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ORIGINAL ARTICLE

The COVID-19 Pandemic: Quantification of Temporal Variations in Air Pollutants Before, During and Post the Lockdown in Jeddah City, Saudi Arabia

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Abstract

The government of Saudi Arabia imposed a strict lockdown between March and July 2020 to stop the spread of the coronavirus disease (COVID-19), which has led to a sharp decline in economic activities. The daily temporal variations of PM_{10}, $PM_{2.5}$, carbon monoxide (CO), nitrogen dioxide (NO_2), and ozone (O_3) were used to investigate the changes in air quality in response to COVID-19 lockdown control measures from January to December 2020 in Jeddah, Saudi Arabia. Meteorological parameters (wind speed, direction, temperature, relative humidity) were also analyzed to understand the changes during the pandemic. As a result, significant reductions in the concentrations of NO_2 (– 44.5%), CO (– 41.5%), and $PM_{2.5}$, PM_{10} (– 29.5%, each) were measured in the capital city of Jeddah during the quarantine compared to the pre-lockdown average. In contrast, the lockdown caused a significant increase in O_3 by 41%. The changes in air quality during the COVID-19 outbreak by comparing the average pollutant concentration before lockdown (January 1–March 21, 2020) and the following 12 weeks during the partial lockdown (March 22–July 28, 2020), reveal a very significant decrease in pollutants, and consequently a significant improvement in air quality. Observed differences are attributable to changes in point source emissions associated with changes in localized activities, possibly related to decreased economic and industrial activity in response to the lockdown. The results of the present study show during the study period indicated a positive response to lockdown during the COVID-19 pandemic. Furthermore, the results can be used to establish future control measures and strategies to improve air quality.

Keywords COVID-19 · Lockdown · Air quality · PM_{10}, $PM_{2.5}$, NO_2, O_3 · Saudi Arabia

1 Introduction

Air quality is deteriorating due to anthropogenic activities (e.g. vehicle exhaust, industrial emissions, fossil fuel combustion, resident, and household smoking and heating) (Feng et al. 2021; Ismail et al. 2021). Exhausts from motor vehicles cause about 50% of air pollution in Iran (Ghaffarpasand et al. 2020). Moreover, motor vehicles are responsible for about 36% of NO_x concentrations in the atmosphere of china (Zhong et al. 2018). In Brunei Darussalam, 88% of the total annual CO comes from transport, while steel smelting contributed about 38% of the total annual CO emissions in China (Lee et al. 2018). Fossil fuel combustion contributed about 16% and 32% of PM_{10} and $PM_{2.5}$ emissions in China, respectively (Jiang et al. 2020). Recently, Ji et al. (2020) stated that the transportation of NO_x emissions is the major cause of O_3 photochemical formation. However, emission data for Arab countries are scarce and fragmentary

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(Butenhoff et al. 2015; Harrison et al. 2016a, b; Basahi et al. 2017; Haiba and Hassan 2018). Air quality is determined by measuring the concentrations of PM_{10}, $PM_{2.5}$, Carbon monoxide (CO), Nitrogen dioxide (NO_2), and ambient ozone (O_3) (Chhikara and Kuma, 2020; Said et al. 2022). Variations in the concentration of different air pollutants could be detected by analyzing these air quality parameters. Moreover, meteorological conditions (e.g. temperature, wind speed, wind direction, and relative humidity) could affect the concentration levels of different air pollutants in a given period (Tello-Leal and Macias-Hernandez 2021). Economic and social activities were disrupted worldwide by the outbreak of the novel coronavirus (COVID-19), which was declared a pandemic on March 11, 2020 (WHO 2020a; b, c). This pandemic resulted in a tremendous lifestyle change. Many countries around the globe responded in an unprecedented way to protect the public health of their nations (e.g., quarantine, curfews, travel restrictions, etc.) (Rohrer et al. 2020; Farahat et al. 2021; Selcuk et al. 2021; Saddique et al. 2021; Hassan et al. 2021).

Jeddah is the second most polluted city in Saudi Arabia (Hassan et al. 2013; Harrison et al. 2016a, b). Air quality has mostly surpassed the air quality standards recommended by WHO and local authorities (National Centre of Meteorology "NCM") (Basahi et al. 2017; Harrison et al. 2016a, b; Ismail et al. 2021). Recently, Ali et al. (2021) stated that climatic indicators (wind speed, humidity, temperature, rainfall, and air quality) are strongly correlated with COVID-19 (Siciliano et al. 2020; Xu et al. 2020; Dogan et al. 2020; Fattorini and Regoli 2020; Ding et al. 2021).

In Saudi Arabia, due to the increase in positive cases, the government introduced a series of measures and strategies on March 22, 2020 to restrict human activities, as a proactive step, to prevent the spread of COVID-19. These include social distancing, the suspension of ritual activities and prayers in all mosques (including the two holly mosques), the closure of all schools, universities, and shopping malls, traffic and travel restrictions, and the suspension of construction sites. Moreover, the pandemic caused a sharp reduction in the number of visitors and pilgrimages (1000 visitors per day during the lockdown compared to about 2,000,000 during 2019 i.e., before the pandemic) (SPA 2021; Farahat et al. 2021).

Lockdown and reductions in human activities improved air quality in many countries worldwide (Aman et al. 2020; Bauwens et al. 2020; Gupta et al. 2020; Bashir et al. 2020; Chhikara and Kumar 2020; Marquès and Domingo 2022). On the other hand, it harmed the economy (e.g. travel restrictions, suspension of industries and construction, and a drastic collapse of almost all sectors). Although several studies were conducted in the USA, Asia, and Europe, to the best of our knowledge, no such study has been conducted in Saudi Arabia. Therefore, this study was carried out to fill this gap of knowledge.

The present study aimed to investigate the impact of the Lockdown and the reduction of economic activities during the pandemic COVID-19 on air quality in Saudi Arabia. Moreover, it was aimed to investigate the changing pattern of different pollutants before and during the lockdown as well as after the lockdown was eased.

2 Materials and Methods

The lockdown in Saudi Arabia came into effect on March 22, 2020, and was eased on June 29, 2020. Therefore, this study was carried out to investigate the changing pattern of different pollutants during the months before the lockdown (January 1–March 21, 2020), the months during the lockdown (March 22–June 28, 2020), and the months after the lockdown was eased (June 29–December 31, 2020).

2.1 Sampling Site and Environmental Indicators

Jeddah is located on the Red Sea coast of Saudi Arabia (N 21° 67´, E 39° 15´). The meteorology is characterized by frequent dust storms, with limited rainfalls, and therefore, the climate is generally dry and warm (Hassan et al. 2013). Traffic is the primary mobile source of air pollution in Jeddah, while the main stationary sources include a desalinization plant, an oil refinery, a major harbor, and a power generation plant.

The environmental indicators (CO, NO_2, O_3, PM_{10}, and $PM_{2.5}$) have been considered to evaluate the deviation of air quality during the lockdown, pre-lockdown, and post-lockdown periods. The concentrations of these parameters have been compared between the lockdown session during 2020, and a similar time in the preceding year (i.e. 2019).

The sampling site was located in a residential area of Jeddah, at a height of 11 m above the ground level on the roof of a residential building. PM samples were collected onto Quartz microfiber filters (47 mm) using a sequential air sampler (Partisol Plus 2025-D, Thermo Fisher Scientific, Waltham, MA, USA) (Ismail et al. 2021). Filters were weighed before and after sampling, using a micro-balance (Model XPE206DR, Mettler Toledo, Muntinlupa, Philippines), to determine the mass concentrations of the $PM_{2.5}$ and PM_{10} samples. Samples were collected daily for a 12-month period starting January through December 2020 covering the different four seasons as well as the periods before, during and post the lockdown. Each sample was collected every day for 24 h at flow rates of 15 and 10 L min^{-1} for PM_{10} and $PM_{2.5}$, respectively. Different environmental parameters were recorded simultaneously (atmospheric pressure, atmospheric temperature, wind speed, and relative humidity).

Ambient ozone (O_3), NO_x, and CO concentrations were monitored simultaneously (8:00—20:00 h, Saudi local time) using a fully integrated air quality monitoring system POLLUDRONE SAMRT (Modbus, RS—485, Savoie Technol. France) that was located adjacent to the Partisol on the top of the residential building (Ismail et al. 2021).

2.2 Statistical Analysis

A one-way analysis of variance (ANOVA) was performed, using the SATATGRAPHICS statistical software package, to examine the temporal variations in PM_{10}, $PM_{2.5}$, CO, NO_2, and O_3 before, during, and after the lockdown.

The relationship between the concentrations of different pollutants and meteorological parameters (temperature, relative humidity, and absolute humidity) was assessed using correlation analysis.

To quantify the variations in air quality, in terms of either concentration, the relative change (RC) is defined using an Eq. that was suggested by Ji et al. 2020 (Eq. 1)

$$\mathrm{RC} = \frac{C_i - C_{\mathrm{ref}}}{C_{\mathrm{ref}}} \times 100, \mathrm{RC} = \frac{C_i - C_{\mathrm{ref}}}{C_{\mathrm{ref}}} \times 100, \quad (1)$$

where C_i is the air pollutant concentration or index value in year i, and C_{ref} is the value in the reference year 2019. Therefore, RCs indicate variations in a certain year relative to the value in the reference year. Moreover, the influence of the lockdown period and meteorological conditions on changes in the concentrations of pollutants was determined using correlation base Principal Component Analysis (PCA).

The dataset was log-transformed prior to analysis to be sure that they were normally distributed. This was verified by the Shapiro–Wilk normality test (Menebo 2020).

3 Results and discussion

Temporal variations of $PM_{2.5}$ (Fig. 1), PM_{10} (Fig. 2), and NO_2 (Fig. 3) were observed in air quality samples collected daily for 1 year from January to December 2020, with the elevated concentrations observed in the pre- and post-lockdown periods. During the lockdown (March 22–June 28, 2020), concentrations were significantly lower than before and post lockdown periods. The annual concentrations of $PM_{2.5}$, PM_{10} and NO_2 were 21.9 µg m^{-3}, 123.08 µg m^{-3} and 33.57 nl l^{-1}, respectively, during the sampling period (Figs. 1, 2, and 3).

The average $PM_{2.5}$ concentration was 22.2 µg m^{-3} during the pre-lockdown period (January, February and the first 3 weeks in March 2020). This concentration was declined during the lockdown period (April –July 2020) and reached 15.5 µg m^{-3} (Table 1 and Fig. 1). The lockdown resulted in a 31.7% reduction in PM2.5 concentration (Table 2). $PM_{2.5}$ concentration increased to 23.42 µg m^{-3} in the post-lockdown period (Table 1). Similarly, PM10 concentrations were 128.8 and 82.40 µg m^{-3} in pre-lockdown and during lockdown periods, respectively (Table 1 and Fig. 2). The PM_{10} concentration increased in post-lockdown period (117.06 µg m^{-3}) (Table 1). Table 2 shows that the lockdown caused a 36% reduction in PM10 concentration. The $PM_{2.5}$/PM_{10} ratio did not vary significantly in the pre-, during and post-lockdown periods of COVID-19, indicating insignificant changes in coarse particles due to reduced emissions

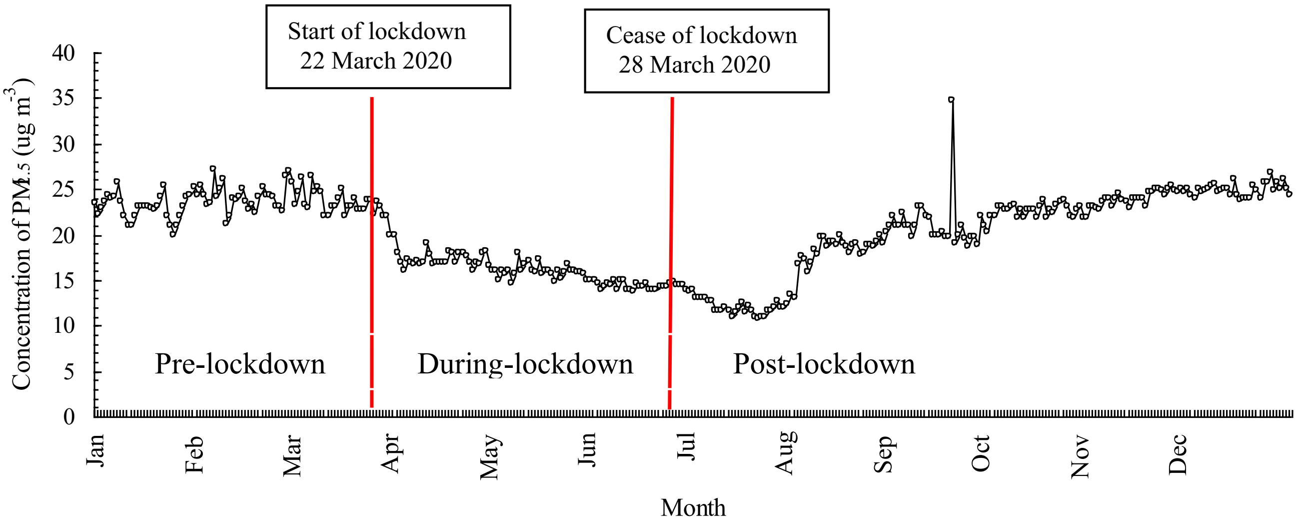

Fig. 1 Temporal variations in the concentration of $PM_{2.5}$ (µg m^{-3}). Red lines state the beginning and the end of lockdown in Jeddah city

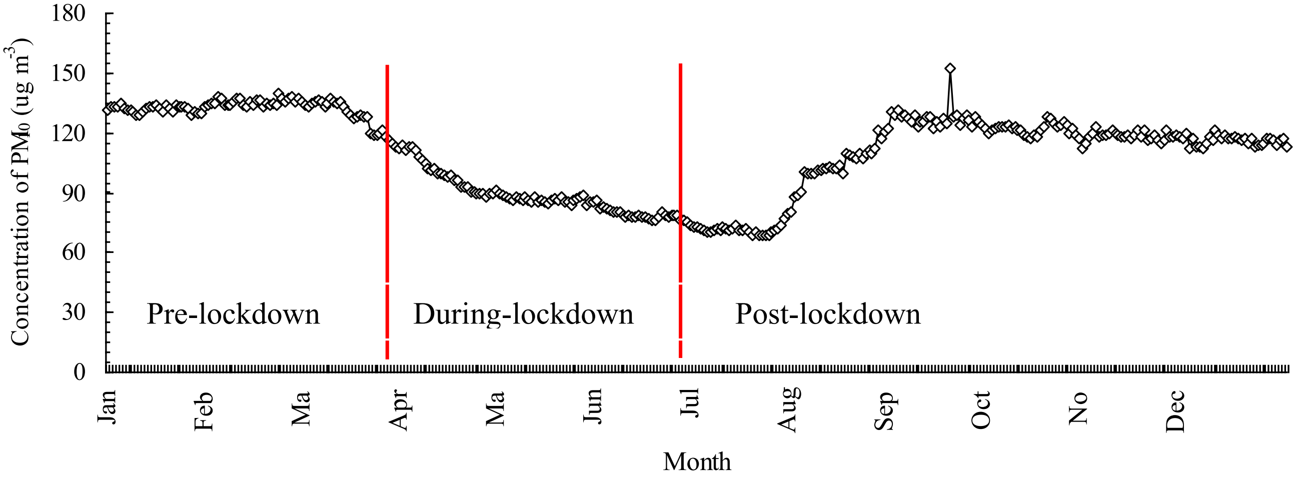

Fig. 2 Temporal variations in the concentration of PM_{10} (μg m^{-3}). Legend as Fig. 1

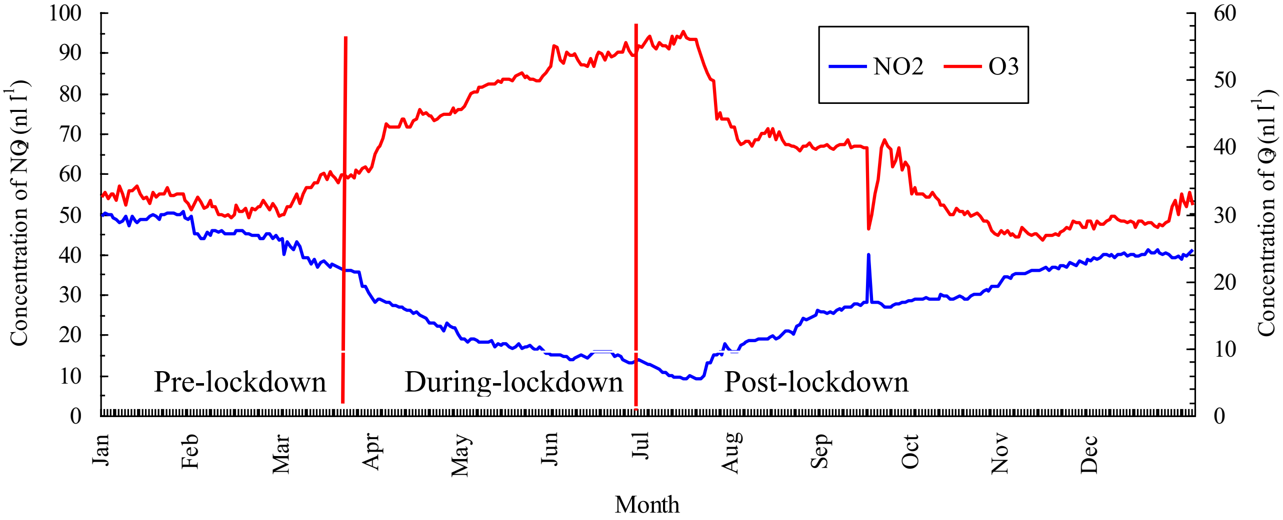

Fig. 3 Temporal variations in the concentration of NO_2 and O_3 (nl L^{-1}). Legends as Fig. 1

Table 1 Concentrations of different pollutants during the different periods of COVID-19 lockdown (means + SE)

	$PM_{2.5}$ (μg m^{-3})	PM_{10} (μg m^{-3})	CO (mg m^{-3})	NO_2 (nl L^{-1})	O_3 (nl L^{-1})
Pre-lockdown	22.70 ± 2.24	128.81 ± 11.17	5.39 ± 1.38	43.8 ± 8.11	32.93 ± 3.33
During- Lockdown	15.50 ± 1.71	82.40 ± 9.27	3.26 ± 1.11	16.3 ± 2.01	51.35 ± 6.38
Post-lockdown	23.42 ± 2.12	117.06 ± 12.22	5.98 ± 1.27	29.84 ± 4.38	33.36 ± 4.21

from anthropogenic activities (Feng et al. 2021). Weather conditions were almost the same before and during the lockdown, confirming the stability of the $PM_{2.5}$ fraction of PM_{10}. The restriction on travel, suspension of industrial and economic activities caused a significant reduction in primary emissions during the lockdown, i.e. limited oxidation in the atmosphere (Feng et al. 2021).

CO and NO_2 concentrations dropped from 5.39 mg m^{-3} and 43.8 nl L^{-1}, respectively, in the pre-lockdown period to 3.26 mg m^{-3}, and 16.30 nl L^{-1}, respectively, during the lockdown period (Table 1). Subsequently, they increased to 5.98 mg m^{-3} and 29.84 nl L^{-1} in the post-lockdown period, respectively (Table 1). The lockdown resulted in a 39.58% and 62.78% reduction in the concentrations of CO and NO_2,

Table 2 The impact of COVID-19 lockdown on the during lockdown/pre-lockdown ratio of different air quality parameters in different regions over the world

City	Pollutant					References
	$PM_{2.5}$	PM_{10}	CO	NO_2	O_3	
Jeddah (Saudi Arabia)	– 31.72%	– 36.0%	– 39.58%	– 62.78%	+ 55.94%	The Present Study
Alexandria (Egypt)	– 29%	– 23%	–	– 26%	–	El Sheekh and Hassan (2021)
Ankara (Turkey)	– 37.7%	– 37.8%	– 20.1%	– 41.2%	+ 6.78%	Goren et al. (2021)
Madrid (Spain)	– 25.2%	– 28.4%	– 32.6%	– 61.5%	+ 13.8%	Viteri et al. (2021)
Victoria, (Mexico)	– 45%	– 45%	– 42%	– 47%	–	Tello-Leal and Macías-Hernandez (2021)
São Paulo (Brazil)	–	–	– 64.80%	– 35%	+ 30%	Kerimray et al. (2020)
Delhi (India)	– 42%	– 50%	– 41%	– 53%	+ 2.0%	Shehzad et al. (2021)
Tehran (Iran)	–	– 11.33%	– 13%	– 13%	+ 3%	Broomandi et al. (2020)
Almaty (Kazakhstan)	–	–	– 49%	– 35%	+ 15%	Kerimray et al. (2020)
Suzhou (China)	– 37.2%	– 38.3%	– 26.1%	– 64.5%	+ 104.7%	Wang et al. (2021)
Wuhan (China)	– 35%	– 36%	– 10%	– 53%	+ 58%	Chu et al. (2021)
Xi'an (China)	– 17%	– 27%	– 25%	– 52%	+ 160%	Feng et al. (2021)

respectively, when compared with concentrations in the pre-lockdown (Table 2). The reduction in pollutants due to the containment measures implemented by the COVID -19 pandemic was very significant. The concentration of CO decreased by about 40% during the closure, with combustion processes being the main emitters, in our case road traffic in urban areas, especially diesel and gasoline vehicles. In addition, Table 2 shows a simplified comparison of the effect of the COVID-19 Lockdown implementation on air quality in selected cities around the world. It clearly shows that the lockdown measures had a positive effect on air quality around the world. All pollutants studied exhibited significant reductions during the lockdown, with the exception of O_3. Recently, El Sheekh and Hassan (2021) found that the reduction in concentrations of pollutants was significantly ($p < 0.01$) correlated with the decrease in transportation, industrial processes and other economic activities in Egypt. The main contributors to air pollution (vehicular emissions, various industrial processes, and commercial activities) were adversely affected by the lockdown measures worldwide (Bauwens et al. 2020; Feng et al. 2021; Viteri et al. 2021). The results of the present study are consistent and in agreement with previous studies that travel restrictions during the lockdown caused the most significant reduction in NO_2.

The average mass concentrations of $PM_{2.5}$ and PM_{10} during the sampling period exceeded the annual average levels recommended by the World Health Organization (WHO) for $PM_{2.5}$ and PM_{10} (15 μg m^{-3} and 25 μg m^{-3}, respectively) (Table 3). Moreover, the recorded levels exceeded the recommended levels by Environmental Protection Agency (EPA) for PM2.5 and PM10 (15 and 50 μg m^{-3}, respectively). However, $PM_{2.5}$ levels were lower than the levels recommended by National Center for Meteorology (NCM) (30 μg m^{-3}), while PM_{10} concentrations were higher than the levels recommended by NCM (80 μg m^{-3}) (Table 3).

On contrary to the other pollutants, O_3 levels were higher (51.35 nl L^{-1}) during lockdown than the pre- and post-lockdown concentrations (32.39 and 33.36 nl L^{-1}, respectively) (Table 2). The average concentering of O_3 during the sampling period was 32.69 nl l^{-1} (Fig. 3). The increased O_3 concentration during the lockdown, compared to the pre-lockdown levels, is an evidence of the occurrence of the secondary chemical reactions in the atmosphere (Feng et al. 2021). Sicard et al. (2020) found that ambient O_3 levels were amplified in many cities around the world during the COVID-19 pandemic, and they owed this increase in O_3 levels to the reduction in NO_2 levels. Hassan et al. (2013) found that reductions in NO_2 concentrations resulted in an increase in ambient O_3 levels in Jeddah, indicating the NO scavenging effect on O_3 (Jain et al. 2021). Chang et al. (2018), found similar results in Malaysia, they found that the ozone concentration was somehow higher during the

Table 3 Annual air quality standards

	$PM_{2.5}$ (μg m^{-3})	PM_{10} (μg m^{-3})	PM_{10} (μg m^{-3})	CO (mg m^{-3})	NO_2 (ppb)	O_3 (ppb)
WHO	15	25	25	10	21	50
EPA	15	50	50	10	50	75
GAMEP	30	80	80	10	50	80

weekend and afternoon hours which was associated with lower NO_2 concentrations at that times. Recently, Shi and Brasseur (2020) found that the decrease in ambient NO_2 was associated with an increase in tropospheric O_3 in China. Moreover, Xu et al. (2020) stated that the formation of O_3 in the urban environment involves complex processes with no direct source of emission but is produced through reactions involving NOx, CO, and volatile organic compounds which serve as precursors. The lower O_3 concentration after the lockdown was due to the more favorable weather conditions and the weakening of secondary reactions, which can also explain the variations in $PM_{2.5}$ and PM_{10} in this study. Chu et al. (2021) found that the concurrent reductions in NO_x and $PM_{2.5}$ concentrations led to an increase in O_3 concentrations across China during the COVID-19 pandemic. They suggested coordinated control of other pollutants. The elevated O_3 levels could be directly attributed to the relative high air temperature (Hassan et al. 2013) and low wind speed during the COVID-19 lockdown in 2020 as well as to the emission sources (Feng et al. 2021). Ozone pollution in Jeddah must be further investigated in a future study.

It was observed that the levels of $PM_{2.5}$, PM_{10} and NO_2 were tremendously increased on September 23 (Figs. 1 and 2). These elevated levels of these pollutants coincided with the National Day of Saudi Arabia when Saudis celebrate on the streets and drive their cars. The elevated concentration of these pollutants are ascribed to an increased traffic on September 23. In contrast, the concentration of O_3 decreased on September 23 (Fig. 3).

Table 4 shows that $PM_{2.5}$, PM_{10} had a very strong positive correlation with each other ($r = 0.99$, $P < 0.001$). In addition, statistically moderate positive correlations were found between $PM_{2.5}$ and CO ($r = 0.66$, $P < 0.05$) and between PM_{10} and CO ($r = 0.74$, $P \leq 0.01$). However, a correlation between particulate matter and NO_2 and O_3 was insignificant ($P > 0.05$) (Table 4). Furthermore, the statistical analysis of wind speed (WS) revealed a very strong correlation ($0.89 \geq r \geq 0.91$) with PM factions and other pollutants. There was a strong negative correlation coefficient between WS and O_3 ($r = -0.79$, $P < 0.01$) (Table 4). Temperature exhibited a consistently moderate correlation with all the air pollution variables ($0.71 \geq r \geq 0.79$), except for NO_2, the relationship was insignificant ($P > 0.05$). The high correlation of $PM_{2.5}$ with PM_{10}, CO, and NO_2 during the lockdown, reflecting the common origin of these species from fossil fuel combustion (Wang et al. 2014). Moreover, the positive correlations between O_3, and $PM_{2.5}$ as well as PM_{10}, indicating the simultaneous formation of secondary O_3 and PM by photochemical reactions under favorable weather conditions. Similar correlations among pollutants were also observed interannually, but the correlations were slightly weaker than those in the lockdown. Our results are consistent and in agreement with those of several studies that demonstrate significant relationships between meteorological conditions (temperature, humidity, and wind speed) and air pollutants ($PM_{2.5}$, PM_{10}, CO NO_2, and O_3) (Bolâno-Ortiz et al. 2020; Dogan et al. 2020; Tello-Leal and Macias-Hernandez 2021, Said et al. 2022).

Table 4 Pearson correlation coefficient matrix for main variables using a dataset during the lockdown

	PM2.5	PM10	CO	NO_2	O_3	WS	RH	T
During lockdown (Seasonal)								
PM2.5	1.00	**0.99**	**0.66**	0.49	0.43	**0.89**	**0.66**	**0.71**
PM10		1.00	**0.74**	0.51	0.35	**0.88**	**0.68**	**0.77**
CO			1.00	0.52	0.55	**0.90**	0.44	**0.75**
NO_2				1.00	**− 0.89**	**0.91**	0.32	0.52
O_3					1.00	**− 0.89**	0.45	**0.79**
WS						1.00	**0.61**	**− 0.60**
RH							1.00	0.55
T								1.00
Yearly								
PM2.5	1.00	**0.85**	**0.66**	0.51	− 0.18	**0.65**	0.50	0.52
PM10		1.00	**0.64**	0.28	− 0.32	**0.58**	0.48	0.55
CO			1.00	0.39	− 0.22	0.52	0.33	**0.59**
NO_2				1.00	**− 0.55**	**0.59**	0.47	0.21
O_3					1.00	**− 0.58**	0.11	**0.58**
WS						1.00	0.44	0.31
RH							1.00	0.42
T								1.00

Bold Figures are significant at $P \leq 0.05$

Table 5 shows non-significant variation between meteorological conditions (WS, T and RH) before and during the lockdown, except for relative humidity. Non-significant variation indicates that the decrease in air pollution during the lockdown period was not solely dependent on meteorological conditions (Navinya et al. 2020). However, significant variation in relative humidity could be attributed to the coastal weather of Jeddah with its warm sea (Qari and Hassan 2017). Moreover, the lockdown was implemented between the spring and summer season (April–July) and the slight rise in temperature (not significant, $P^{>}$ 0.05) is linked to the timing of the season. Patlakas et al. (2019) reported that the temperature is strongly correlated with the increase in the percentage of relative humidity in the atmosphere (Cichowicz et al. 2020; Hassan et al. 2021).

Table 5 Variation in meteorological parameters (mean ± SE)

	WS (ms^{-1})	Temp. (^0C)	RH
Pre-lockdown	$1.79^a \pm 0.32$	$28.85^a \pm 3.12$	$55.36^a \pm 5.28$
During-lockdown	$1.85^a \pm 0.41$	$31.47^a \pm 3.88$	$63.48^b \pm 6.38$
F-Value	5.083	3.735	5.891
P-Value	0.136	0.087	0.041

Means not followed by the same letter are significantly different at $P \leq 0.05$

Although pollutant concentrations decreased during the lockdown, the concentrations of $PM_{2.5}$, PM_{10}, NO_2, and O_3 were still above WHO annual mean limit levels. This confirms that not only emission from traffic that contribute to increases in air pollutants, but also stationary sources from the industries, with fossil fuel combustion playing a key role in the complex mix of sources (Kerimray et al. 2020). Feng et al. (2021) stated that emissions from stationary sources (e.g. coal-fired power factories) were not reduced compared to emissions from mobile sources (e.g. traffic). Desalination plants in Jeddah were working with full capacity to provide Saudis with the necessary amounts of drinking water, and this could be a major and an important source of pollution emission in Jeddah. Moreover, electricity and heat were still provided as usual by the thermal power plants to ensure normal supply during the lockdown. One could argue that the systematic analysis of the data has limitations because of the general seasonal characteristics of the region and the corresponding months of the previous year. However, we analyzed air quality index (AQI) in the corresponding months of the previous year (2019) using the equation of Ji et al**.** (2020) to test this hypothesis. The relative changes (RC) exhibited decreases AQI (negative RC), which implied improved air quality during the lockdown in 2020 (Fig. 4). Moreover, Principal Component Analysis (PCA) for different pollutants and meteorological conditions in 2019 and the same period in 2020 during the lockdown period is presented in Fig. 5.

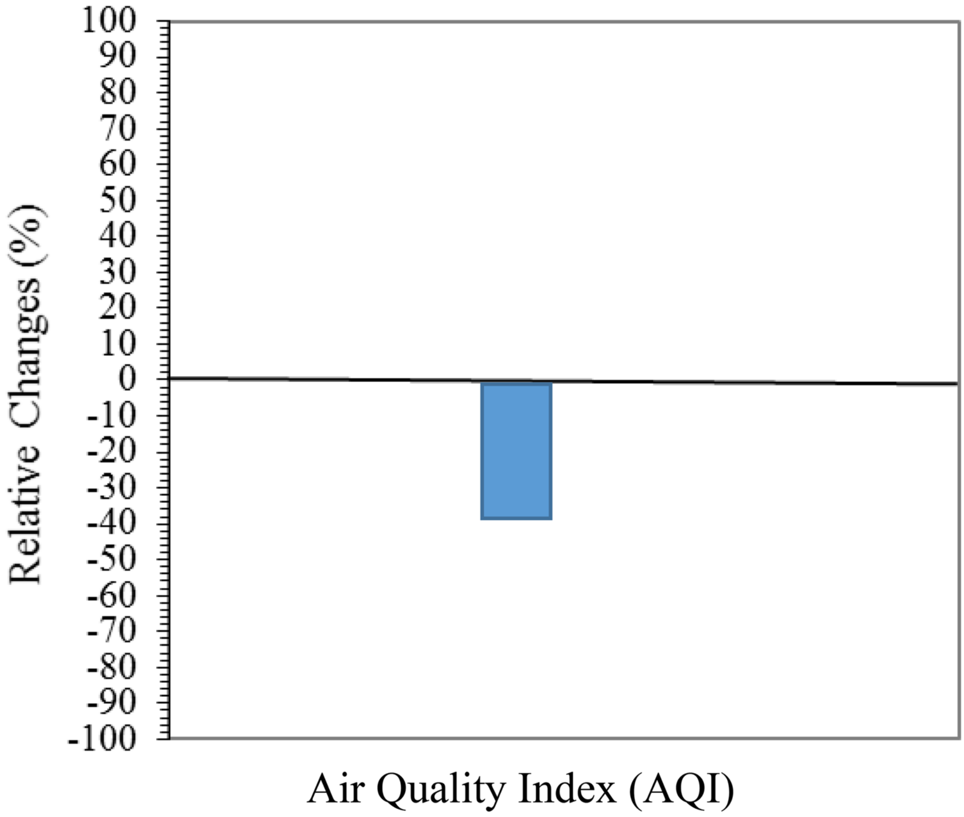

Fig. 4 Relative Changes (RCs) in seasonal mean AQI against the reference year 2019

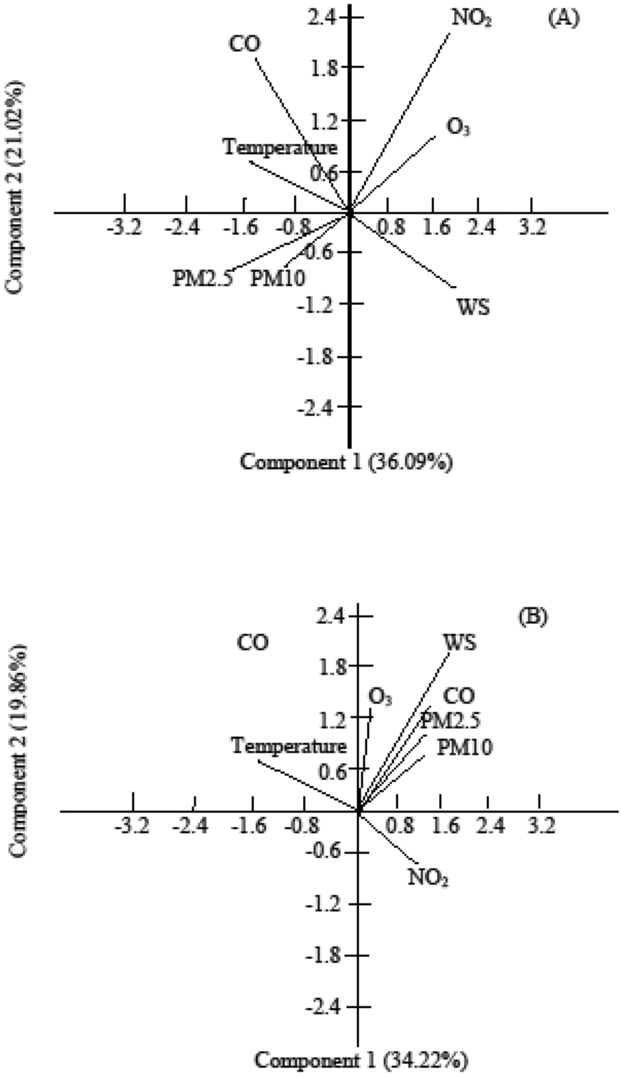

Fig. 5 Principal component analysis for the influence of meteorological data and pollutants concentration before and during COVID-19 lockdown (**A**) and during 2019 (**B**)

Component 1 and 2 accounted for 57.11%, and 54.05%, of the total variation in 2019 and in 2020, respectively. There was an influence of COVID-19 lockdown on PM_{10}, CO, and O_3 with also a positive correlation between these pollutants and temperature (Fig. 5A). On the other hand, PCA for 2019 showed a different situation, with a positive correlation with humidity and wind speed (Fig. 5B).

To the best of our knowledge, this study provides the first comprehensive analysis of the variations in $PM_{2.5}$, PM_{10}, CO, NO_2, and O_3 concentrations before, during, and after the lockdown in Jeddah, Saudi Arabia. The results of the present study clearly show that exhaust emissions from vehicles and industrial plants were tremendously decreased when the Saudis were enforced to be home quarantined to curb the virus spread. As a result, their rate of entry into the atmosphere was reduced. Generally, curbing anthropogenic activities could improve air quality.

4 Conclusions

In this work, the improvement of urban air quality due to the COVID-19 mitigation measures was investigated for the first time in Saudi Arabia. The time series for PM_{10}, $PM_{2.5}$, CO, and NO_2 during quarantine showed a clear reduction of pollutant concentrations which is directly associated with anthropogenic emissions. The targeted emission controls significantly improved air quality in the city. Although meteorological conditions did not change significantly during the lockdown, they still affected changes related to pollutant concentrations.

Emission controls should be more stringent to ensure that air quality improvements are permanent and not temporary, e.g., by controlling traffic, and industry activities, as well as introducing green transportation programs such as green commuting programs.

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Declarations

Conflict of interest Authors declare that there is no conflict of interest.

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