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Impacts of nationwide lockdown due to COVID-19 outbreak on air quality in Bangladesh: a spatiotemporal analysis

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Abstract

In Bangladesh, a nationwide lockdown was imposed on 26 March 2020, due to the COVID-19 pandemic. Due to restricted emissions, it was hypothesized that the air quality has been improved during lockdown throughout the country. The study is intended to assess the impact of nationwide lockdown measures on air quality in Bangladesh. We analyzed satellite data for four different air pollutants (NO_2, SO_2, CO, and O_3) to assess the changes in the atmospheric concentrations of pollutants in major cities as well as across the country. In this study, the concentrations of NO_2, SO_2, CO, and O_3 from 1 February to 30 May of the year 2019 and 2020 were analyzed. The average SO_2 and NO_2 concentrations were decreased by 43 and 40%, respectively, while tropospheric O_3 were found to be increased with a maximum of > 7%. Among the major cities, Dhaka, Gazipur, Chattogram, and Narayanganj were found to be more influenced by the restricted emissions. In Dhaka, NO_2 and SO_2 concentrations were decreased approximately by 69 and 67%, respectively. Our analysis reveals that NO_2 concentrations are highly correlated with the regional COVID-19 cases ($r = 0.74$). The study concludes that the lockdown measures significantly reduced air pollution because of reduced vehicular and industrial emissions in Bangladesh.

Keywords COVID-19 · Lockdown · Air pollution · Air quality · Correlation · Bangladesh

Introduction

The novel coronavirus disease 2019 (COVID-19), is a transmissible disease, caused by the acute respiratory syndrome coronavirus-2 (SARS-CoV-2) (Lu et al. 2020; Sohrabi et al. 2020; Dong et al. 2020). It was first detected in Wuhan City, Hubei Province of China on 31 December 2019 (WHO 2020a), which is assumed to be associated with exposures in a local seafood market in Wuhan. This novel coronavirus has become a severe public health issue throughout the world. The World Health Organization (WHO) declared the novel coronavirus disease as a pandemic on 11 March 2020 (WHO 2020b). In 6 months after the first confirmed case in Wuhan, more than 10.6 million people have been infected by COVID-19, and 514,315 people have been reported dead due to the infection in 215 countries, areas, or territories around the world (Worldometer 2020b) (Fig. 1).

Bangladesh, home of ~ 165 million people (as of June 2020) with a population density of 1265 people per km^2 (Worldometer 2020a), is now struggling with the outbreak of COVID-19. On 8 March 2020, the Institute of Epidemiology, Disease Control and Research (IEDCR) has reported the first three confirmed cases of COVID-19 in Bangladesh (IEDCR 2020). As of 26 June 2020, a total of 126,606 confirmed cases has been reported with 1621 deaths (WHO 2020c). However, among the total number of confirmed cases around the country, only the capital city Dhaka has ~ 29% of infected cases (IEDCR 2020).

Air pollution in Bangladesh is a serious concern due to its detrimental impacts. The current air quality index in

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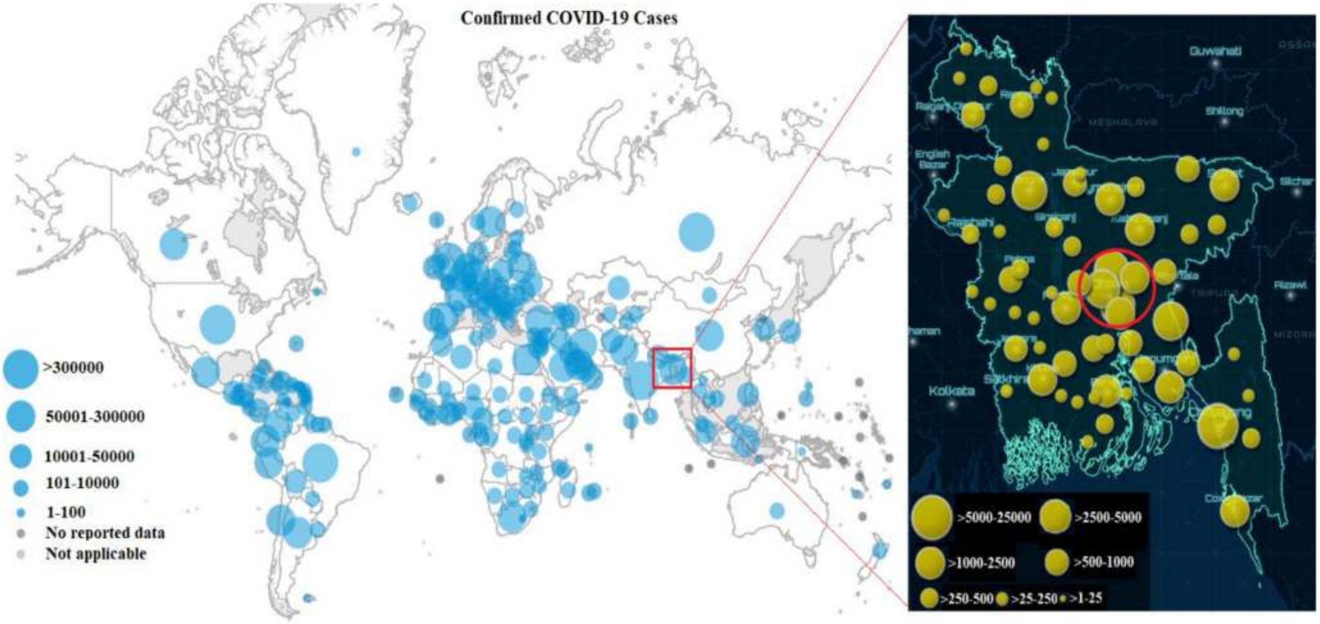

Fig. 1 Distribution of confirmed COVID-19 cases as of 26 June 2020 (WHO 2020c; IEDCR 2020)

Bangladesh is one of the lowest among the countries (rank: 166/180), leading to poor environmental performance index (rank: 162/180) (EPI 2020). Air pollution is strongly associated with respiratory diseases such as asthma, chronic obstructive pulmonary disease (COPD), and lung cancer (Ling and van Eeden 2009; Hoek et al. 2013; Gorai et al. 2016; Guan et al. 2016). Ischemic heart disease and stroke are also caused by air pollution (WHO 2020d). Additionally, it has profound impacts on the transmission of infectious diseases like SARS, influenza, etc. (Cui et al. 2003; Landguth et al. 2020). In Bangladesh, increased air pollution is mainly caused by uncontrolled industrial emissions, vehicle exhausts, and open burning of solid wastes. Every year, a significant number of deaths have been observed due to numerous diseases linked to air pollution (Mahmood 2011).

Like other countries, COVID-19 forced to lock down industries, mass transportation, and other anthropogenic activities in Bangladesh. Hence, it is assumed that the complete or partial lockdown may result in improved air quality, as it is correlated with the amount of emissions. Isaifan (2020) reported a significant drop in N_2O and carbon emissions (i.e., 30 and 25%, respectively) in China, due to industrial lockdown. Karuppasamy et al. (2020) reported a 55% reduction in NO_2 in India during the lockdown period. Additionally, it is hypothesized that different air pollutants may have a significant relationship with COVID-19 infections, although they are not fully examined, and there remains uncertainty (Li et al. 2020). However, some studies (Zhu et al. 2020; Li et al. 2020) reported a considerable relationship between air pollutants and COVID-19 infected cases.

In Bangladesh, some studies (Anwar et al. 2020; Shammi et al. 2020; Islam et al. 2020; Alam et al. 2020) have been conducted to show the socioeconomic impacts of COVID-19 and key challenges to control it and to assess the severity of COVID-19 in the country. However, to the best of our knowledge, there have been no studies on COVID-19 impacts on air quality in Bangladesh. Therefore, this study is conducted to explore the possible impacts of COVID-19 lockdown activities on ambient air quality in Bangladesh as well as to demonstrate the relationships between air pollutants (NO_2, SO_2, CO, and O_3) and infected COVID-19 cases.

Status of industrial and vehicular emissions in Bangladesh and associated air quality: literature review

Economic growth in Bangladesh is one of the fastest growing around the world and largely depends on the country's industrial expansion (Ahaduzzaman et al. 2017). Industrial sector is contributing to more than 35% of GDP, with an average growth rate of 13% per year (BER 2019). Almost all of these industries are in major cities of the country, including Dhaka, Narayanganj, Chattogram, Gazipur, Rajshahi, and Khulna (Mahmood 2011; Sabur et al. 2012). Figure S1 depicts the spatial distribution of major industries in Bangladesh. Consequently, these cities comprise a considerable number of motorized vehicles, increasing gradually every year. For instance, in Dhaka, motor vehicle population has increased significantly with a growth rate of 7–16% in the past 10 years (Begum et al. 2008). Table S1 shows the area and population of major cities of Bangladesh along with the observed air pollutants and number of motor vehicles. As a result, these cities have been experiencing severe air pollution problems compared with other parts of the country (Mahmood 2011), while Dhaka is among the most polluted cities in the country and the third most polluted megacities of the world (WHO 2016; Rahman et al. 2019).

In Bangladesh, comprehensive air pollutant emission inventory is still unavailable. Vehicular and industrial emissions are considered the major sources of air pollution in Bangladesh (Mahmood 2011). Alam (2009) reported five industries, including food, cement/clay, pulp and paper, textile, and tobacco, contributed to about 84% of the country's total industrial air pollution in 2001. Apart from these, brick kilns also cause massive air pollution in the country, particularly in dry season (Mahmood 2011; Guttikunda and Khaliquzzaman 2014; Tusher et al. 2018).

Bangladesh is consistently ranked as one of the most polluted countries in the world for decades. According to the world air quality report (2019) by IQAir, Bangladesh was the most polluted country in 2019. Among the global megacities, Dhaka is consistently ranked as one of the top polluted capital cities. A recent study on air quality in the world's most polluted 50 cities by Rodriguez-Urrego and Rodriguez-Urrego (2020) found that Dhaka is the second most polluted cities in the world with an average annual $PM_{2.5}$ level of 97.1 μg/m^3. Generally, the level of air pollutants varies with time and seasons. In Dhaka, the average concentrations of major air pollutants except for O_3 show strong seasonal variation, with the maximum during winter and minimum during monsoon (Rahman et al. 2019). During the dry season (November–April), the urban areas in Bangladesh suffer from severe air quality problems. During these months, PM concentrations frequently rise to 7–8 times than the WHO standard (Rana and Khan 2020).

Materials and methods

We collected four different air pollutants' (NO_2, SO_2, CO, and O_3) data for Bangladesh during the period of 1 February to 30 May in 2019 and 2020 using Google Earth Engine (GEE). We acquired daily data from GEE, which is collected by the Sentinel 5 mission of Copernicus ESA with the spatial resolution of 0.01 arc degrees. A detailed summary of the dataset used in this study can be found in Table 1. Statistical data relevant to our study were collected from different secondary sources. District wise confirmed COVID-19 case data (until 26 June 2020) were collected from the Institute of Epidemiology, Disease Control and Research (IEDCR), Bangladesh (https://www.iedcr.gov.bd/). To calculate COVID-19 cases per 100,000 people in Bangladesh, district wise population data have been collected from the Bangladesh Bureau of Statistics (BBS) (http://www.bbs.gov.bd/).

After extracting the daily data on pollutant concentrations, we first classified it into four groups. As our intention was to observe the variation in air quality due to lockdown measures, we divided the data into during lockdown (26 March–30 May 2020), immediate before lockdown (1 February–25 March 2020), same dates during lockdown days in 2019, and same dates of before lockdown in 2019. Hereafter, the daily data of each group were averaged, which are therefore visualized using the ArcMap 10.5.

Summary statistics were calculated for different variables during the lockdown and pre-lockdown periods. We reported both net difference and percentage change of pollutant concentrations during the lockdown and pre-lockdown periods. To have a closer look at the changes in the urban areas, this study also reported change in pollutant concentrations during lockdown vs. pre-lockdown period for 9 major cities in Bangladesh including Sylhet, Rangpur, Rajshahi, Narayanganj, Khulna, Gazipur, Dhaka, Chattogram, and Barisal. A $p < 0.05$ was considered statistically significant. Both simple and multiple linear regression analyses were performed to assess the interrelationships between air pollutants and COVID-19 cases. We used district level COVID-19 cases per 100,000 people as dependent variable and air pollutants as independent variable. Pearson's correlation coefficient analysis was employed to analyze the correlation between regional COVID-19 cases and the air pollutants as well as among the air pollutants. The JMP software was used for all statistical analyses in our study.

Results and discussion

Nitrogen dioxide

During the lockdown period (i.e., 26 March–30 May 2020) in Bangladesh due to the COVID-19 pandemic, a drastic reduction in NO_2 (nitrogen dioxide) concentration has been observed. The significant spatiotemporal changes in NO_2 levels (before and during the lockdown) in Bangladesh are shown in Fig. 2. The study revealed that urban areas experienced the most decrease in NO_2 concentrations than the rural areas due to restricted traffic and shutdown of industries. This finding is consistent with other previous studies done in different parts of the world (Shi and Brasseur 2020; Sharma et al. 2020; Dantas et al. 2020; Baldasano 2020).

Our study shows that the average decrease in NO_2 concentration in all major cities in the country was considerable (~ 40%) during this period (Table 2). However, among the major cities, Narayanganj experienced the highest reduction in NO_2 levels (i.e., 69.2%) compared with the average NO_2 concentrations during lockdown with the average concentrations immediately before the lockdown. A similar percentage of NO_2 reduction has been observed for Dhaka and Gazipur, ranging from 62 to 69%, while for other cities, it was ~ 5 to 38%

Table 1 Summary of the datasets used in this study

Data source	Parameter	Spatial resolution	Temporal resolution	Data access link
Sentinel 5	Tropospheric NO_2 column	0.01 arc degrees	Daily	https://scihub.copernicus.eu/
Sentinel 5	SO_2 column	0.01 arc degrees	Daily	https://scihub.copernicus.eu/
Sentinel 5	CO column	0.01 arc degrees	Daily	https://scihub.copernicus.eu/
Sentinel 5	O_3 column	0.01 arc degrees	Daily	https://scihub.copernicus.eu/
IEDCR, Bangladesh	COVID-19 cases in BD	-	-	https://www.iedcr.gov.bd/
BBS, Bangladesh	Population data	-	2011	http://www.bbs.gov.bd/

(Table 2). Note that emission of NO_2 is strongly related to the fuel combustion in the industrial sector (e.g., power plants and small-scale heating sources) and in road transport (e.g., gasoline-powered vehicles). Therefore, it is

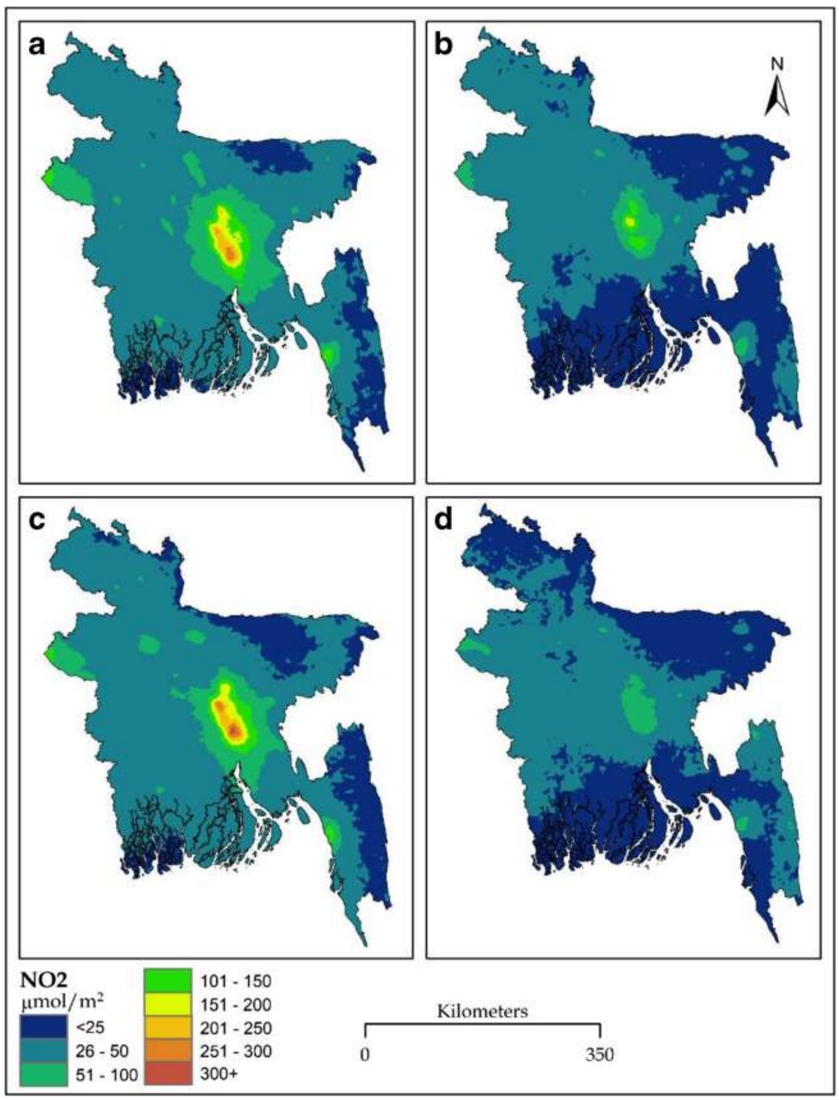

Fig. 2 Spatiotemporal distribution of average NO_2 over Bangladesh: (a) 1 February–25 March 2019, (b) 26 March–30 May 2019, (c) 1 February–25 March 2020, and (d) 26 March–30 May 2020

Table 2 Mean concentrations and variations of NO_2 at major cities in Bangladesh before and during lockdown

City	NO_2 (μmol/m^2)					Variation*	
	2019[a]	2019[b]	2020[a1]	Average[#]	2020[b1]	Net	Percent (%)
Sylhet	46.12	30.84	40.5	39.15	31	− 9.5	− 23.46
Rangpur	32.68	28.51	35.56	32.25	33.87	− 1.69	− 4.75
Rajshahi	58.53	43.32	54.1	51.98	42.92	− 11.18	− 20.67
Narayanganj	248.44	95.61	278.32	207.46	85.62	− 192.7	− 69.24
Khulna	49.23	34.02	46.84	43.36	30.24	− 16.6	− 35.44
Gazipur	189.31	153.3	225.41	189.34	83.76	− 141.65	− 62.84
Dhaka	212.51	103.6	221.9	179.35	68.73	− 153.17	− 69.03
Chattogram	115.09	71.78	90.3	92.39	58.57	− 31.73	− 35.14
Barisal	39.61	25.84	39.3	34.92	24.34	− 14.96	− 38.07

[a] Average of daily concentration from 1 February to 25 March; [a1] NO_2 concentration before the lockdown; [b] average of daily concentration from 26 March to 30 May; [b1] NO_2 concentration during the lockdown; *variation before and during the COVID-19 lockdown period; [#] average concentration of 2019a, 2019b, and 2020a

expected that these sectoral activities' restrictions result in a significant reduction in NO_2 concentration during the lockdown period.

Compared with the average NO_2 values before lockdown, Dhaka was found to be experienced with the highest NO_2 reduction (62%). Surprisingly, ~ 5% increase in NO_2 concentration has been observed for Rangpur. We assume that the long-range transport from northern India could be the potential reason behind this increasing NO_2. However, while comparing the 2019 NO_2 concentrations with the same time slot in 2020 (i.e., during the lockdown period), significant NO_2 reduction is observed for most of the major cities except Rangpur. The highest decline was in Gazipur (45%), followed by Dhaka (34%) and Chattogram (18%), as presented in Table 2.

These results are consistent with the findings of the previously published works. Baldasano (2020) reported similar findings for Madrid (Spain) during the lockdown compared with the same period in 2019. In Delhi (India), NO_2 concentrations were reduced by approximately 53% during the lockdown period compared with the same period in 2019 (Mahato et al. 2020). Agarwal et al. (2020) reported an average NO_2 reduction of ~ 49% and > 76% during the lockdown in China and Mumbai (India), respectively. In summary, this reduction in NO_2 concentrations in different time slots indicates that lockdown measures due to the COVID-19 pandemic have considerable impacts on changing NO_2 concentrations in Bangladesh.

Sulfur dioxide

Considerable reduction in SO_2 (sulfur dioxide) concentrations has also been observed owing to the nationwide lockdown as presented in Fig. 3. The study revealed that SO_2 concentrations during this period are relatively lower than the 2019 levels for the same time frame (Fig. 3). It indicates the reduced SO_2 emissions due to the shutdown of industrial processes, power plants, and heating systems. A similar pattern of SO_2 reduction has been reported in China (Wang et al. 2020; Bao and Zhang 2020; Li et al. 2020), Italy (Collivignarelli et al. 2020), and India (Mahato et al. 2020). Moreover, lower SO_2 concentrations are usually found in Bangladesh during the end of March to May 2019, compared with the early January to end of March 2019 (Fig. 3), which might be attributed to the increased rainfall during these months (Shahid 2010).

Besides, we observed notable findings when making the analysis and inter-comparing among the nine major cities of the country. The study found that all the studied cities experienced a substantial reduction in SO_2 concentrations, except Rangpur (Table 3). Among the nine cities, Chattogram experienced a maximum decrease in SO_2 levels (i.e., 69.15%) during the lockdown period compared with the concentrations observed immediately before the lockdown. However, a considerable reduction has also been observed in Dhaka, Narayanganj, Khulna, Rajshahi, and Gazipur, which ranged from 40.5 to 66.6% (Table 3), as industrial zones are mostly concentrated in these cities (Sabur et al. 2012). Therefore, the highest reduction in the SO_2 concentrations is reasonable due to the stoppage of all industrial activities and limited vehicle movements. A similar result has been observed in New Delhi (India) and Milan (Italy) where about 18 and 25.4% reduction in SO_2 concentrations were reported, respectively, during partial/total lockdown period in comparison with the pre-lockdown period (Mahato et al. 2020; Collivignarelli et al. 2020). Comparatively, a lower reduction in SO_2 has been observed in other cities. We assume that uncontrolled or partial controlled industrial and vehicular activities could be the inherent reason in this regard.

Interestingly, we observe a slight increase in SO_2 concentrations in Rangpur (Table 3), which might be attributed to the

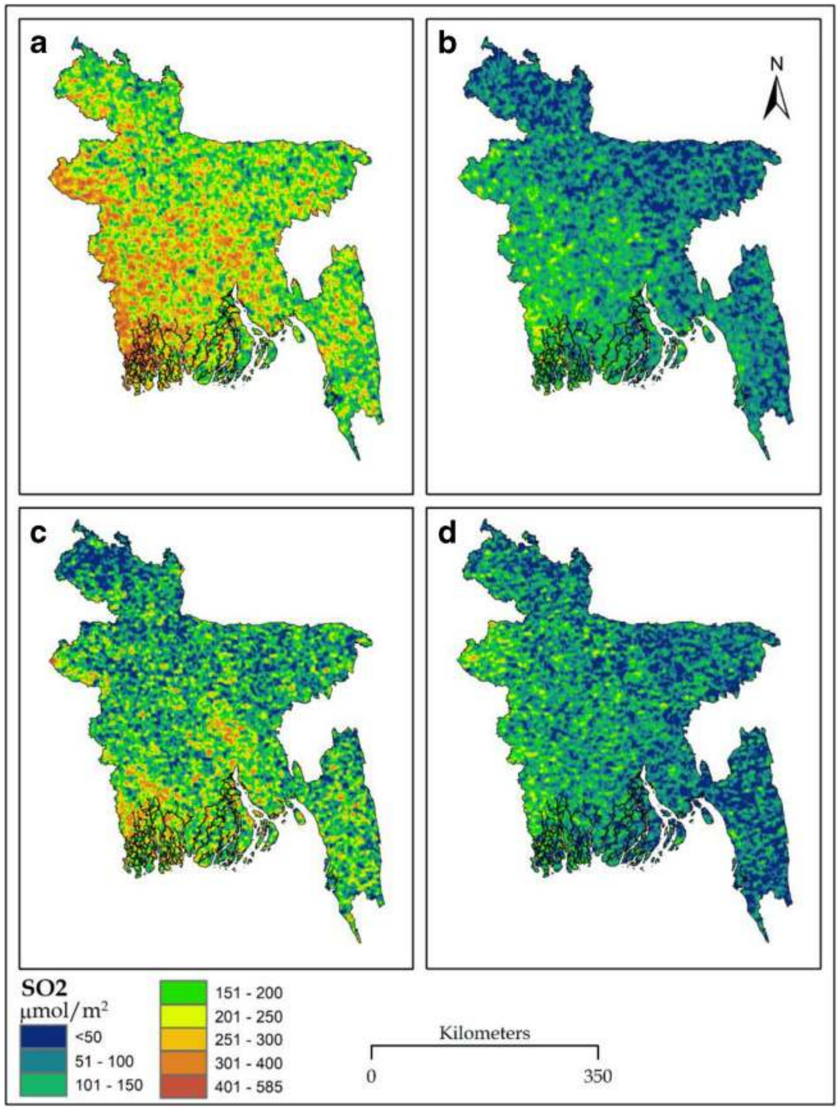

Fig. 3 Spatiotemporal distribution of average SO_2 over Bangladesh: (a) 1 February–25 March 2019, (b) 26 March–30 May 2019, (c) 1 February–25 March 2020, and (d) 26 March–30 May 2020

Table 3 Mean concentrations and variations of SO_2 at major cities in Bangladesh before and during lockdown

City	SO_2 (μmol/m^2)					Variation*	
	2019[a]	2019[b]	2020[a1]	Average[#]	2020[b1]	Net	Percent (%)
Sylhet	129.77	75.94	86.94	97.55	69.57	− 17.37	− 19.98
Rangpur	180.18	53.82	140.25	124.75	147.2	6.95	4.96
Rajshahi	300.71	133.01	231.35	221.69	101.91	− 129.44	− 55.95
Narayanganj	265.98	100.68	330.78	232.48	118.94	− 211.84	− 64.04
Khulna	261.36	115.78	286.72	221.29	109.63	− 177.09	− 61.76
Gazipur	265.14	137.05	218.42	206.87	129.97	− 88.45	− 40.50
Dhaka	299.71	124.44	262.4	228.85	87.61	− 174.79	− 66.61
Chattogram	204.68	119.76	209.61	178.02	64.67	− 144.94	− 69.15
Barisal	175.31	113.56	150.13	146.33	131.89	− 18.24	− 12.15

[a] Average of daily concentration from 1 February to 25 March; [a1] SO_2 concentration before the lockdown; [b] average of daily concentration from 26 March to 30 May; [b1] SO_2 concentration during the lockdown; *variation before and during the COVID-19 lockdown period; [#] average concentration of 2019a, 2019b, and 2020a

transboundary SO_2 emission sources. For example, Sharma et al. (2020) observed a slight increase in SO_2 concentrations when studying the changes in air pollutants' levels during the lockdown in 22 Indian cities. They correlated such an increase in SO_2 concentration to the resultant emissions originating from power plants in the northern India, where no restriction was enforced.

Carbon monoxide

Like NO_2, a substantial reduction in CO (carbon monoxide) concentration was observed, as presented in Fig. 4. Even the average concentration of CO during the lockdown period was less than the average CO values in 2019 for the same period. The study shows that urban areas experienced a substantial reduction in CO concentration compared with rural areas, mainly due to restricted traffic movement and the shutdown of industrial activities. As high emission of CO is the result of the incomplete fuel combustion (i.e., incomplete oxidation of hydrocarbons), mainly from the automobiles (Miller 2011; Reşitoğlu et al. 2015), therefore, a significant reduction in CO due to limited vehicle movement is reasonable. The spatiotemporal changes in CO concentrations in Bangladesh for the selected time slots are presented in Fig. 4.

Table 4 shows a noticeable decrease in CO concentrations in all major cities in Bangladesh during the lockdown period compared with before lockdown, ranging from 1.6 to > 7%. The highest reduction in CO has been observed in Narayanganj, as it is the major industrial zone with heavy congestion of commercial transportation (gasoline and diesel-powered), and other public and private vehicles. However, a considerable emission reduction has also been observed in other industrial cities (i.e., Dhaka, Gazipur, and Chattogram), where the average reduction was 5.3% (Table 4). Similarly, while the CO concentrations during the lockdown in 2020 were compared with 2019 emission levels

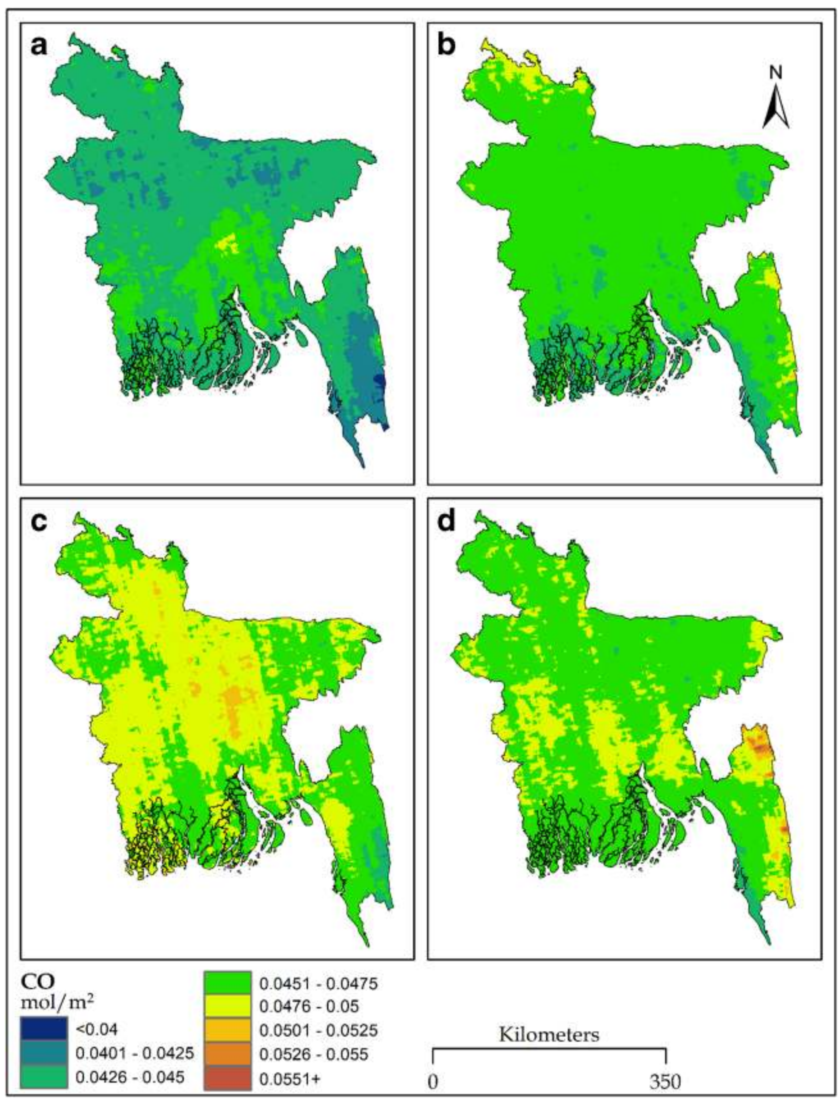

Fig. 4 Spatiotemporal distribution of average CO over Bangladesh: (a) 1 February–25 March 2019, (b) 26 March–30 May 2019, (c) 1 February–25 March 2020, and (d) 26 March–30 May 2020

Table 4 Mean concentrations and variations of CO at major cities in Bangladesh before and during lockdown

City	CO (mol/m^2)					Variation*	
	2019[a]	2019[b]	2020[a1]	Average[#]	2020[b1]	Net	Percent (%)
Sylhet	0.0437	0.0456	0.0476	0.0456	0.0467	− 0.0009	− 1.89
Rangpur	0.0440	0.0473	0.0488	0.0467	0.0474	− 0.0014	− 2.87
Rajshahi	0.0436	0.0465	0.0477	0.0459	0.0469	− 0.0009	− 1.68
Narayanganj	0.0468	0.0458	0.0502	0.0476	0.0466	− 0.0036	− 7.17
Khulna	0.0448	0.0453	0.0480	0.0460	0.0472	− 0.0007	− 1.67
Gazipur	0.0469	0.0467	0.0500	0.0479	0.0474	− 0.0026	− 5.20
Dhaka	0.0476	0.0461	0.0496	0.0478	0.0468	− 0.0029	− 5.65
Chattogram	0.0435	0.0437	0.0477	0.0450	0.0453	− 0.0024	− 5.03
Barisal	0.0453	0.0461	0.0481	0.0465	0.0471	− 0.0009	− 2.08

[a] Average of daily concentration from 1 February to 25 March; [a1] CO concentration before the lockdown; [b] average of daily concentration from 26 March to 30 May; [b1] CO concentration during the lockdown; *variation before and during the COVID-19 lockdown period; [#] average concentration of 2019a, 2019b, and 2020a

for the same period, relatively lower CO concentration was found during the lockdown period. These results are consistent with the findings reported for Madrid (Spain) and Delhi (India) during the lockdown period (Mahato et al. 2020; Baldasano 2020).

Ozone

Like other pollutants, partial or complete lockdown measure also has a noticeable impact on O_3 (ozone) concentration, as presented in Fig. 5. Our study reveals that O_3 concentration in Bangladesh has increased during the lockdown period. A similar observation has been reported for Spain and Italy during the lockdown period in 2020 (Tobías et al. 2020; Coccia 2020).

Table 5 shows an increased O_3 concentration during the lockdown in all major cities in Bangladesh, with a percentage increase of 1.26 to 5%. Among all major cities, Chattogram experienced a maximum increase in O_3 concentration compared with the levels observed immediately before the lockdown (i.e., 271.95 vs. 285.75 DU), as shown in Table 5. A similar pattern of variation in O_3 concentration is found for other major cities with an average change of 281.37 vs. 288.59 DU before and during the lockdown. Even the O_3 concentration was also found higher in all major cities during the lockdown period in 2020 compared with the 2019 levels for the same period. This increase in O_3 concentration is possibly due to the significant reduction in NO_2 concentration, which leads to more photochemical activity in the atmosphere, resulting in more O_3 production (Dang and Liao 2019; Li et al. 2019).

Interestingly, a slight decrease in O_3 concentration has been found in Rangpur during the lockdown period compared with before the lockdown (i.e., 294.12 vs. 293.56 DU) (Table 5). This study assumes some reasons behind the decreasing O_3 levels in Rangpur. First, it might be due to the lack of proper implementation of lockdown measures in Rangpur, and second, emissions from the northern India might have considerable impacts on the reducing O_3 concentration in Rangpur, as the emissions of NO from industries and vehicles diminish the level of O_3 (titration, $NO + O_3 = NO_2 + O_2$). Overall, this study assumes that restricted anthropogenic activities lead to an increase in O_3 concentration during the lockdown period in Bangladesh.

Relationship between COVID-19 cases and air pollutants

The associations between daily air pollutants' concentrations and COVID-19 confirmed cases (from 8 March to 26 June 2020) as well as the correlations among the studied air pollutants are presented in Figs. 6 and 7 and Table 6. In Fig. 6, the linear regression analysis indicated that infection by COVID-19 was greatly influenced by the atmospheric concentrations of each air pollutants, while positive associations were observed with NO_2 ($R^2 = 0.55$), SO_2 ($R^2 = 0.14$), and CO ($R^2 = 0.07$), and negative association was found with O_3 ($R^2 = 0.09$). These results exhibited strong association between NO_2, as a single predictor, with COVID-19 cases per 100,000 persons (Fig. 6). On the other hand, the multiple linear regression model observed that all the studied air pollutants, except CO, were significantly associated with the COVID-19 cases in Bangladesh ($R^2 = 0.65$) (Table 6). Similarly, Pearson's correlation matrix also showed significant interrelations among air pollutants and between COVID-19 confirmed cases with daily mean concentrations of air pollutants (Fig. 7). Significantly positive correlations were observed among NO_2-CO ($r = 0.56$****), NO_2-SO_2 ($r = 0.44$***), NO_2-COVID-19 cases ($r = 0.74$****), SO_2-COVID-19 cases ($r = 0.38$**), CO-O_3 ($r = 0.30$*), and CO-COVID-19 cases ($r = 0.27$*), whereas significantly negative

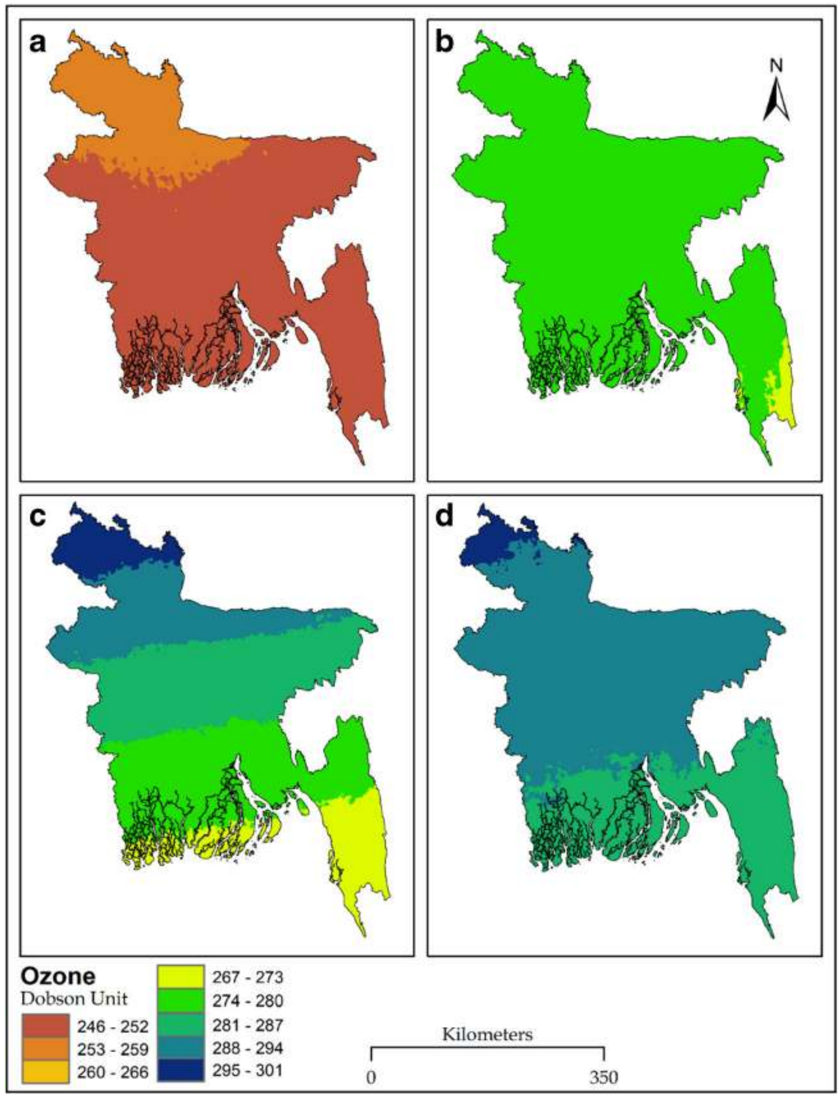

Fig. 5 Spatiotemporal distribution of average O_3 over Bangladesh: (a) 1 February–25 March 2019, (b) 26 March–30 May 2019, (c) 1 February–25 March 2020, and (d) 26 March–30 May 2020

Table 5 Mean concentrations and variations of O_3 at major cities in Bangladesh before and during lockdown

City	O_3 (Dobson unit)					Variation*	
	2019[a]	2019[b]	2020[a1]	Average[#]	2020[b1]	Net	Percent (%)
Sylhet	251.04	275.34	286.18	270.85	290.61	4.43	1.55
Rangpur	254.35	278.64	294.12	275.70	293.56	− 0.56	− 0.19
Rajshahi	251.24	277.05	286.76	271.68	290.37	3.61	1.26
Narayanganj	250.47	275.84	279.56	268.62	287.86	8.3	2.97
Khulna	250.22	275.27	276.65	267.38	286.6	9.95	3.60
Gazipur	250.83	275.73	281.16	269.24	288.53	7.37	2.62
Dhaka	250.66	275.9	280.76	269.11	288.18	7.42	2.64
Chattogram	249.07	274.61	271.95	265.21	285.75	13.8	5.07
Barisal	250.23	274.8	275.2	266.74	285.85	10.65	3.87

[a] Average of daily concentration from 1 February to 25 March; [a1] O_3 concentration before the lockdown; [b] average of daily concentration from 26 March to 30 May; [b1] O_3 concentration during the lockdown; *variation before and during the COVID-19 lockdown period; [#] average concentration of 2019a, 2019b, and 2020a

Table 6 Multiple regression model results for the relation between air pollutants and COVID-19 cases

Term	Estimate	t Ratio	Lower 95%	Upper 95%	Prob > |t|
Intercept	794.65091	3.61	353.65572	1235.6461	0.0006*
Carbon monoxide (CO)	− 4338.958	− 1.05	− 12637.74	3959.8276	0.2997
Nitrogen dioxide (NO_2)	0.9633442	8.25	0.7296115	1.1970768	< 0.0001*
Ozone (O_3)	− 1.990334	− 3.28	− 3.205185	− 0.775483	0.0018*
Sulfur dioxide (SO_2)	− 0.243428	− 2.33	− 0.452871	− 0.033985	0.0235*

R^2 = 0.65, *RMSE* = 21.05

correlations were found among O_3-SO_2 ($r = -0.71$****) and O_3-COVID-19 cases ($r = -0.30$*) (Fig. 7). However, statistically non-significant positive and negative relations were observed among SO_2-CO (r = 0.03) and O_3-NO_2 (r = −0.09), respectively. The higher correlation coefficient value with positive association among two air pollutants possibly exhibited mutual dependence and common pollution sources (e.g., industrial and vehicular emissions).

Our findings are found to be in line with the results of other studies conducted in other COVID-19-affected cities or regions (Martelletti and Martelletti 2020; Ogen 2020; Zhu et al. 2020; Fattorini and Regoli 2020), which clearly exhibited that atmospheric concentration of air pollutants is an important risk factor for COVID-19. It can, therefore, be stated that cities with higher concentrations of air pollutants are at high risk of COVID-19 infection. However, we could not include PM pollution in our analysis owing to data unavailability, which is one of the major air pollutants and has the potential to influence COVID-19 causality. In addition, the correlations among air pollutants imply that reduction in the atmospheric concentrations of air pollutants was the resultant effect of the enforcement of lockdown in anthropogenic activities. Several other studies (Sharma et al. 2020; Dantas et al. 2020; Kerimray et al. 2020; Mahato et al. 2020; Bao and Zhang 2020) also observed the similar types of interrelationship and reported the decreased concentrations of atmospheric NO_2, SO_2, and CO, while the concentration of O_3 was increased, resulting in improved air quality in the studied cities and/or the country.

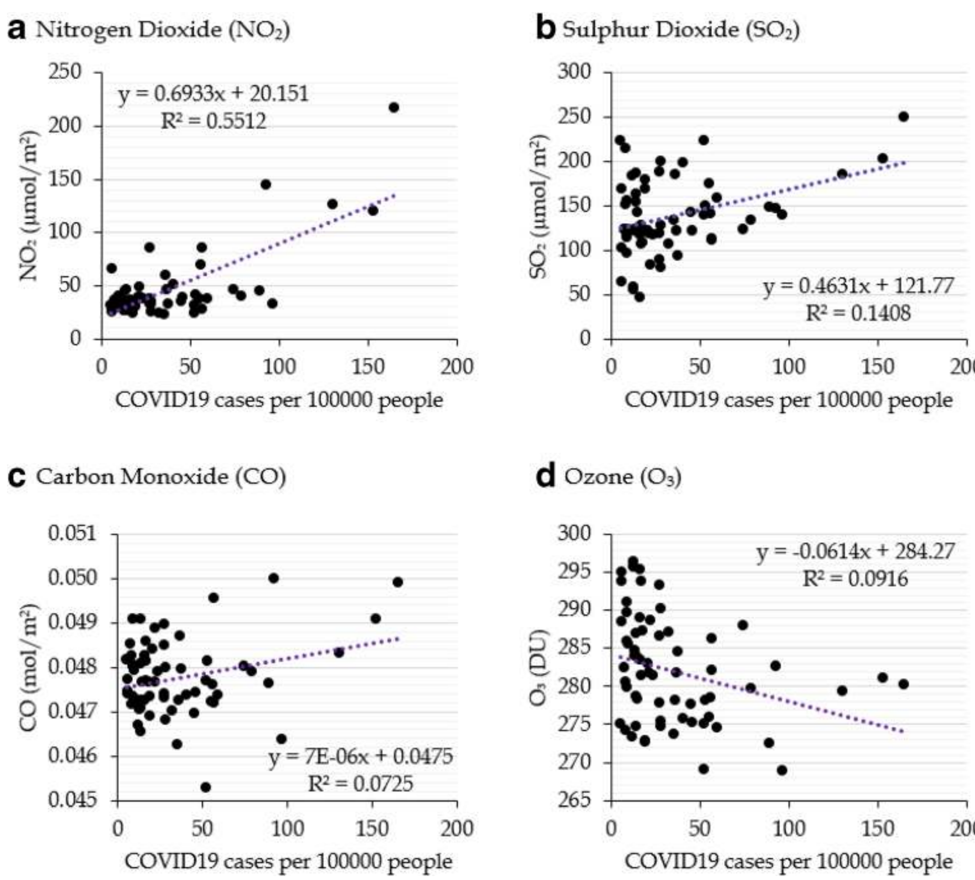

Fig. 6 Linear regression analysis of regional COVID-19 cases and daily air pollutants' concentrations in Bangladesh: number of COVID-19 cases per 100,000 people vs. daily mean levels of NO_2 (a), SO_2 (b), CO (c), and O_3 (d)

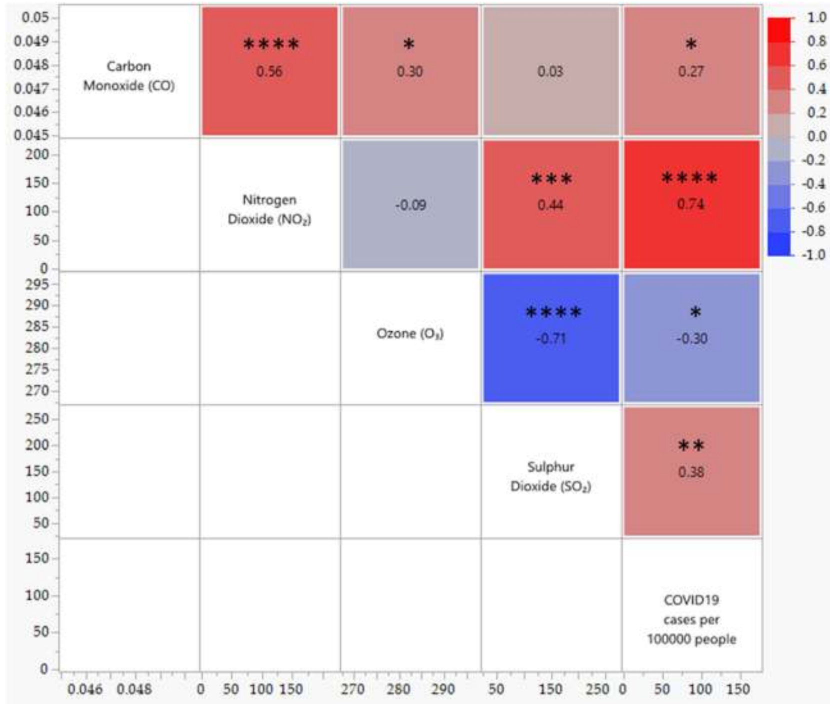

Fig. 7 Scatterplot matrix of Pearson's correlation among air pollutants and between air pollutants' concentrations and COVID-19 confirmed cases. ****indicates $P < 0.0001$, ***indicates $P < 0.001$, **indicates $P < 0.01$, and *indicates $P < 0.05$; the scale bar represents the correlation coefficient value (r)

Conclusion

The effects of lockdown in anthropogenic activities due to the COVID-19 pandemic on air quality in Bangladesh were studied by analyzing the concentrations of air pollutants and analyzing the spatial distribution changes. Satellite data of different pollutants during 2019–2020 were used to illustrate how restricted anthropogenic activities during COVID-19 lockdown reduced air pollution in Bangladesh. The study revealed that among all pollutants, the highest average reduction was in SO_2 (i.e., ~ 43%) followed by NO_2 and CO during the lockdown period. On the contrary, an average increase of ~ 3% was observed for O_3, which we believe was due to the significant reduction in NO_2 concentration during the lockdown period. The study shows that major industrial cities experienced a significant reduction in pollutant concentrations compared with less urbanized cities. The study also identified that NO_2 is highly correlated with the number of COVID-19 confirmed cases.

In most developing countries, including Bangladesh, updated emission data and air quality data are not available due to limited resources, lack of comprehensive emission inventory, and lack of proper planning and policy concerning pollution control. Satellite observations are a tremendous resource for studying air quality over large geographic regions, mainly for most developing countries like Bangladesh. We believe that our study has provided a baseline scenario that will eventually help the concerned authorities for future air quality management in Bangladesh through policy reforms, mainly on industrial and vehicular emission restrictions. Moreover, it will provide the input data for regional air quality simulation. However, in our study, we did not consider the influence of meteorological conditions on air quality. As the country has distinct seasonal variations due to its geographic location, therefore, we believe meteorological parameters have a considerable influence on air quality during the pre-lockdown and lockdown period. Further study is recommended considering the impacts of meteorological conditions on air quality in Bangladesh.

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