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Original article

Impact of novel coronavirus disease (COVID-19) lockdown on ambient air quality of Saudi Arabia

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ABSTRACT

The outbreak of COVID-19 has spread globally affecting human activities but with improvement in ambient air quality. The first case of the virus in the Kingdom of Saudi Arabia was on the 2nd of March 2020. The impact of COVID-19 lockdown on the ambient air quality of the Kingdom of Saudi Arabia for the first time using data from nine cities was determined in this study. Hourly air quality data, based on concentrations of carbon monoxide (CO), particulate matter (PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2) and ozone (O_3), and meteorological conditions (atmospheric temperature, relative humidity, and wind speed) of the nine cities studied were obtained from Saudi Arabian General Authority of Meteorology and Environmental Protection (GAMEP), for the period between January 2019 to May 2020. Significant variation ($p < 0.05$) was recorded for the five atmospheric pollutants across the cities before and during the lockdown, with lower concentrations during the lockdown except for the concentration of O_3 in Tabuk, Al Qasim, and Haql. This can be a result of NO and O_3 reaction, causing the inability of effective O_3 depletion. The percentage changes in concentrations of CO (33.60%) and SO_2 (44.16%) were higher in Jeddah; PM_{10} (91.12%) in Riyadh, while NO_2 (44.35%) and O_3 (18.98%) were highest in Makkah. However, even though there was a decrease in pollutants concentrations during the lockdown, the concentrations for CO, PM_{10}, SO_2, $NO_{2,}$ and O_3 were still above WHO 24 h and annual mean limit levels. The COVID-19 lockdown in the Kingdom of Saudi Arabia revealed the possibility of significant atmospheric pollutant reduction by controlling traffic, activities by industries, and environmentally friendly transportation programs such as green commuting programs.

1. Introduction

COVID-19 have spread globally and rocketed into one of the largest threat to human health and economic crises of the 21st Century (Briz-Redón et al., 2020; Yu et al., 2020), leading to its consideration as one of the major disasters ever recorded to affect the modern world (Singh and Chauhan, 2020). In December 2019, Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) was identified in Wuhan, China. The World Health Organization (WHO) later declared the COVID-19 outbreak as an emergency of public health with international concern on the 30th of January 2020 after enforcement of lockdown. The lockdown was enforced by a way of placing the whole city of Wuhan under quarantine on the 23rd of January 2020 (WHO, 2020). Between February and March 2020, the number of cases in people and death rates caused by coronavirus (COVID-19) was rising exponentially, leading to the enforcement of lockdown in most cities of the world to curb the infection and death rate (Muhammad et al., 2020). Restriction of human activities including mobility was put in place to control the spread of the virus, this led to a reduction of traffic on the roads, closure of commercial, entertainment, and industrial activities.

Kingdom of Saudi Arabia (KSA) is the second largest country in the Arabian world (Algaissi et al., 2020; GASKSA, 2020) and took early measures to prevent and control the COVID-19 outbreak. In preparation before the outbreak, a national committee was set up in early January 2020 to track worldwide updates and make necessary preparations for any eventual outbreak or spread of the virus. The first case of COVID-19 in KSA was on the 2nd of

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March 2020. However, before the first case, an early decision made by the government of KSA as a way of responding to the spread of the virus was through the stoppage of flights coming from China to KSA (Algaissi et al., 2020). Later on, the government decided to regulate the entrance of individuals from countries with COVID-19 cases to KSA (Barry et al., 2020). That decision was taken on the 28th of February 2020. Regardless of the measures that were put in place before the first case of COVID- 19 in KSA, the cases were still rising at an exponential pattern. When the cases got to 500 towards the end of March 2020, the government of KSA issued a curfew (Badreldin et al., 2020) with a huge penalty of financial type for individuals that refuse to abide by the law. In the long run, the lockdown in some cities and restrictions on movement between provinces was imposed by the government of KSA (Algaissi et al., 2020).

The response to The COVID-19 outbreak such as the lockdown of cities has been beneficial to the environment looking at the reduction in atmospheric pollution (Bherwani et al., 2020; Sharma et al., 2020a, 2020b). Globally, reports from different studies revealed a decrease in atmospheric pollutions as a result of enforcement of lockdown amidst the COVID-19 outbreak, this is due to a reduction in social and economic activities (Jain and Sharma 2020; Sharma et al., 2020a, 2020b). Correlation between atmospheric pollution and lockdown due to COVID-19 outbreak or spread has been revealed in many parts of the world. For example, a relationship was established between pollutants such as $PM_{2.5}$, PM_{10}, NO_2, and O_3 with confirmed cases of COVID-19 (Zhu et al., 2020). Several conclusions were also made in Europe, Asia, Africa, Latin America, and the United States as regards the influence of drastic decrease in anthropogenic activities such as social and economic variables and decline in air pollutants such as PM_{10}, $PM_{2.5}$, SO_2, NO_2, and O_3 (Muhammad et al., 2020; Nakada and Urban, 2020; Otmani et al., 2020; Xu et al., 2020).

Our study aims to report the impact of COVID-19 lockdown on the ambient air quality of the Kingdom of Saudi Arabia for the first time using data from nine cities in the kingdom.

2. Materials and methods

2.1. Study area

Saudi Arabia is the second largest country in the Arabian world with a population of over 34 million with non-indigenes representing about 37% of the population. The population of the country is dominated by the middle age group of 15–64 years, while 32.4% and 2.8% are within the age groups of 15–64 years and 0–14 years respectively (Algaissi et al., 2020; GASKSA, 2020). Nine cities namely Makkah (21°22′54.33″N and 39°51′24.29″E), Ha'il (27°30′49.48″N and 41°43′10.76″E), Jeddah (21°29′06.96″N and 39°11′28.82″E), Jazan (16°53′28.23″N and 42°34′12.99″E), Tabuk (28°23′06.66″N and 36°33′58.29″E), Al Madinah (24°31′41.19″N and 39°34′09.06″E), Al Qasim (26°14′05.65″N and 43°29′01.45″E), Riyadh (24°43′21.21″N and 46°40′31.06″E) and Haql (29°17′13.96″N and 34°56′42.54″E) were considered for this study (Fig. 1). The nine cities considered in this study were selected due to the increased industrial activities and the human population in these cities. This made the populace requirement for the quality of the environment on the increase as a result of the release of pollutants from the industries and automobiles into the atmosphere, and their human health consequences.

The lockdown in Saudi Arabia took effect around the ending of March 2020 and was eased on 21st of June 2020; as a result, we concluded to carry out this study on the changing pattern of air quality in the months before the lockdown (Jan 2019 to Feb 2020) and the months during the lockdown (March 2020 to May 2020).

2.2. Data analyses

Hourly air quality data, based on concentrations of carbon monoxide (CO), particulate matter (PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2) and ozone (O_3), and meteorological conditions (atmospheric temperature, relative humidity, and wind speed) of the nine cities studied were obtained from Saudi Arabian General Authority of Meteorology and Environmental Protection (GAMEP) for the period between January 2019 to May 2020. The considered validly of data used was based on hourly concentration above 75% availability (Broomandi et al., 2020).

Significant variations in atmospheric pollutants (CO, PM_{10}, SO_2, NO_2, and O_3) before and during the COVID-19 lockdown across the nine cities studied were determined using One-way analysis of variance (ANOVA): Duncan multiple range test (DMRT). Prior to ANOVA test, the normality of the data was assessed using the Shapiro-Wilk test. Students' *t*-test was used to test for significant variation in atmospheric pollutants and meteorological conditions each before and during COVID-19 lockdown. The influence of the lockdown period and meteorological conditions on changes in atmospheric pollutants was determined using correlation base Principal component analysis (PCA).

IBM SPSS v.22.0, GraphPad Prism 5 and Minitab v.17.0 Statistics Software Package were used to analyze the data.

3. Results

3.1. Impacts of COVID-19 lockdown on the air quality of Saudi Arabia

The variation in mean concentrations of atmospheric pollutants before and during COVID-19 lockdown in Saudi Arabia is presented in Tables 1 and 2 respectively. The range for mean concentrations of CO, PM_{10}, SO_2, NO_2 and O_3 before COVID-19 lockdown in Saudi Arabia (Jan 2019 to Feb 2020) were (678.23 ± 13.39) $\mu g\ m^{-3}$ to (2162.01 ± 214.31) $\mu g\ m^{-3}$ in Ha'il and Riyadh, (83.90 ± 5.18) $\mu g\ m^{-3}$ to (518.42 ± 29.98) $\mu g\ m^{-3}$ in Ha'il and Riyadh, (6.40 ± 0.52) $\mu g\ m^{-3}$ to (24.22 ± 3.55) $\mu g\ m^{-3}$ in Ha'il and Jazan, (6.41 ± 1.15) $\mu g\ m^{-3}$ to (44.30 ± 1.99) $\mu g\ m^{-3}$ in Al Qasim and Riyadh and (22.53 ± 1.96) $\mu g\ m^{-3}$ to (93.29 ± 3.71) $\mu g\ m^{-3}$ in Jazan and Tabuk respectively.

Ranges of mean concentrations for CO, PM_{10}, SO_2, NO_2 and O_3 during the lockdown (March 2020 to May 2020) were (528.70 ± 1 5.46) $\mu g\ m^{-3}$ to (1557.87 ± 218.75) $\mu g\ m^{-3}$ in Ha'il and Riyadh, (24. 10 ± 4.78) $\mu g\ m^{-3}$ to (160.50 ± 20.36) $\mu g\ m^{-3}$ in Riyadh and Al Qasim, (5.07 ± 0.20) $\mu g\ m^{-3}$ to (18.83 ± 1.05) $\mu g\ m^{-3}$ in Riyadh and Makkah, (5.70 ± 0.26) $\mu g\ m^{-3}$ to (39.60 ± 5.81) $\mu g\ m^{-3}$ in Al Qasim and Al Madinah, and (20.43 ± 2.92) $\mu g\ m^{-3}$ to (110.57 ± 1. 27) $\mu g\ m^{-3}$ in Al Madinah and Tabuk respectively. Significant variation ($p < 0.05$) was recorded for the five atmospheric pollutants across the cities before and during the lockdown, with lower concentrations during the lockdown except for the concentration of O_3 in Tabuk, Al Qasim, and Haql. Percentage change was further used to ascertain the significant variation in atmospheric pollutants and presented in Table 3. Similarities and differences between our results and results reported from other previous studies are shown in Table 4.

The percentage changes in concentrations of CO (33.60%) and SO_2 (44.16%) were higher in Jeddah; PM_{10} (91.12%) in Riyadh, while NO_2 (44.35%) and O_3 (18.98%) were highest in Makkah. However, a significant reduction in mean concentrations for CO (1316.95 ± 70. 07 to 654.47 ± 14.12) $\mu g\ m^{-3}$ and SO_2 (19.44 ± 2.12 to 7.53 ± 1.74) $\mu g\ m^{-3}$, PM_{10} (518.42 ± 29.98 to 24.10 ± 4.78) $\mu g\ m^{-3}$,

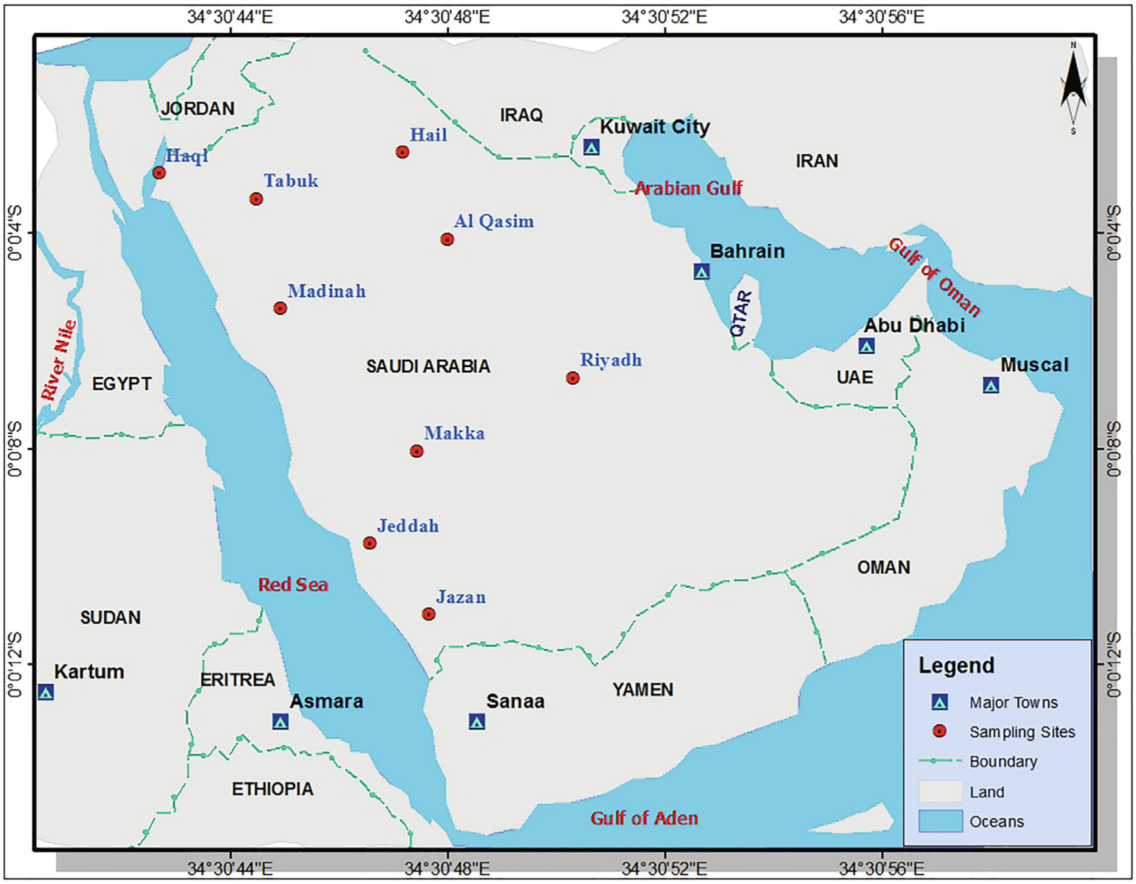

Fig. 1. Map of Saudi Arabia showing nine cities used for this study (2020). Source: Geographic Information System (GIS) using ArcGIS 10.3 Software.

Table 1
Mean (mean ± SE) concentrations of pollutants before COVID-19 lockdown.

	CO	PM_{10}	SO_2	NO_2	O_3
Makkah	966.53 ± 38.65^{cd}	195.06 ± 6.03^{b}	20.80 ± 2.46^{a}	22.05 ± 2.06^{cd}	50.85 ± 21.16^{cde}
Ha'il	678.23 ± 13.39^{d}	83.90 ± 5.18^{c}	6.40 ± 0.52^{d}	18.86 ± 4.41^{d}	69.27 ± 2.25^{abc}
Jeddah	1316.95 ± 70.07^{b}	190.19 ± 12.38^{b}	19.44 ± 2.12^{b}	35.59 ± 3.29^{b}	56.72 ± 5.95^{bcd}
Jazan	1289.82 ± 57.60^{cd}	98.54 ± 14.94^{c}	24.22 ± 3.55^{a}	19.16 ± 2.20^{d}	22.53 ± 1.96^{f}
Tabuk	1182.64 ± 110.25^{bc}	94.95 ± 3.51^{c}	12.96 ± 0.52^{c}	12.39 ± 1.23^{e}	93.29 ± 3.71^{a}
Al Madinah	959.40 ± 56.79^{cd}	116.60 ± 9.76^{bc}	15.66 ± 2.05^{bc}	42.19 ± 3.49^{a}	29.96 ± 2.41^{ef}
Al Qasim	997.15 ± 128.83^{cd}	186.99 ± 7.34^{b}	6.51 ± 0.75^{d}	6.41 ± 1.15^{f}	41.53 ± 1.75^{def}
Riyadh	2162.01 ± 214.31^{a}	518.42 ± 29.98^{a}	10.62 ± 1.81^{cd}	44.30 ± 1.99^{a}	46.36 ± 6.31^{cdef}
Haql	757.92 ± 71.89^{d}	174.57 ± 10.79^{b}	15.21 ± 3.06^{bc}	23.95 ± 7.43^{cd}	79.61 ± 7.87^{ab}
F value	18.968	2.298	7.700	11.593	7.722
P value	0.000	0.025	0.000	0.000	0.000

Mean±S.E with different superscripts (a-g) along the same column were significantly different ($p < 0.05$).

Table 2
Mean (mean ± SE) concentrations of pollutants during COVID-19 lockdown.

	CO	PM_{10}	SO_2	NO_2	O_3
Makkah	705.27 ± 10.37^{bc}	114.37 ± 10.37^{abcd}	18.83 ± 1.05^{a}	8.50 ± 2.43^{c}	34.63 ± 0.64^{e}
Ha'il	528.70 ± 15.46^{c}	81.57 ± 1.13^{cd}	5.80 ± 0.29^{ef}	17.10 ± 0.85^{b}	67.10 ± 1.01^{c}
Jeddah	654.47 ± 14.12^{c}	98.10 ± 23.60^{bcd}	7.53 ± 1.74^{de}	31.63 ± 2.83^{a}	46.37 ± 3.25^{d}
Jazan	1176.33 ± 33.26^{ab}	25.73 ± 2.18^{f}	13.13 ± 0.34^{b}	8.40 ± 1.14^{c}	21.87 ± 2.95^{fg}
Tabuk	731.43 ± 21.20^{bc}	73.07 ± 11.10^{d}	9.10 ± 0.06^{cd}	7.20 ± 1.10^{c}	110.57 ± 1.27^{a}
Al Madinah	783.17 ± 75.90^{bc}	125.03 ± 13.18^{abc}	10.40 ± 0.35^{c}	39.60 ± 5.81^{a}	20.43 ± 2.92^{g}
Al Qasim	957.27 ± 180.79^{bc}	160.50 ± 20.36^{a}	5.90 ± 0.06^{ef}	5.70 ± 0.26^{c}	49.23 ± 3.76^{d}
Riyadh	1557.87 ± 218.75^{a}	24.10 ± 4.78^{f}	5.07 ± 0.20^{f}	29.10 ± 8.55^{a}	28.27 ± 1.36^{ef}
Haql	702.93 ± 70.00^{bc}	130.93 ± 23.36^{ab}	8.40 ± 0.12^{cd}	13.13 ± 1.64^{b}	82.40 ± 0.89^{b}
F value	4.806	9.981	37.995	11.101	174.434
P value	0.003	0.000	0.000	0.000	0.000

Mean±S.E with different superscripts (a-g) along the same column were significantly different ($p < 0.05$).

Table 3
Percentage changes in mean (mean ± SE) concentrations of pollutants during COVID-19 lockdown relative to pre-lockdown period.

	Percentage change in CO	Percentage change in PM_{10}	Percentage change in SO_2	Percentage change in NO_2	Percentage change in O_3
Makkah	15.63%	26.08%	4.97%	44.35%	18.98%
Ha'il	12.39%	1.41%	4.92%	4.89%	1.59%
Jeddah	33.60%	31.94%	44.16%	5.89%	10.04%
Jazan	4.60%	58.59%	29.69%	39.04%	1.49%
Tabuk	23.57%	13.02%	17.50%	26.49%	−8.48%
Al Madinah	10.11%	4.42%	20.18%	3.17%	18.91%
Al Qasim	2.04%	7.62%	4.92%	5.86%	−8.48%
Riyadh	16.24%	91.12%	35.37%	20.71%	24.24%
Haql	3.76%	14.28%	28.84%	29.18%	−1.72%

Table 4
The comparison in the decrease (%) caused by COVID-19 lockdown in some selected studies.

	CO	PM_{10}	SO_2	NO_2	O_3	
KSA	13.55%	27.61%	21.17%	19.95%	6.28%	Current study
Tehran	−13%	−11.33%	−12.50%	−13%	3%	(Broomandi et al., 2020)
Almaty	−49% (674.0–343.0)	–	+7% (49.0–52.0)	−35% (37.0–24.0)	+15% (30.0–34.0)	(Kerimray et al., 2020)
São Paulo	−64.80%	–	–	−54.30%	30%	(Nakada and Urban, 2020)
Delhi	−30%	−60%	–	−53%	–	(Mahato et al., 2020)
Suzhou	−5.8% (0.91–0.86)	−19.0% (138.1–111.9)	−67.1% (6.72–2.21)	−36.5% (23.9–15.2)	−0.06% (37.3–37.1)	(Xu et al., 2020)
Wuhan	−16.2% (0.88–0.73)	−47.9% (88.2–46.0)	−29.9% (3.79–2.66)	−54.7% (30.0–10.41)	+27.1% (27.7 35.2)	(Xu et al., 2020)

NO_2 (22.05 ± 2.06 to 8.50 ± 2.43) µg m^{-3}, and O_3 (50.85 ± 21.16 to 34.63 ± 0.64) µg m^{-3} were recorded in Jeddah, Riyadh and Makkah respectively (Fig. 2).

3.2. Meteorological changes and its influence on air quality during COVID-19 lockdown

Variations in meteorological conditions such as relative humidity (H), temperature (T), and wind speed (WS) before and during COVID-19 lockdown, are presented in Table 5. Generally, there was no obvious change or variation between the values for meteorological conditions (Humidity, temperature, and wind speed) between pre-lockdown (Jan 2019 to Feb 2020) and the COVID-19 lockdown period (March 2020 to May 2020).

Students' *t*-test ($p < 0.05$) revealed no significant variation between meteorological conditions before lockdown and lockdown period for the nine cities under study, except for Jeddah where significant variation was observed in relative humidity (Table 4).

Principal component analysis (PCA) biplot for atmospheric pollutants and meteorological conditions in nine cities of Saudi Arabia studied before the lockdown and during the lockdown period is presented in Fig. 3. Component 1 and 2 accounted for 53.64%, 60.65%, 56.85%, 79.84%, 69.85%, 59.22%, 54.11%, 62.12%, and 56.45% of the total variation in Makkah, Ha'il, Jeddah, Jazan, Tabuk, Al Madinah, Al Qasim, Riyadh, and Haql respectively.

In Makkah, there was an influence of COVID-19 lockdown on PM_{10}, CO, and O_3 with also a positive correlation between these three pollutants and temperature. The influence of the lockdown on PM_{10} was also recorded in the city of Ha'il, but in contrast, PM_{10} was negatively correlated with humidity. The city of Jeddah presents a different situation from Makkah and Ha'il with a lockdown period influencing NO_2, $O_{3,}$ and SO_2 with a positive correlation with humidity and wind speed. CO and O_3 were influenced by the lockdown and a negative correlation was established between CO, O_3, humidity, and wind speed.

For the city of Tabuk, PM_{10}, $O_{3,}$ and SO_2 were revealed to have been impacted during COVID-19 lockdown, besides correlating positively with WS and temperature. In Al Madinah, more importantly, PM_{10} was influenced by the introduction of lockdown and also a negative correlation with wind speed and humidity. The lockdown period in the city of Al Qasim influenced PM_{10}, CO, O_3, $NO_{2,}$ and SO_2, and revealed a positive correlation between these five atmospheric pollutants and humidity. A negative correlation was also revealed between PM_{10}, humidity, and wind speed in Riyadh. However, the impact of the lockdown on PM_{10} was also established. A similar outcome was realized in the city of Haql, with the impact of the lockdown on PM_{10}, but also includes NO_2 and O_3. Moreover, a negative correlation existed between PM_{10}, $NO_{2,}$ and humidity, and wind speed correlating positively with O_3.

4. Discussion

The decrease in the concentration of CO, PM_{10}, SO_2, $NO_{2,}$ and O_3 in KSA regarding the nine cities under study are a result of the COVID-19 lockdown that led to the decrease in pollution emissions from traffic after the outbreak of COVID-19.

However, the contrasting pattern of O_3 as compared to other atmospheric pollutants in Tabuk, Al Qasim, and Haql is a result of NO and O_3 reaction, causing the inability of effective O_3 depletion. Other reasons could be conditions that are favorable to reactions by photochemical which are linked to a decrease in NO_2 and upsurge in solar insolation. This causes changes in photochemical reactions responsible for the buildup and destruction of O_3 (Broomandi et al., 2020; Sharma et al., 2020a, 2020b; Xu et al., 2020). Usually, a negative correlation exists between O_3 and NO_x. Factors that influence O_3 accumulation in the atmosphere are the principal chemistry that exists between the concentration of O_3 and emissions due to human activities. For example, NO_x in an environment with low VOC together with meteorological conditions (Broomandi et al., 2020; Jain and Sharma, 2020). A decrease in NO_2 concentration leads to a decrease in NO concentration and causes a reduction in the possibility of reaction between NO and O_3 resulting in prevention in O_3 accumulation. Azarmi and Arhami (2017) have also reported road vehicles as the cause for emission of oxides of nitrogen (NO_x), PM_{10}, and CO in their study on challenges of atmospheric pollution in a megacity.

The percentage change in atmospheric pollutant between the period before the lockdown and during lockdown is in line with the findings by several authors such as Mahato et al. (2020) and Xu et al. (2020) where they report a significant decrease in

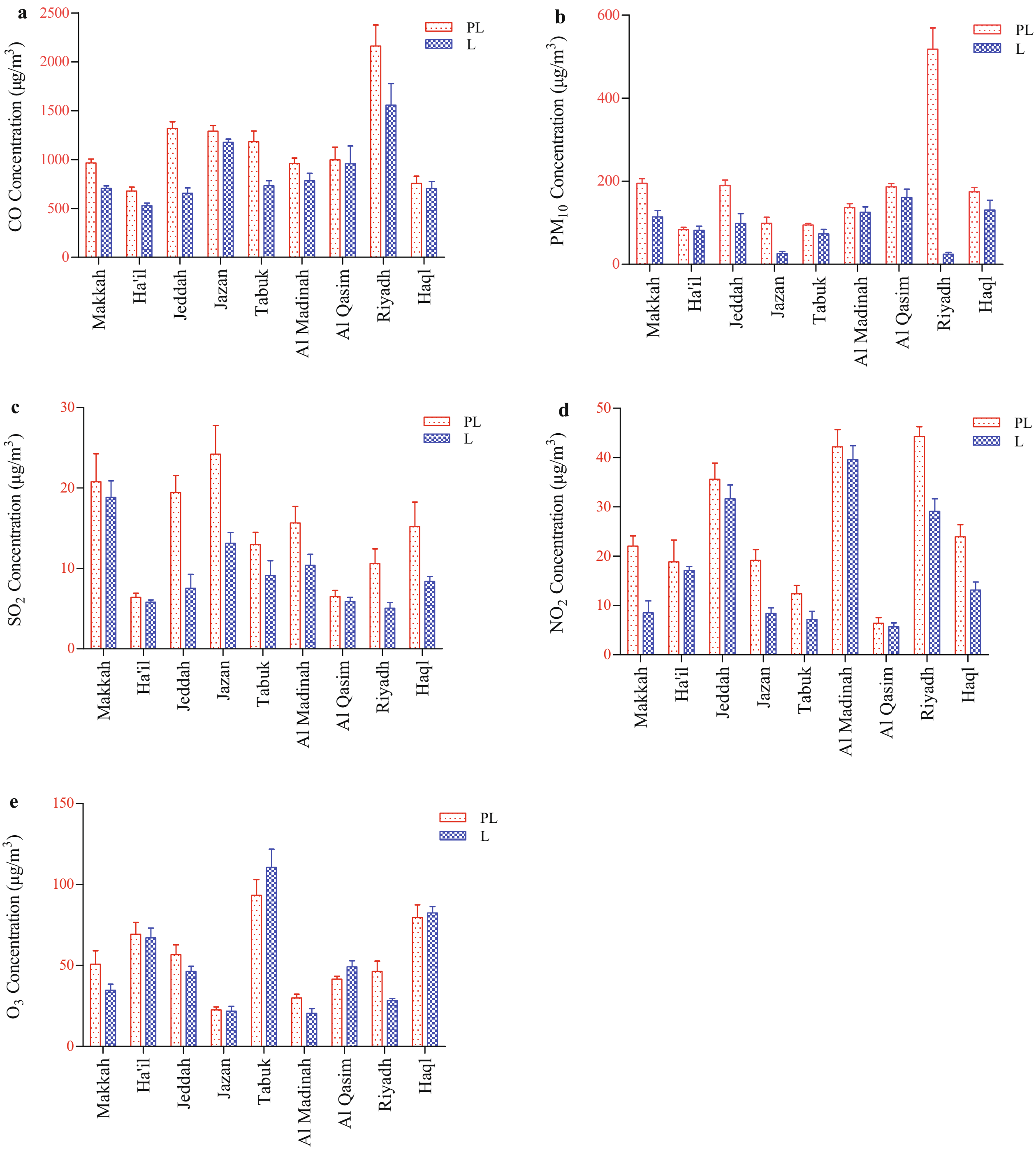

Fig. 2. Mean concentrations of a) CO, b) PM_{10}, c) SO_2, d) NO_2 and e) O_3 in different cities of Saudi Arabia before and during COVID-19 lockdown. L = Lockdown, PL = Before lockdown.

atmospheric pollutants during the period of COVID-19 lockdown in Delhi and Wuhan. Their studies were to assess the impact of COVID-19 lockdown on atmospheric pollutants when compared with the pre-COVID-19 lockdown.

Even though there was a decrease in pollutants concentration during the lockdown, the concentrations for CO, PM_{10}, SO_2, NO_2, and O_3 were still above WHO 24 h and annual mean limit levels. This confirms non-traffic source emission contributing to an increase in atmospheric pollutants. This can be stationary sources from the industries with the combustion of fossil fuel playing a key role in the complex source mix (Halek et al., 2004). Kerimray et al. (2020) report similar findings in Almaty, stating the reason for pollutants exceeding levels of WHO during the COVID-19 lockdown due to contribution by non-traffic sources. A study similar to our work was carried out in Eastern China with a reported result revealing a significant decrease of 30% and 20% in concentrations for NO_2 and CO respectively. It was attributed to reduced anthropogenic activities link to urban transportation and growth in the economy during the period of COVID-19 lockdown (Filonchyk et al., 2020).

In another study in Iran on the impact of COVID-19 event on the air quality of 12 locations, reports a total reduction of −13%,

Table 5
Variation in meteorological conditions (mean ± SE) during COVID-19 lockdown relative to pre-lockdown period.

		Humidity	Temperature	WS		Humidity	Temperature	WS		Humidity	Temperature	WS
Makkah	PL	36.43 ± 2.56	29.75 ± 1.44	1.32 ± 0.04	**Ha'il**	27.20 ± 3.30	22.04 ± 2.44	3.345 ± 0.11	**Jeddah**	54.68 ± 3.07	30.17 ± 1.07	1.70 ± 0.25
	L	29.90 ± 2.25	31.15 ± 2.15	1.32 ± 0.06		22.62 ± 3.99	24.27 ± 3.16	4.04 ± 0.11		65.95 ± 2.06	31.05 ± 1.24	2.93 ± 0.06
	F value	1.751	1.599	0.945		1.964	3.334	4.464		5.803	3.703	8.255
	P value	0.206	0.225	0.346		0.181	0.088	0.052		0.029	0.073	0.012
Jazan	PL	54.68 ± 3.07	30.17 ± 1.07	1.70 ± 0.25	**Tabuk**	34.47 ± 2.60	20.21 ± 2.30	1.66 ± 0.08	**Al Madinah**	27.86 ± 2.99	25.20 ± 1.99	1.85 ± 0.06
	L	65.95 ± 2.06	31.05 ± 1.24	2.93 ± 0.06		29.59 ± 4.49	22.21 ± 2.85	2.18 ± 0.13		23.78 ± 3.89	26.52 ± 3.27	1.76 ± 0.09
	F value	5.803	3.703	8.255		0.719	3.606	0.749		1.359	1.379	0.678
	P value	0.029	0.073	0.012		0.410	0.077	0.401		0.262	0.259	0.423
Al Qasim	PL	28.50 ± 3.41	24.01 ± 2.42	2.06 ± 0.08	**Riyadh**	24.7 ± 3.19	26.82 ± 2.44	1.73 ± 0.06	**Haql**	38.48 ± 1.16	24.45 ± 1.71	4.94 ± 0.26
	L	23.02 ± 5.00	26.91 ± 2.99	2.38 ± 0.27		18.99 ± 4.62	29.77 ± 3.03	1.81 ± 0.16		36.82 ± 3.01	25.13 ± 2.42	5.13 ± 0.31
	F value	1.146	3.754	1.026		1.766	3.565	0.348		0.155	2.639	1.412
	P value	0.301	0.072	0.327		0.204	0.078	0.564		0.699	0.125	0.253

11.33%, −12.5%, −13%, and +3% for CO, PM_{10}, SO_2, NO_2, and O_3 respectively (Broomandi et al., 2020). Similar findings were also reported by Xu et al. (2020a) with reduction of 46.5%, 48.9%, 52.5%, 36.2%, and 52.8% for $PM_{2.5}$, PM10, SO_2, CO, and NO_2 in their study in Anhui Province, close to central China with insight to atmospheric pollutants concentrations during COVID-19 lockdown in three cities (Table 3).

Non-significant variation recorded between meteorological conditions before the lockdown and during the lockdown indicates meteorological conditions alone not to be the major reason for atmospheric pollution decline during the lockdown period (Navinya et al., 2020; Schiermeier, 2020). However, significant variation in relative humidity recorded in Jeddah can be as a result of the warm sea close to Jeddah and the rise in temperature linked with the time of the season, as the lockdown period with the increase in humidity falls between spring and summer seasons. Properties such as solar radiation and temperature have been reported to contribute to the causation of an increase in the percentage of relative humidity in the atmosphere (Jasaitis et al., 2016; Patlakas et al., 2019).

Our result agrees with the findings of Navinya et al. (2020) where they report an increase in relative humidity during the COVID-19 lockdown after they examine the effect of the lockdown on ambient air quality of an urban setting in India. Patlakas et al. (2019) also report the link between a rise in temperature and relative humidity during spring and summer seasons. Their report captures the aspect of an increase in the variation of regional features as related to Arabian Peninsula climatic conditions. In contrast, Almazroui (2012) gave a different report opposite to our finding of a rise in temperature and relative humidity in spring and summer in their work on dynamical downscaling of rainfall and temperature.

Relationships between the lockdown period, atmospheric pollutants, and meteorological conditions revealed by PCA can be due to some important phenomena or factors. Phenomenon such as an increase in temperature due to increasing solar radiation during the lockdown period, affecting photochemical reactions involved in the formation of O_3, and also a favorable environment for the accumulation of O_3 (Xu et al., 2020). While humidity and wind speed have been reported to influence the dispersion of atmospheric pollutants generally (Broomandi et al., 2020). However, 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 VOCs (volatile organic compounds) which serve as precursors (Biswas et al., 2019; Xu et al., 2020). The involvement of PM_{10} in this relationship is not a coincidence, as it is also produced from factors such as soil dust and sand storms. These are natural and can influence the increase of PM_{10} even without other anthropogenic influences, even if the increase is not as rapid or much like before the lockdown (Liu et al., 2020). This might form a key reason for its positive correlation with temperature and other pollutants during the lockdown period.

Despite the enforcement of lockdown in Saudi Arabia during the period captured in this study, there was a partial activity in some cities by some of the important parastatals such as the petroleum industries. Generally, the enforcement of the lockdown varies with the cities at the beginning of the lockdown. This might have been the cause of SO_2 involvement in some of the relationships and the spread aided by meteorological conditions such as wind speed (Algaissi et al., 2020). SO_2 are produced mainly from activities of coal and petroleum combustion and smelting of ores containing sulfur. Our results are in line with other findings such as Lokhandwala and Gautam (2020); Navinya et al. (2020), and Xu et al. (2020).

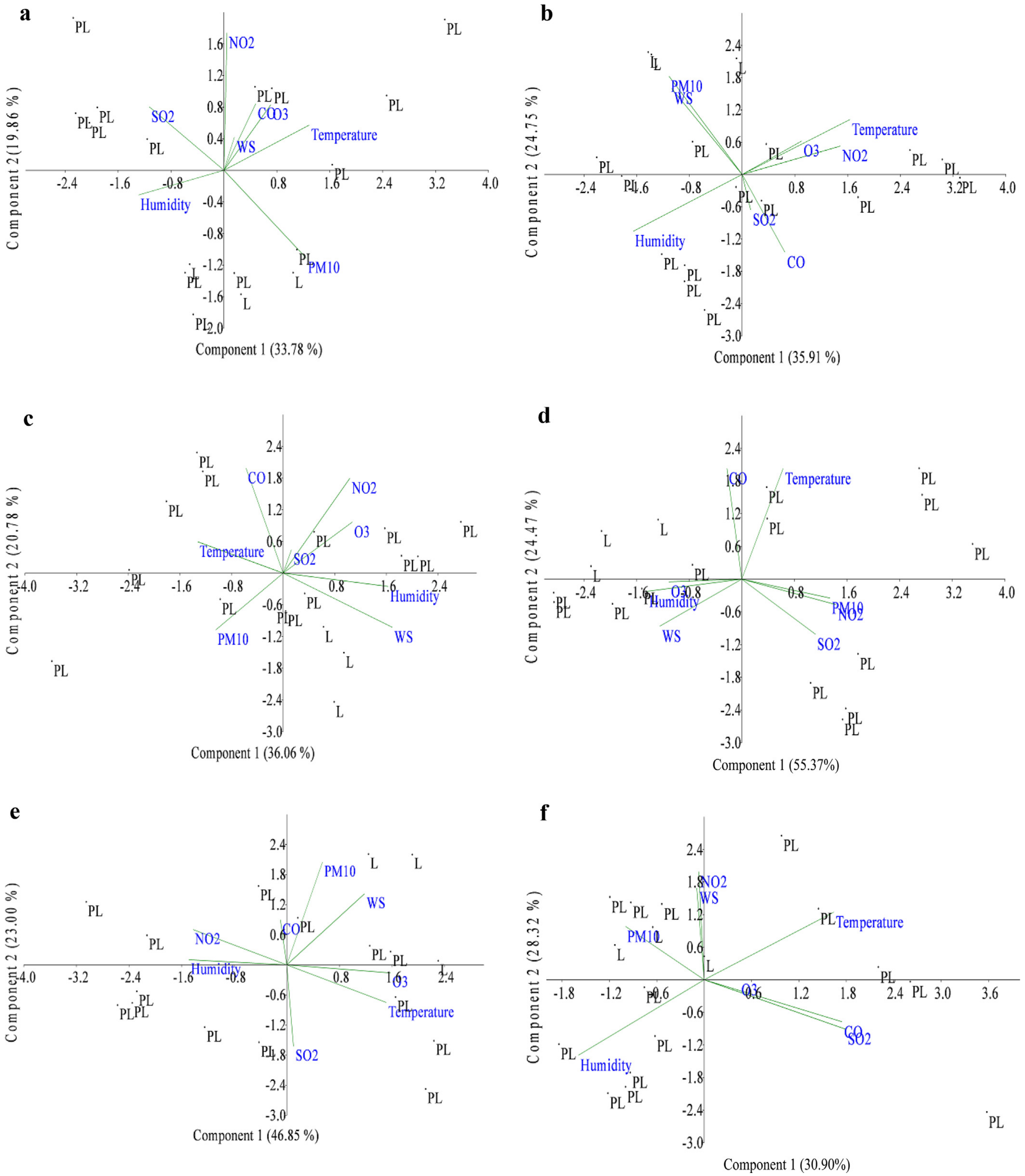

Fig. 3. Principal component analysis biplot for the influence of meteorological data and pollutants concentration before and during COVID-19 lockdown in a) Makkah, b) Ha'il, c) Jeddah, d) Jazan, e) Tabuk, f) Al Madinah, g) Al Qasim, h) Riyadh and i) Haql. L = Lockdown, PL = Before lockdown.

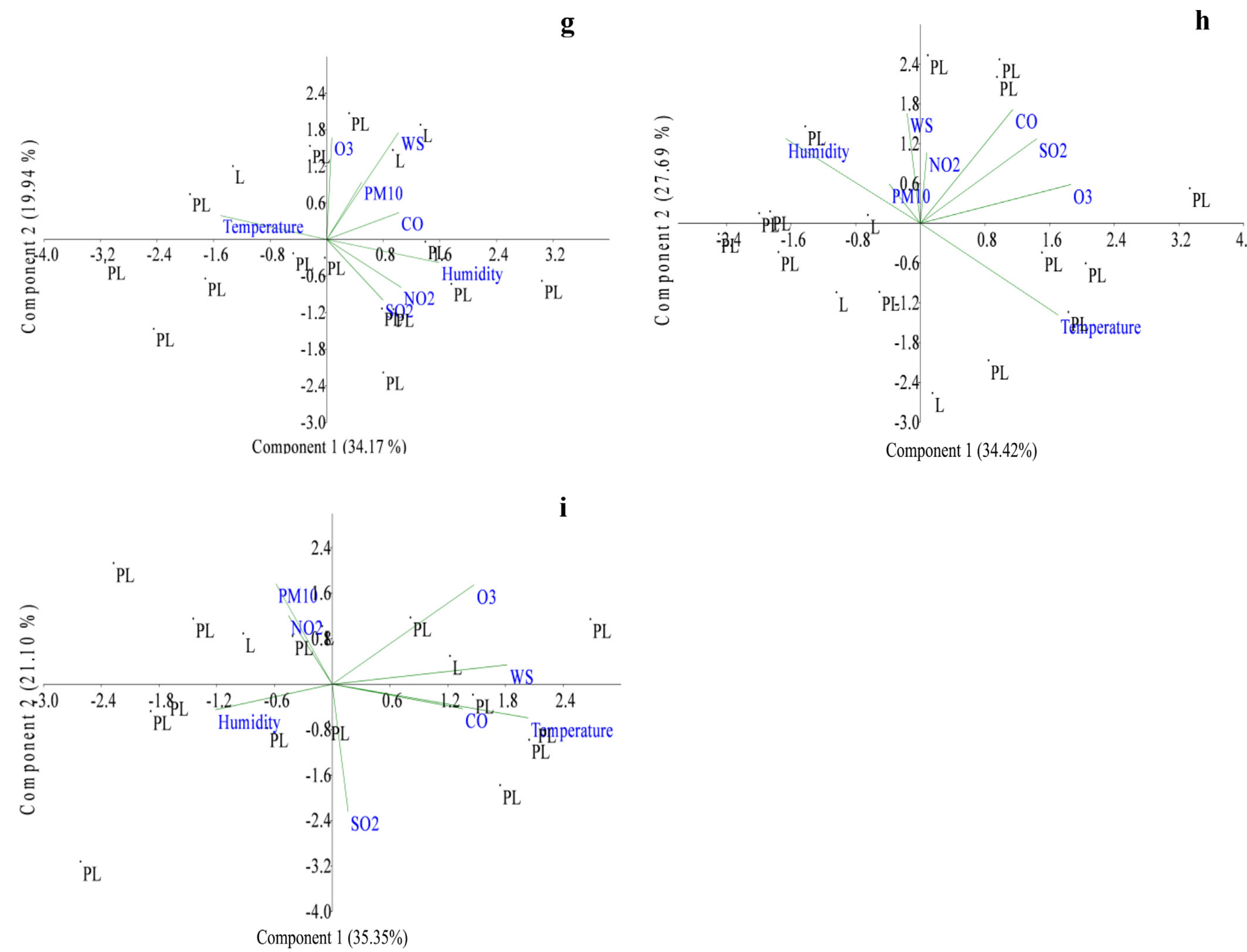

Fig. 3 (*continued*)

5. Conclusions

In this article, the effect of COVID-19 lockdown in the Kingdom of Saudi Arabia on atmospheric pollutants (CO, PM_{10}, SO_2, NO_2, and O_3) using data from nine cities was determined. Significant variation ($p < 0.05$) was recorded for the five atmospheric pollutants across the cities before and during the lockdown, with lower concentrations during the lockdown except for the concentration of O_3 in Tabuk, Al Qasim, and Haql. The percentage changes in concentrations of CO (33.60%) and SO_2 (44.16%) were higher in Jeddah; PM_{10} (91.12%) in Riyadh, while NO_2 (44.35%) and O_3 (18.98%) were highest in Makkah.

The significant decrease in atmospheric pollutants during the pandemic captured in this study was due to enforcement of the lockdown which affects industrial production and traffic. A significant change was not recorded in meteorological conditions before and during the lockdown for the nine cities under study except for Jeddah where significant variation was observed in relative humidity. However, even though there was no significant change in meteorological conditions during the lockdown, they still influence changes associated with concentrations of pollutants. The COVID-19 lockdown in the Kingdom of Saudi Arabia revealed the possibility of significant atmospheric pollutant reduction by controlling traffic, activities by industries, and environmentally friendly transportation programs such as green commuting programs.

Declaration of Competing Interest

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

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