The concentration of SO_2 on the pre-pandemic period (January 1 to March 10, 2020) was averaged for all six AQMS distributed in the districts of Makkah; then, the data were coordinated by utilizing “SURFER” software packages, and contoured to show the spatial variation of SO_2 in Makkah, which was between 3.5 and $10 \mu\text{g}/\text{m}^3$. The low concentrations of $3.5\text{--}5.5 \mu\text{g}/\text{m}^3$ were presented in the southwest (Shawqia) part, while the high concentrations were focused on the eastern part with a range of $8\text{--}10 \mu\text{g}/\text{m}^3$, and all the rest of Makkah stations were featured by moderate concentrations between 5 and $7.5 \mu\text{g}/\text{m}^3$ (Fig. 12a), while during the lockdown of the COVID-19 pandemic period (March 11 to August 31, 2020) (Fig. 12b), the concentrations of SO_2 have been in the range of $3.0\text{--}6.6 \mu\text{g}/\text{m}^3$; also, the southwestern part indicated very low concentrations. It is well observed that the decrease of SO_2 between the two previously mentioned periods is a direct response to the suspension of all trucks and huge vehicles through the lockdown period in Makkah, in addition to the suspension of Hajj and Umrah with the associated traffic effects.

A similar way of spatial variation of SO_2 was designed for the two periods (pre and during the pandemic) for the ambient air pollutants NO_2 , CO, O_3 , and PM_{10} . NO_2 values ranged between 16 and $30 \mu\text{g}/\text{m}^3$ and the maximum concentrations were found in the southwestern part of Makkah during the pre-pandemic periods that ranged between 26 and $30 \mu\text{g}/\text{m}^3$, and the lowest concentrations were represented in the eastern and northern parts of Makkah (Fig. 13a), while during the lockdown during the COVID-19 pandemic period (March 11 to August 31, 2020) (Fig. 13b), there was an abrupt decrease of range of NO_2 concentrations between 10 and $19 \mu\text{g}/\text{m}^3$. Similarly, the behavior of the SO_2 and NO_2 , CO, O_3 , and PM_{10} was marked by different ranges of concentrations of $0.71\text{--}0.93 \text{ mg}/\text{m}^3$; $20.0\text{--}28.0 \mu\text{g}/\text{m}^3$, and $0.57\text{--}0.73 \text{ mg}/\text{m}^3$; $18.0\text{--}26.0 \mu\text{g}/\text{m}^3$; $143.0\text{--}111.0 \mu\text{g}/\text{m}^3$, respectively, during the periods of pre-pandemic and pandemic lockdown (Figs. 14a, b, 15a, b and 16a, b).

Quantifying percent reduction of air quality during COVID-19 lockdown

To quantify the impact of the suspended activities due to the impact of COVID-19 on the air pollutants in Makkah, the hourly averages of the five main pollutants (SO_2 , NO_2 , CO, O_3 and PM_{10}) were utilized for providing the daily averages; then, the mean concentrations were evaluated for the two periods (pre-pandemic and during the pandemic lockdown) as illustrated in Fig. 17; SO_2 has been decreased from 7.28 to $5.31 \mu\text{g}/\text{m}^3$, NO_2 has been reduced from 18.11 to $13.48 \mu\text{g}/\text{m}^3$, CO has been reduced from 0.93 to $0.67 \text{ mg}/\text{m}^3$, O_3 has been decreased from 26.99 to $24.76 \mu\text{g}/\text{m}^3$, and PM_{10} has been reduced from 26.99 to $24.76 \mu\text{g}/\text{m}^3$.

By application of Equation (1), the rates of percent reduction of ambient air pollutants (SO_2 , NO_2 , CO, O_3 , and PM_{10}) for the six AQMS (Haram; Umrah; Otebiah; Shawqia; Aziziah; and Shara'a) in Makkah were estimated and averaged to indicate the average concentration of SO_2 decreased by a rate of 26.34%, NO_2 by a rate 28.99%, CO by a rate of 26.24%, O_3 by a rate of 11.62%, and PM_{10} by a rate of 30.04% (Fig. 18).

Conclusions and recommendations

The ambient air quality data from six AQMS stations in Makkah City, KSA for five pollutants including (SO_2 , NO_2 , CO, O_3 , and PM_{10}) were recorded continuously on hourly average basis, in addition to meteorological conditions (atmospheric temperature, relative humidity, atmospheric pressure, wind speed, and wind direction). The main objective of the current research was to investigate and analyze the impact of COVID-19 lockdown on air quality in the different districts of Makkah.

Findings showed that since the control measures adapted by the Saudi government during COVID-19 crisis at the start of March 2020, levels of air pollutants have been greatly lowered. The hourly average, daily averages, and diurnal

variations confirmed the significant improvement of levels of air pollutants throughout the distributed AQMS all-over Makkah. The hourly averages for the main pollutants of SO₂, NO₂, CO, O₃, and PM₁₀ indicated a decrease from 7.27 to 5.31 µg/m³, 18.10 to 13.48 µg/m³, 0.93 to 0.67 mg/m³, 26.76 to 24.77 µg/m³, and 143.0 to 111 µg/m³, respectively, between the pre-pandemic and pandemic periods.

These results indicated that the vehicular traffic activities represent about 25–30% of the total air pollution load in Makkah city, in addition to the anthropogenic factors that were mainly responsible for the variations in air quality. Further analysis suggested that source apportionment must be conducted especially for PM₁₀, which is the main factor influencing air quality. This research work provides a new view for a comprehensive understanding of the current state of air pollution in Makkah. The findings will provide a theoretical basis for the formulation of future air-pollution control policies in Makkah.

All the ambient air pollutants exhibit a decreasing trend in 2020 compared with 2019. The calculation of the average decrease rate of the five air quality parameters indicated that the average concentration of SO₂ decreased by a rate of 26.34%, NO₂ decreased by a rate 28.99%, CO decreased by a rate of 26.24%, O₃ decreased by a rate of 11.62%, and PM₁₀ decreased by a rate of 30.04%. These rates of percent reduction are essentially due to the reduction in traffic activities; concentrations of NO₂ and CO are related mainly to the traffic activities, especially from diesel-fuel combustion, and to a low extent from gasoline transport vehicles, manufacturing industry, and power plants, especially in Umrah station (close to the industrial city and power plant northwest of Makkah).

Consequently, based on the confirmed case studies worldwide in different cities, we suggest a group of recommendations to enhance the air quality regime in Makkah city: (1) maximizing the public transportation via metro lines; (2) strengthening use of ultra-non-sulfuric fuel as advised by Euro 5 and 6; (3) encouragement and facilitating use of hybrid and electric vehicles; (4) firm control management of environmental topics such as industrial activities and power plants; and (5) expanding and increasing the green landscape around Makkah and its main entrances.

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Declarations

Conflict of interest The authors approve that the current manuscript has no conflict of interest.

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