Air Quality, Atmosphere, and Health

The impact of COVID-19 lockdown on the air quality of Eastern Province, Saudi Arabia

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Abstract

Since the identification of the COVID-19 outbreak in Wuhan, China, in December 2019, the death toll from the direct infection by COVID-19 has exceeded 1.3M and more than 55M million cases have been reported to the World Health Organization (WHO) around the world. It is strongly believed that its impact might be worsened by poor outdoor and indoor air qualities, particularly on older adults. The nationwide lockdown measures were imposed between March 23 and June 20, 2020, to stop the spread of the COVID-19 pandemic in the Kingdom of Saudi Arabia (KSA). In this work, the possible effects of the lockdown on the air quality were investigated using meteorological and air quality datasets obtained from four monitoring stations covering the Eastern Province of the KSA. The studied air pollutants include carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), and inhalable particulate matter (PM_{10}). The NO_2 was found to be the marker pollutant responding best to the lockdown measures since its concentrations decreased at all sites during- and post-lockdown periods. Compared with the pre-lockdown period, the Eastern Province also experienced significant concentration reductions at varying rates for PM_{10}, CO, and SO_2, while O_3 concentrations showed increasing rates. The consequences of these reductions were reflected in easing the outdoor air quality,

which might reduce the impact of the COVID-19 pandemic, especially on elderly and sensitive groups.

Further, we had collected the perceived air-quality data before and after lockdown from 10 different and qualitatively conducted statistical studies to infer whether there is any evidential difference in perception regarding pollution. The dataset deals with the air quality perceived by citizens before and during the enforcement of COVID-19 restrictions in ten countries around the world: Australia, Brazil, China, Ghana, India, Iran, Italy, Norway, South Africa, and the United States. An online survey conveniently translated into Chinese, English, Italian, Norwegian, Persian, Portuguese collected in-formation regarding the perceived quality of air pollution ac- cording to a Likert scale. The questionnaire was distributed between 11-05-2020 and 31-05-2020 and 9 394 respondents took part. Both the survey and the dataset (stored in a Microsoft Excel Worksheet) are available in a public repository. The collected data offer the people's subjective perspectives related to the objective improvement in air quality that occurred during the COVID-19 restrictions. Furthermore, the dataset can be used for research studies involving the reduction in air pollution as experienced, to a different extent, by populations of all the ten countries.

Specification table

Subject	Social Sciences
Specific subject area	Health psychology, Perceived air pollution
Type of data	Primary data, Table
How data were acquired	The data were collected by an online survey hosted on two platforms: Google Forms (English, Italian, Norwegian, Persian, Portuguese versions) and WenJuanXing (Chinese version). An English copy is available in the data repository. The survey was distributed by means of professional and social networks
Data format	Raw Analyzed
Parameters for data collection	The survey data were obtained from 9 394 respondents older than 18 years old having internet access
Description of data collection	The online survey was distributed using a combination of purposive and snowball techniques
Data source location	Countries: Australia, Brazil, China, Ghana, India, Iran, Italy, Norway, South Africa and the United States
Data accessibility	Dataset is uploaded on Mendeley Data Repository name: Perceived air pollution in Australia, Brazil, China, Ghana, India, Iran, Italy, Norway, South Africa, USA before and during COVID-19 restrictions Data identification number: DOI: 10.17632/fb38h4tyzn.2 Direct URL to data: https://data.mendeley.com/datasets/fb38h4tyzn/2

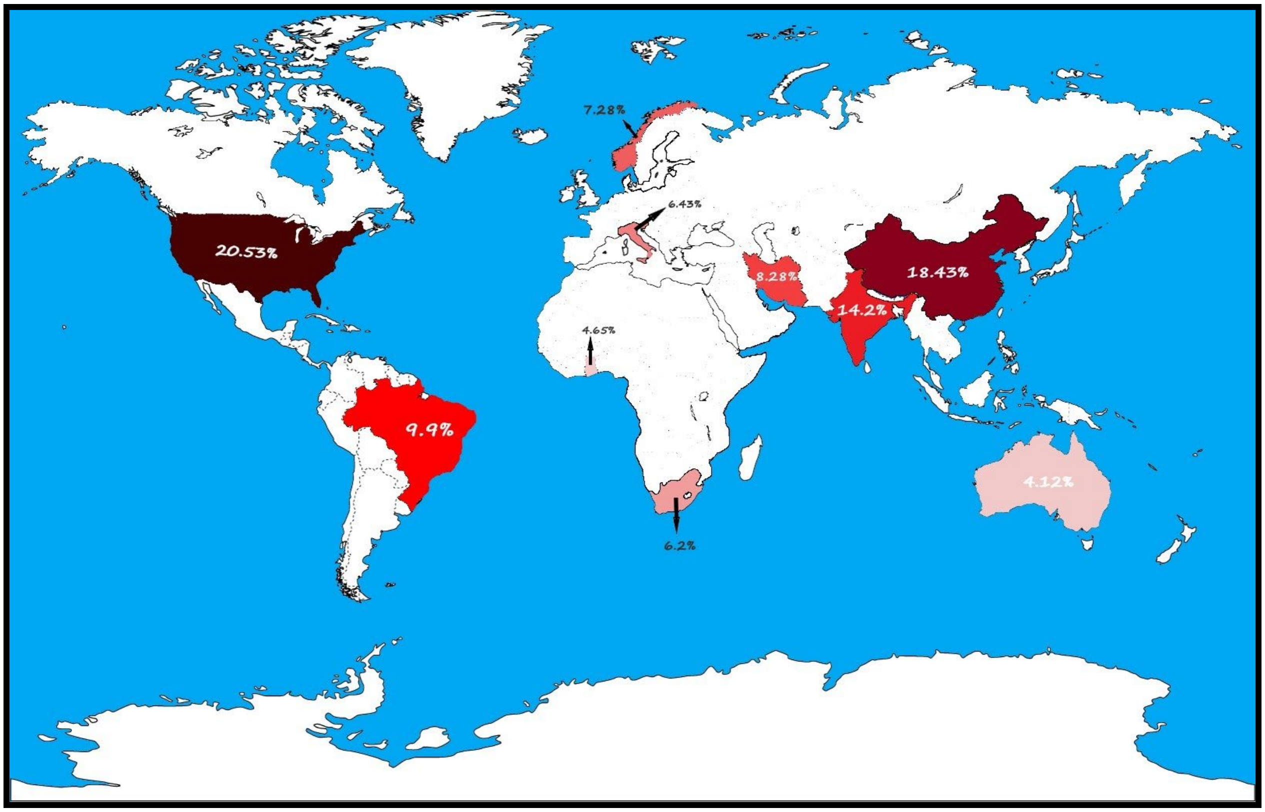
Value of the data

- The data are related to the perception of air quality and air pollution during the COVID-19 restrictions as experienced by a large pool comprising 9 394 respondents located in ten countries on six continents
- The data can be useful for researchers dealing with the environmental and tropospheric changes occurring during the COVID-19 restrictions
- The data can be used to assess the relationship between the perceived and the quantified change in air quality and air pollution during the COVID-19 restrictions
- The data can be of interest to both citizens and policymakers to realize the tremendous lesson learned during COVID-19, being air quality a key indicator for sustainable development

Data description

The dataset provides information regarding the quantity of air pollution perceived before and during the restrictions enforced in ten countries around the world as a consequence of the COVID-19 pandemic: Australia, Brazil, China, Ghana, India, Iran, Italy, Norway, South Africa, and the United States (also referred to as AU, BR, CH, GH, IN, IR, IT, NO, ZA and USA, respectively). The dataset is stored in a public repository as Microsoft Excel Worksheet. The total number of respondents who joined the survey is 9 394, their geographical distribution is reported. Information regarding gender and age are reported with box-and-whisker plots: overall, the largest portion of the surveyed population is composed of young and middle-aged individuals. Furthermore, the participants have high education. The two questions of the survey are “How do you regard the amount of air pollution before the epidemic?” and “How do you regard the amount of air pollution during the restrictions?”: the respondents expressed their opinions according to a 7-point Likert scale varying from “extremely low/absent air pollution” to “extremely high air pollution”.

Geographical distribution of survey respondents.



As it is clear the maximum number of respondents were from the United States of America, followed by China and India. The data was sampled by the Snowball technique.

SNOWBALL TECHNIQUE

Snowball sampling (also known as chain-referral sampling) is a non-probability (non-random) sampling method used when characteristics to be possessed by samples are rare and difficult to find. For example, if you are studying the level of customer satisfaction among elite Nirvana Bali Golf Club in Bali, you will find it increasingly difficult to find primary data sources unless a member is willing to provide you with contacts of other members.

This sampling method involves primary data sources nominating other potential primary data sources to be used in the research. In other words, the snowball sampling method is based on referrals from initial subjects to generate additional subjects. Therefore, when applying this sampling method members of the sample group are recruited via chain referral.

Also, snowball sampling is the most popular in business studies focusing on a specific company that involves primary data collection from employees of that company. Once you have the contact details of one employee she/he can help you to recruit other employees to the study by providing contact details.

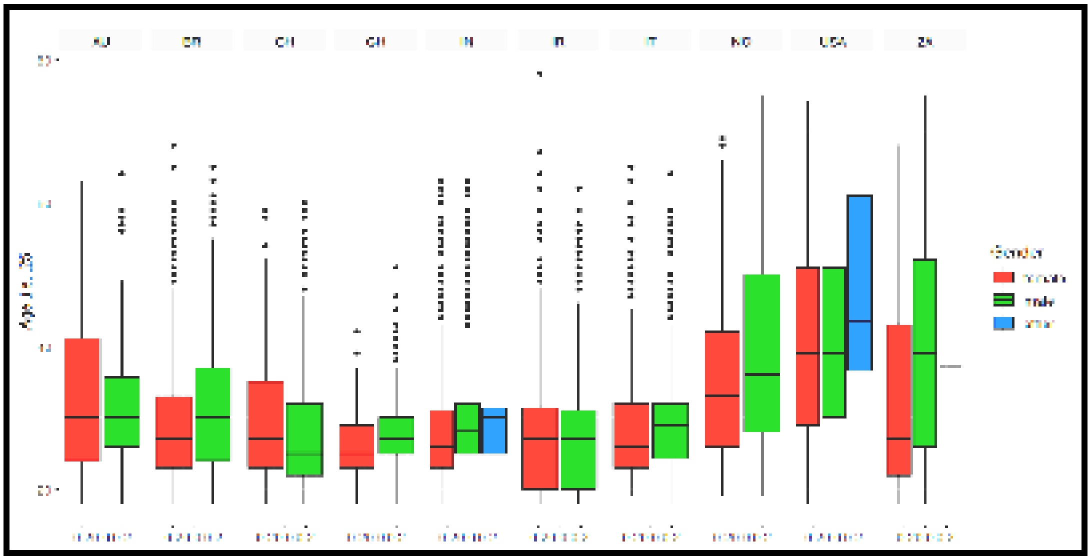
Advantages of Snowball Sampling

- The ability to recruit hidden populations
- The possibility to collect primary data in a cost-effective manner
- Studies with snowball sampling can be completed in a short duration of time
- A very little planning is required to start a primary data collection process

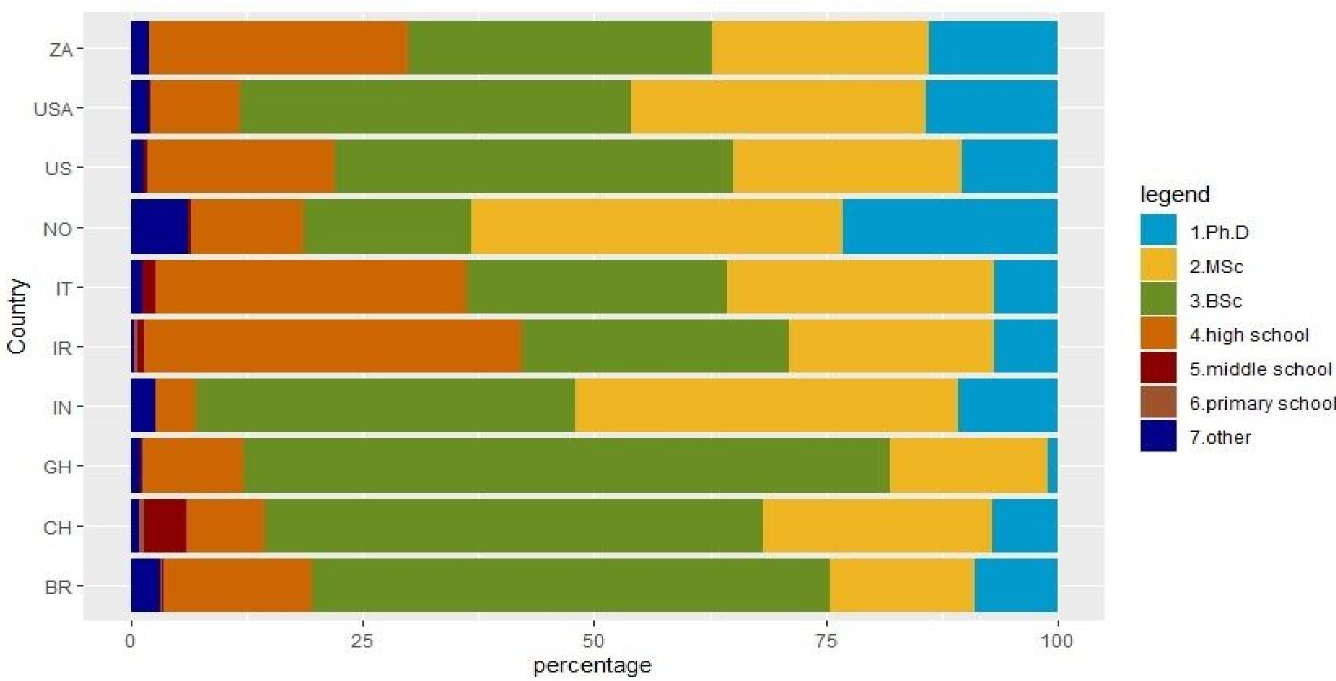
Disadvantages of Snowball Sampling

- Oversampling a particular network of peers can lead to bias
- Respondents may be hesitant to provide names of peers and asking them to do so may raise ethical concerns
- There is no guarantee about the representativeness of samples. It is not possible to determine the actual pattern of distribution of the population.
- It is not possible to determine the sampling error and make statistical inferences from the sample to the population due to the absence of a random selection of samples

Age and gender of the respondents for each country.



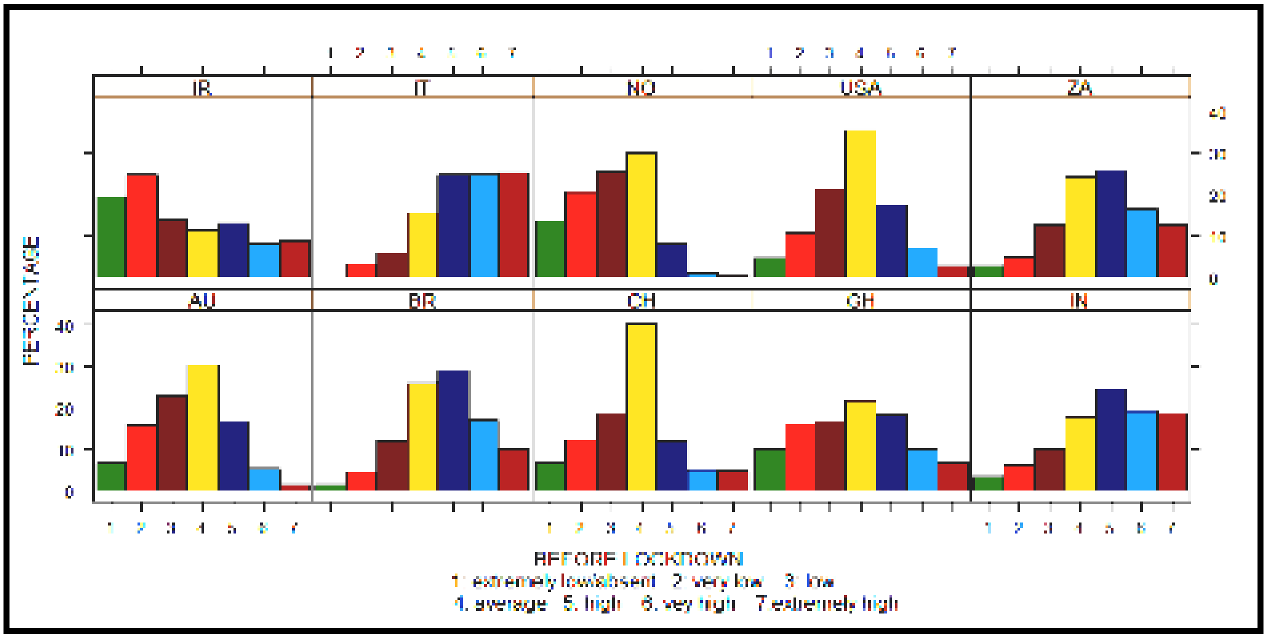
Education of the respondents for each country.

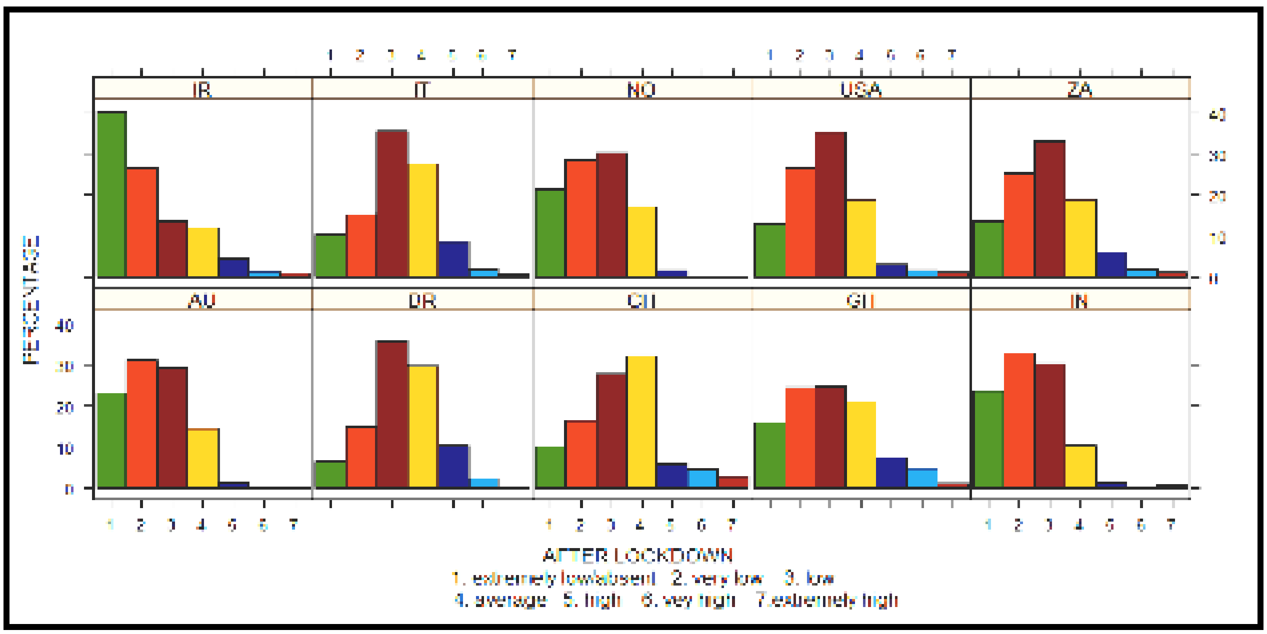


As the median age of the respondents of each country lies within the range of 25-40 and mostly the respondents are educated well(having at least an undergraduate degree, so the data set is trustable.

Experimental design, materials, and methods

The online survey has assessed the air quality as subjectively perceived by citizens in ten countries: Australia, Brazil, China, Ghana, India, Iran, Italy, Norway, South Africa, and the United States. The online questionnaire was hosted on two platforms: Google Forms (English, Italian, Norwegian, Persian, Portuguese versions) and WenJuanXing (Chinese version) and promoted on professional and social networks. The survey content was the same for each language; only the question regarding the respondents' geographical location was tailored for each country. A Likert scale was employed to collect information about subjective perceptions regarding both the situation before and during the enforcement of the restrictions due to the COVID-19 pandemic. The online survey was distributed using a combination of purposive and snowball techniques between 11-05-2020 and 31-05-2020. Previously, other opinion surveys at the regional and national scale also dealt with the perception of air quality and examined the psychological impacts on people's subjective emotional state. The created dataset can allow us to explore how air quality was experienced by the populations dealing with different levels of air pollution before the COVID-19 outbreak.





LOCKDOWN

The World Health Organization (WHO) announced on Wednesday, March 11, 2020, the new coronavirus “COVID- 19” disease as “a global epidemic” (WHO 2020). In response to that, governments around the world have been taking a range of actions and measures, including the closing of schools, worship places, and workplaces, postponing and canceling huge public events, restricting public transport, the lockdown of movement of people, and ceasing domestic and international flights. According to many studies, the COVID-19 is believed to transmit through airborne bioaerosol droplets. Nevertheless, different parameters such as the extent of urban air pollution and weather conditions might have a significant impact on the elevated rates of COVID-19 cases After the discovery of the first case of COVID-19 in the KSA on March 2, 2020, a series of actions were taken in response to the COVID-19 pandemic. The first three significant actions are taken to control the spread of the pandemic were as follows: (i) suspension of Umrah pilgrimage (March 4), (ii) suspension of all schools and universities (March 8), and (iii) suspension of all international flights (March 9). With the spread of COVID-19 and the absence of vaccine and medication globally, the Saudi government imposed a nationwide partial lockdown (from 7 PM to 6 AM) on March 23 followed by the restriction on movement between provinces on March 25. After that, the full lockdown was imposed nationwide on April 6. On May 28, the lockdown was partially lifted in all cities except Mecca, the movement between regions was eased, and shopping malls were opened. Following this, prayers were allowed in mosques except for the Great Mosque of Mecca, and the restrictions on domestic flights, restaurants, and cafes, and parks were eased on May 31. The latest action was on June 21, where the partial lockdown was lifted on all regions. However, international flights remain suspended except for repatriation flights for residents. Lastly, the Pilgrimage (Haj) was allowed to domestic residents and Saudi nationals only with limited numbers.

This study focuses on investigating the possible effects of the lockdown due to the COVID-19 pandemic on the air quality using meteorological and air quality datasets in the Eastern Province of the KSA.

Methodology

Description of the study area

The Eastern Province is the easternmost of the thirteen provinces of the KSA and located between latitudes of 29.16° N and 19.11° N and longitudes of 44.65° E and 55.66° E. The Eastern Province is the third most populated province with a total population of 4.9 million and the largest province (by area) of the KSA. The weather is hot in the summer season and mild for the rest of the seasons of the year. The long-term annual average values of the temperature and relative humidities are 27 °C and 41%, respectively. Wind systems from northern directions dominate over the area with an average ground-level wind speed of 4.2

m/s. The region has an arid precipitation regime and receives a total of 100 mm rainfall in a year between November and April. The Eastern Province has been facing severe local and long-range dust storms because of the pressure gradients. During the summer season, hot, dry, and low-level northwesterly winds called “Shamal winds" blowing at a minimum speed of 10 m/s lift dust and sand to the local and remote regions. Remarkable amounts of PM10 have been inhaled during episodic periods, resulting in a tremendous rise in the number of hospital admissions regarding respiratory issues. Recently reported that the daily average PM10 concentrations of Dhahran, Khobar, and Dammam districts of the Eastern Province were 177, 380, and 126 μg/m−3, respectively, which were quite above than the WHO’s daily PM10 guideline value of 50 μg/m−3 (WHO 2006).

Air quality data and study period

The air quality dataset discussed in this research was obtained from the database of the website called www.aqicn.com including CO, SO2, NO2, O3, and PM10 in four different locations of Eastern Province, which are Jubail (Station no. 1), Qatif (Station no. 2), Rakah (Stations nos. 3–5), and Al Ahsa cities. To reveal the impact of the lockdown due to the COVID-19 on the air quality, the obtained air quality datasets were divided into three periods: (i) pre-lockdown (September 15, 2019– March 22, 2020), (ii) during-lockdown (March 23, 2020– June 20, 2020), and (iii) post-lockdown (June 21, 2020–July 18, 2020).

Statistical analysis and data visualization

Descriptive statistics and outlier analysis methods were performed on the obtained air quality data sets. Box and whisker plots were depicted using the calculated mean, median, first quartile, third quartile, the range within 1.5 times of interquartile range (IQR), and outliers of each pollutant observed at each station for pre-lockdown, lockdown, and post- lockdown periods.

Results and discussions

Concentration variations of air pollutants before, during, and after lockdown periods

Central tendencies of each pollutant

RAKAH		PM10	O3	NO2	SO2	CO
PRE LOCKDOWN (N1 = 58)	*MEAN*	*19.46*	*14.75*	*14.68*	*1.79*	*15.87*
	SD	*22.88*	*10.62*	*10.87*	*1.57*	*9.01*
	MEDIAN	*17*	*17*	*1*	*2*	*18.5*
LOCKDOWN (N2 = 32)	*MEAN*	*18.29*	*7.96*	*2.06*	*9.90*	*20.65*
	SD	*11.52*	*3.13*	*2.90*	*9.35*	*12.64*
	MEDIAN	*16.5*	*9.5*	*1*	*7*	*16*

QATIF		PM10	O3	NO2	SO2	CO
PRE LOCKDOWN (N1 = 84)	*MEAN*	*6.22*	*25.94*	*0.41*	*1.91*	*24.98*
	SD	*11.59*	*15.22*	*0.60*	*1.29*	*12.35*
	MEDIAN	0	29	0	2	34
LOCKDOWN (N2 = 115)	*MEAN*	*9.13*	*28.84*	*0.09*	*2.24*	*9.41*
	SD	*11.62*	*22.47*	*0.2*	*3.8*	*9.06*
	MEDIAN	4	35	0	2	6

AL - AHSA		PM10	O3	NO2	SO2	CO
PRE LOCKDOWN (N1 = 87)	*MEAN*	13.93	38.58	1.12	3.83	18.68
	SD	15.92	14.47	1.85	4.17	9.42
	MEDIAN	11	40	1	3	21

LOCKDOWN (N2 = 116)	***MEAN***	**3.25**	**41.53**	**3.32**	**5.90**	**20.28**
	SD	**5.70**	**10.84**	**6.43**	**2.78**	**7.17**
	MEDIAN	**3**	**42**	**1**	**6**	**23**

The units for mean and median values are as follows:

- **NO2** : ppb(parts per billion)
- **O3** : ppb(parts per billion)
- **S02** : ppb(parts per billion)
- **CO** : ppm(parts per million)
- **Pm10** : ug/m3(microgram per cubic metres.)

Testing of hypothesis

After we have the information on central tendencies,we then conducted a hypothesis test for mean for each individual pollutant station wise.

Ho: u_1 equal to u_2 be the null hypothesis

Ha: u_1 is not equal to u_2 be the alternative hypothesis

$$\sigma_{(\bar{x}_1-\bar{x}_2)} = \sqrt{\frac{\sigma_1^2}{n_1}+\frac{\sigma_2^2}{n_2}} \cong \sqrt{\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2}}$$

$$z = \frac{(\bar{x}_1 - \bar{x}_2) - D_0}{\sigma_{(\bar{x}_1-\bar{x}_2)}}$$

Results of the hypothesis tests

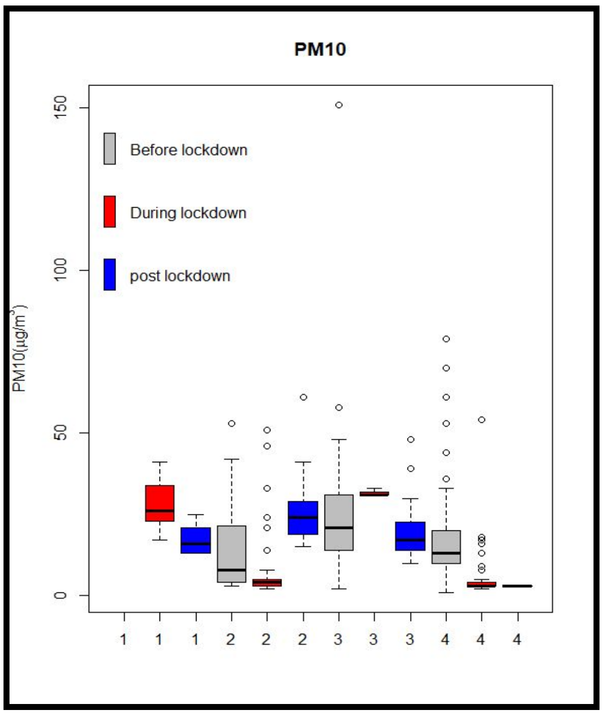
AL - AHSA	*PM10*	*O_3*	*NO_2*	*SO_2*	*CO*
Z	*6*	*-1.71*	*-3.5*	*-4.05*	*-1.33*
$\sigma(\bar{x}_1-\bar{x}_2)$	*1.78*	*1.84*	*0.62*	*0.51*	*1.2*
H_0	*Rejected*	*Not rejected*	*Rejected*	*Rejected*	*Not rejected*

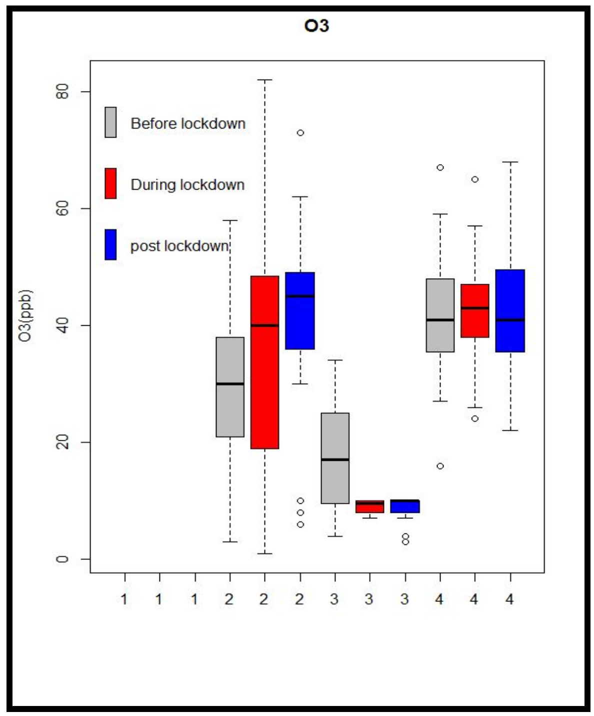
QATIF	*PM10*	O3	NO2	SO2	CO
Z	*-1.75*	*-1.08*	*4*	*-0.86*	*9.77*
$\sigma(\bar{x}_1-\bar{x}_2)$	*1.66*	*2.67*	*0.08*	*0.38*	*1.59*
H_0	*Not rejected*	*Not rejected*	*Rejected*	*Not Rejected*	*Rejected*

RAKAH	*PM10*	*O_3*	*NO_2*	*SO_2*	*CO*
Z	*0.32*	*4.52*	*8.3*	*-4.88*	*-1.89*

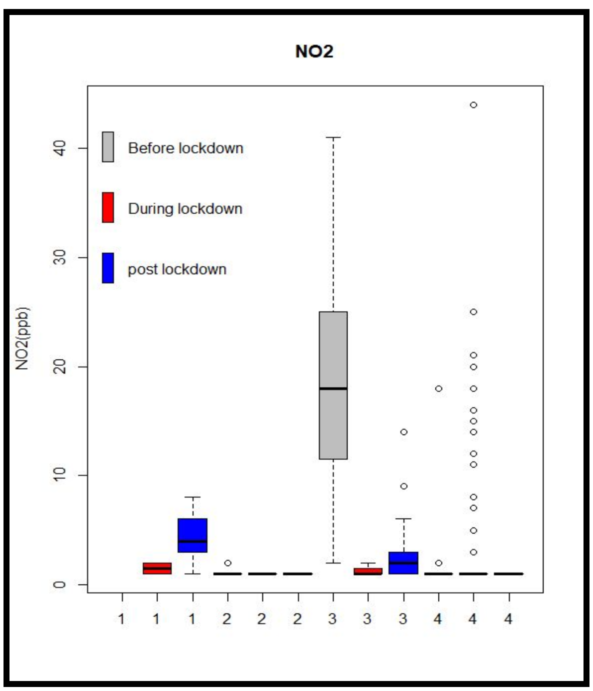
$\sigma(\bar{x}_1-\bar{x}_2)$	***3.62***	***1.5***	***1.51***	***1.66***	***2.52***
H_0	***Not rejected***	***Rejected***	***Rejected***	***Rejected***	***Not rejected***

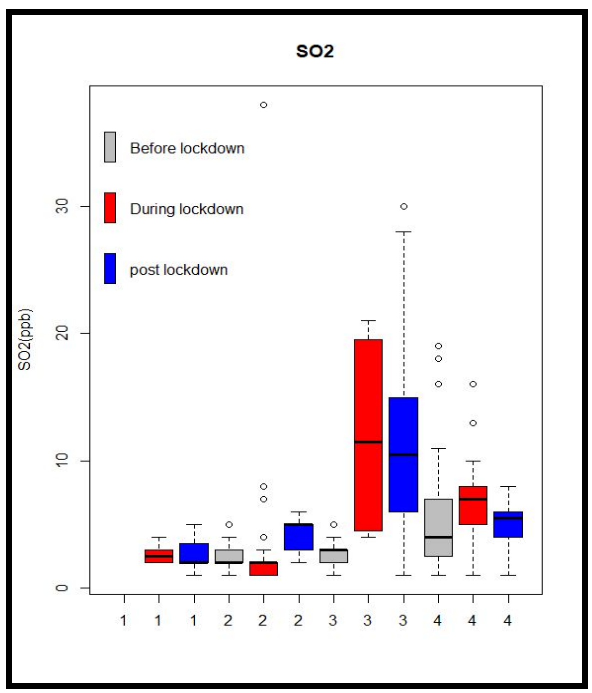
Whisker and Multiple box-plot for individual pollutants



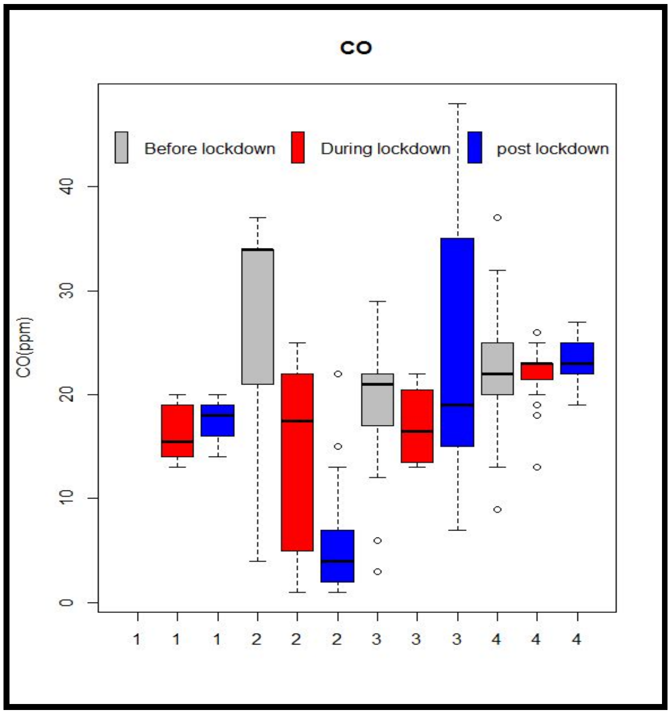


Descriptive statistics of each pollutant such as mean, median, first quartile, third quartile, the range within 1.5 times of interquartile range (IQR), and outliers are represented in box and whisker plots for pre, during, and post-lockdown periods. During the whole study period between September 15, 2019, and July 18, 2020, the observed CO concentrations indicated distinct spatial and temporal variation patterns before, during, and after lockdown periods. The highest CO concentration decrease during the lockdown was found for Qatif, followed by Rakah, Al Ahsa, as compared with the pre-lockdown period. On the other hand, the mean CO concentration at the Jubail site gradually increased during the lockdown and post-lockdown phases. In addition to this, mean CO concentrations at the Rakah site before and after lockdown periods increased. The fluctuations of mean CO concentrations at Al Ahsa were not statistically significant within pre-, during, and post-lockdown periods. As observed in CO concentrations, temporal and spatial changes of SO2 concentrations were quite different. Almost all sites exhibited mild outlier values before, during, and after lockdown periods with an average of mild to extreme outliers of three points. Compared with the pre-lockdown period, Qatif, Jubail, and Al Ahsa sites. On the contrary, in comparison with the pre-lockdown period, mean SO2 concentrations gradually increased at Rakah. The highest SO2 concentration increase during the lockdown was noticed for the Al Ahsa-Traffic site as compared with the pre lockdown period. As was observed for Rakah, the mean SO2 concentrations within the post-lockdown phase at Al Ahsa, Qatif, and Al Ahsa-Industrial site increased ppb, respectively, concerning the pre-lockdown period. It is noteworthy to mention that only the mean SO2 concentration at the Rakah site during the post-lockdown period was higher than the WHO's daily SO2 guideline value of 20 µg/m−3. The increased concentrations noticed for CO and SO2 pollutants at few locations could be linked to the large spectrum of industrial activities generating variable emission rates since most of the essential facilities were not shut down during the lockdown period.



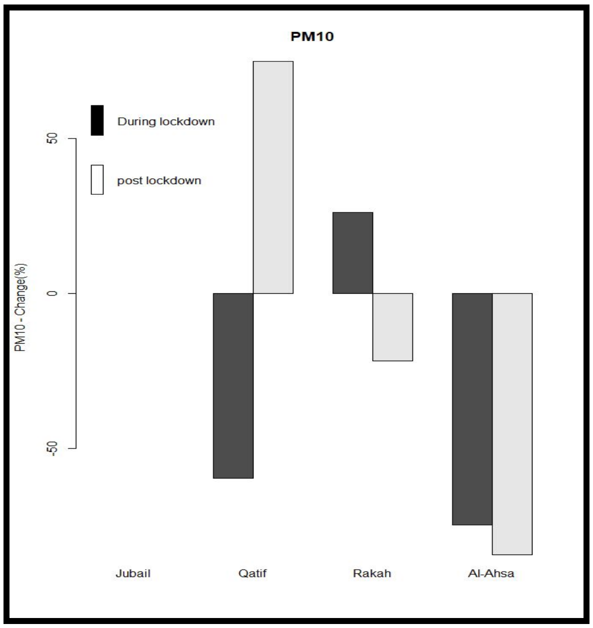


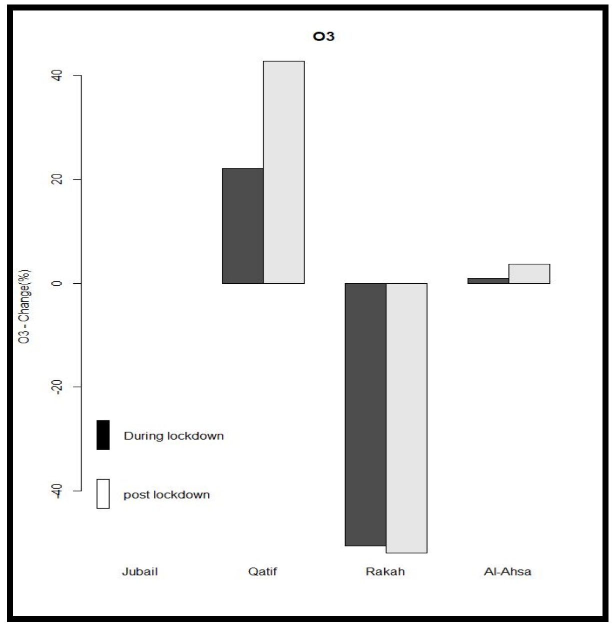
The impact of the lockdown period was most obvious on NO2 concentrations over the Eastern Province.At all monitoring sites, mean NO2 concentrations considerably decreased during the lockdown and post-lockdown phases about the pre-lockdown phase. The magnitude of decrease in mean NO2 concentrations was high, during the lockdown and post-lockdown period for Jubail, Rakahrespectively. As a result of this reduction trend because of the lockdown measures, the mean NO_2 concentrations in the prelockdown period at Jubail,Rakah,sites, being higher than WHO's to 150 ppb (282 μg/m−3), which was quite above the WHO's NO_2 guideline value of 40 μg/m 33.4 μg/m−3 even after the lockdown period. The other possible explanations for the NO_2 concentration decline rather than the significantly reduced transportation activities during the lockdown period might be attributed to the decrease in NO emission rate and/or the photolysis reaction of NO_2. The high combustion processes, including automobile engines, generally produce about > 80% of NO and < 20% of NO_2. Therefore, the photochemical reaction of NO_2 to produce O_3 and quite limited NO emissions to form NO_2 may be the reasons for the observed declines in NO_2 concentrations due to the lockdown. 8-h daily maximum guideline value of 40 μg/m five monitoring sites, the mean O_3 concentrations during and after lockdown periods showed a clear upward trend at vary- ing levels. This result is corroborated with recently published studies focused on the effect of lockdown measures to combat COVID-19 on the air quality of Delhi (India), Almaty , Barcelona (Spain) , São Paulo (Brazil) , Wuhan (China), and Hangzhou (China) et al. . In these cited studies, the increasing trend of O_3 against imposed lockdown measures was linked to (i) sharp drop of NO_x emissions in lockdown period decreasing the possibility of NO + O_3 titration reaction, (ii) increased VOC/NO_x ratio because of more reduced NO_x emission enhancing O_3 production, and (iii) stronger solar radiation compared with pre-lockdown period favoring O_3 formation and accumulation. These three explanations on why O_3 concentrations increased against lockdown measures are also valid for the Eastern Province where



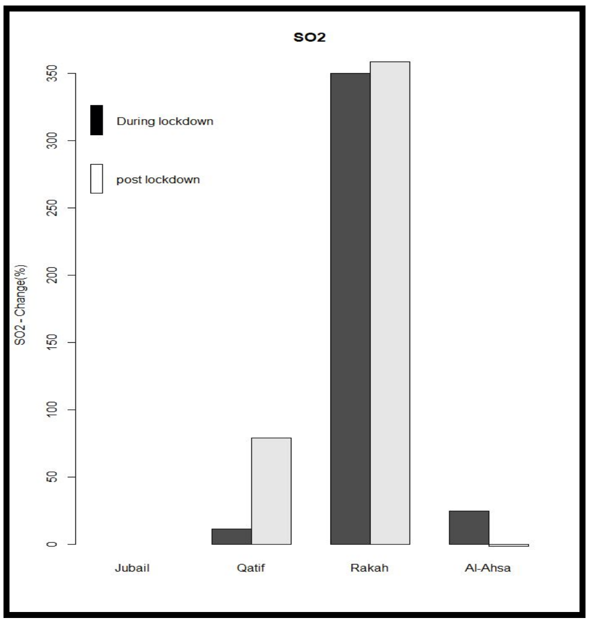
(i) NO2 concentrations remarkably decreased at all sites, (ii) fugitive VOC emissions from continuously operating petrochemical/chemical manufacturing facilities and oil refineries, and (iii) increasing solar radiation throughout the season (pre-lockdown average: 7982 W/m2 day; lockdown: 12,000 W/m2 days; and post-lockdown: 13,681 W/m2 days). The PM10 pollutant demonstrated the highest number of outliers among other pollutants during the whole study period. The number of PM10 outliers (> 1.5IQR) during lockdown is the highest for Jubail, Qatif, and Al Ahsa-Traffic sites. In Addition, the mean values were significantly above the median values for most of the PM10 sampling locations during this study. The effect of lockdown on PM10 pollution was most apparent in Qatif, Dammam-Industrial, and Al Ahsa-Trafficsites where the mean concentrations reduced from 80.3 (median: 82.2) to 24.4 (15.5) μg/m−3, from 63.0 (54.1) to 49.8(41.9) μg/m−3, and from 57.4 (50.1) to 24.8 (13.7) μg/m−3, respectively, and became below the WHO's PM10 guideline–Dammam-Coastal, and Rakah sites did not indicate a decreasing trend during the lockdown, implying that these sites might be under the effect of a wide range of PM10 emission sources.

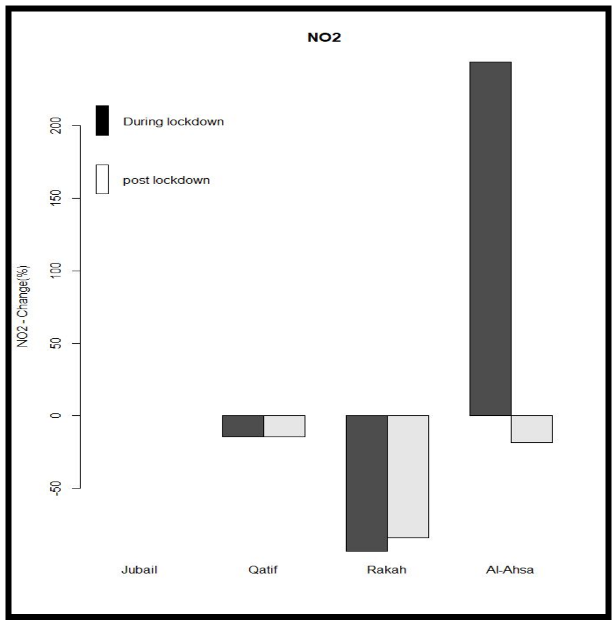
Percentage changes in air pollution levels during COVID-19 pandemic compared with the pre-lockdown period





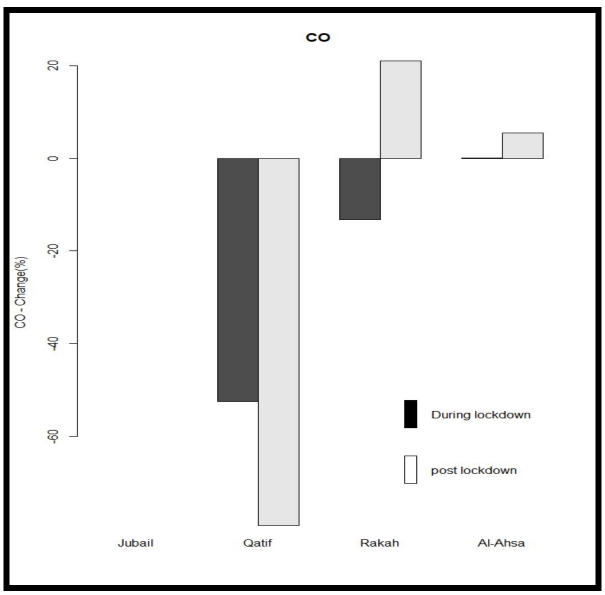
The percent changes in the concentrations of criteria air pollutants monitored at each station during and after the lockdown in reference to before lockdown are depicted. The air quality improvements at Qatif and Al Ahsa-Industrial sites were more evident as compared with the other three sites, and the response level of each site was quite different against the same lockdown measures. The most pronounced decrease was found for NO2 since NO2 concentrations reduced at all sites during the lockdown and after lockdown as well. Within the lockdown phase, the highest NO2 reduction rate was noticed at Rakah, Jubail, and Al Ahsa while the reduction rates were less than 50% at other sites. After the lockdown, NO2 concentrations also dropped at all sites. In response to decreasing NO2 emission during the lockdown period, changes in CO concentrations demonstrated decreasing trends most obviously at Qatif (42%). During the post-lockdown phase, the Qatif Al Ahsa site indicated decreasing CO rates. These results reveal that the CO and NO2 were commonly emitted from transportation activities, which were limited significantly during the lockdown and partially within post-lockdown phases, especially at urban locations.





On the other hand, the CO level at Jubail industrial site gradually increased during and after lockdown, respectively. These remarkable CO increase rates could be attributed to the huge and wide range of industrial activities with variable production capacities that did not respond as expected against imposed lockdown measures at the Jubail industrial city.

The ground level O3 is classified as a secondary pollutant, and its complex formation mechanism is governed by NOx and VOC emissions, VOC/NOX ratio in the atmosphere, the strength of solar radiation, and atmospheric stability. In addition to this, the O3 concentration at a receptor point could be under the effect of a long-range transport mechanism as the atmospheric lifetime of O3 is about 22 days. Contrary to the significant reduction rates in NO2 during and after the lockdown, increasing O3 rates occurred at most of the sites, within lockdown and after lockdown. This increasing pattern might be linked to the substantially dropped NOx emissions (reduction in titration im- pact on O3), increased VOC/NOx ratios, and stronger solar radiation as compared with before the lockdown period. The highest increase rates after lifting lockdown measures were monitored at Al Ahsa industrial sites where decreases in VOC emissions from a large number of petrochemical factories and large oil plants/refineries were not as large as NOx emissions, most probably leading to an enhanced formation of O3 under stronger solar radiation and more stable atmospheric conditions.



After lifting the lockdown, the Rakah station showed the most significant SO2 increase rates during the lockdown and after lockdown, respectively. The highest SO2 increase among other stations after lockdown may be ascribed to new excavation and dredging activities in the nearby residential area of the Rakah site.

Even though the Eastern Province is under the effect of a wide range of PM10 emissions, the decreasing PM10 trend noticed in Qatif, followed by Al

Ahsa-Trafic, Al-Ahsa stations is evidence for the effect of lockdown measures. This remarkable increase compared with other sites may be attributed to local dust storm conditions since the Jubail station is approximately 180 km and 60 km far north from Al Ahsa and Qatif/Dammam monitoring stations, respectively.

The observed reduction trends in NO2 (all sites), CO (Qatif-Urban, and Al Ahsa-Industrial), SO2), and PM10 (Al Ahsa- Traffic and Rakah-Urban) pollutants even after releasing the lockdown measures could be attributed to the multiple factors: (i) preference of people staying home due to the fear of the pandemic, (ii) allowing employees work from home by most of the companies, (iii) partial or full halt of production in some factories because of shattered supply chains, and (iv) different meteorological conditions and atmospheric stabilities compared with a post-lockdown period.

Comparison with other regions

The variations of pollutant concentrations due to COVID-19 lockdown in different countries around the world are shown in the table below. The median values of percent changes in each pollutant monitored at the Eastern Province demonstrated in Table below are in good agreement with those reported for the compared sites. The CO concentrations showed decreasing rates for all monitoring stations around the world. The major change in CO was observed for Almaty (Kazakhstan) from March 19 to April 14, with a percentage reduction of 49%. The same trend was observed in this study, where the median reduction value of CO was 13% during March 23 and June 21. The same similar trend was observed for NO2. All monitoring stations showed significant decreases during lockdown compared with the pre-lockdown period. The highest NO2 reduction was reported to be 96% for Salé (Morocco) from March 21 to April 2. On the other hand, O3 showed an increasing concentration trend in all compared sites around the world, including our study, except for the Anqing, Hefei, and Suzhou areas of China, which indicated a reduction of 9.6%. The changes in SO2 concentrations fluctuated between – 53% (China) and 8% (São Paulo, Brazil), while PM10 concentration changes varied between – 75% (Salé, Morocco) and 19% (Rome, Italy). Besides, SO2 and PM10 pollutants demonstrated decreasing trends at 75% of the locations compared in Table.

Location	Studied lockdown period	Change of pollutant concentration due to COVID-19 control measures (%)				
		CO	SO_2	NO_2	O_3	PM_{10}
Tehran (Iran)	Mar. 21–Apr. 21	−41	−28	−33	103	−30
Delhi (India)	Mar. 24–Apr. 11	−30	−18	−53	0.8	−52
Almaty (Kazakhstan)	Mar. 19–Apr. 14	−49	7	−35	15	n.a.
Salé (Morocco)	Mar. 21–Apr. 2	n.a.	−49	−96	n.a.	−75
Barcelona (Spain)	Mar. 14–Mar. 30	n.a.	1.8	−51	58	−31
São Paulo (Brazil)	Mar. 24–Apr. 20	−30	8	−22	11	7.7
Nice (France)	Mar.–Apr.	n.a.	n.a.	−63	24	−7.8
Rome (Italy)		n.a.	n.a.	−46	14	19
Turin (Italy)		n.a.	n.a.	−30	27	9.9
Valencia (Spain)		n.a.	n.a.	−70	2.4	15
Wuhan (China)		n.a.	n.a.	−57	36	−32
Wuhan (China)	Jan. 23–Feb. 23	−23	−3.9	−53	117	−40
Hangzhou (China)	Jan. 24–Feb. 15	−22	−29	−58	145	−48
Yangtze River Delta Region (China)	Jan. 24–Feb. 25	−39	−26	−47	8.3	−61
	Feb. 26–Mar. 31	−25	−15	−29	2.3	−36
Anqing, Hefei, and Suzhou area (China)	Feb. 1–Feb. 29	−36	−53	−53	3.6	−49
	Mar. 1–Mar. 31	−24	−41	−27	−9.6	−25
Eastern Region (Saudi Arabia)	Mar. 23–Jun. 20	−13 (± 36)	−9.2 (± 54)	−58 (± 26)	17 (± 38)	−21 (± 83)

Conclusions

In this work, the possible effects of the lockdown due to the COVID-19 pandemic on the air quality were investigated in an arid region using meteorological and air quality datasets obtained from eight monitoring stations covering the Eastern Province of the KSA within the period between September 15, 2019, and July 18, 2020. The mean concentrations of NO2 and PM10 pollutants at several monitoring stations were reduced to such levels as lower than the guideline values of WHO under the imposed lockdown, which might reduce the impact of

COVID-19, especially on elderly and sensitive groups. The NO_2 was found to be the marker pollutant responding best to the lockdown measures. In parallel to decreases in the NO_2 concentrations, drops in CO concentrations fluctuated between 5.8 and 55% considering most of the sites, suggesting that CO and NO_2 emissions were mainly from transportation activities, which were substantially restricted during the lockdown phase. Interestingly, O_3 concentrations increased at the majority of the monitoring stations. The results also revealed that controlling the formation of ground-level O_3 is a quite challenging task even by reducing the emissions of primary air pollutants significantly. The Eastern Province is a low-SO_2- emitting region due to the stringent air pollution control regulations, and the monitored SO_2 emissions have been quite below the national standards and WHO's guidelines. For this reason, the reductions in SO_2 concentrations were not distinct. The effect of lockdown measures was also evident in PM_{10} concentrations, which were reduced at most of the sites even though a wide range of emission sources dominates the PM_{10} budget over the Eastern Province's atmosphere. Besides the damaging effects of the COVID-19 pandemic, the imposed lockdown countermeasures have been a unique opportunity to investigate the effects of reduced emission rates of pollutants from various sources on the air quality, to evaluate the existing and future air quality control regulations, and to build short and long-term alternative action plans to enhance the air quality.

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