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Spatiotemporal trends of selected air quality parameters during force lockdown and its relationship to COVID-19 positive cases in Bangladesh

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ARTICLE INFO
Keywords:
Air quality
Lockdown
COVID-19
Bangladesh
COVID-19 positive cases
Statistical analysis

ABSTRACT

Worldwide improved air quality in different cities is reported influenced by lockdown came in force due to COVID-19 pandemic; however, as expected, such changes might have been different in different places. And what is still not very clear whether air quality pollutants have some link to account COVID-19 positive cases and death tolls. This study aims to evaluate the spatiotemporal variability of air pollutants and their relationship to COVID-19 positive cases in major cities in Bangladesh. The relevant data of air pollutants and COVID-19 positive cases are collected, analyzed, discussed for lockdown period of 26 March to 26 April 2020 in comparison to data for same period averaging over 2013 to 2019 for eight major cities in Bangladesh. To characterize air pollutants affected by lockdown, trend and rate of changes were carried out using Mann-Kandle and Sen’s slope methods, while spatial variability across the cities was done using ArcGIS and statistics within ArcGIS. The substantial reduction of mean concentrations in the range of 30–65%, 20–80%, 30 - 80%, 65 - 90% and 75 - 90% across the cities is found during lockdown compared to typical mean in previous years for the PM$_{2.5}$, PM$_{10}$, SO$_2$, CO, and NO$_2$ concentrations in air. Among the cities studied, it is seen that relatively lesser reduction in Dhaka, Gazipur and Narayanganj and moderate reduction in Chittagong, Rajshahi, Khulna and Barisal, while significantly bigger reduction in Sylhet influenced by the city attributes and climatic variabilities. Among all the pollutants studied, the increasing trends of NO$_2$ and CO in Dhaka, Gazipur and Narayanganj are unexpected even in lockdown pointing the effectiveness of lockdown management. Correlation among the air pollutants and confirmed COVID-19 cases across the cities depict foggy relationship, while PCA integrated over the cities revealed association with gaseous pollutants pointing stronger effects of NO$_2$. This relationship illustrates air pollution health effects may increase vulnerability to COVID-19 cases.

1. Introduction

Air is an important component of the environment and hence, maintain quality air for all the living organisms is deemed necessary, unless otherwise it can substantially affect environmental health and livelihood. It has been seen that air pollution reached to an unacceptable level illustrating significantly higher air quality index (AQI) / air pollution index (API) than the threshold value set by
relevant agencies mostly following the guidelines prescribed by the World Health Organization (WHO) and United States Environmental Protection Agency (USEPA). Among many cities in the globe, cities located in South Asia in particular are experiencing air pollution hazard that is ranked sixth of the top ten killers indicating its potential threats to human health and lives along with environmental health, while often ignored. This crucial component of the environment is getting severely polluted by receiving pollutants input from the unplanned urbanization for socio-economic development compromising environmental health, and anthropogenic input from motor vehicles on roads, industrial activities. In a nutshell all these activities causes great damage to the human health, agricultural production, mortality and morbidity in major cities of developing world like Bangladesh (H. A. Haque et al., 2017; Saha, 2011). The air in urban areas of Bangladesh are found with elevated concentrations of air quality pollutants, especially in dry period (November to April) influenced by meteorological parameters, such as of scarce rainfall, northwesterly wind and relatively comfortable temperature with low humidity (CASE-DoE, 2019). A few studies reported that brick kilns within the close proximity, burning dumped wastes (household and industrial) in open air, vehicular emissions, sand fields along the banks of the rivers, construction activities, coal and biomass burning as fuel etc. are primarily responsible for air pollution in most of the cases (Haque et al., 2014; Rana et al., 2016). In this period, the air pollutants such as, volatile organic compound (VOC), carbon dioxide (CO2), carbon monoxide (CO), oxygen (O2), sulfur dioxide (SO2), nitrogen oxide (NOx), hydrogen sulfide (H2S), suspended particulate matter (SPM), particulate matter (PM10 and PM 2.5) have been found to be increasing in trends in major cities of Bangladesh (Kitada and Azad, 1998; Mohiuddin, 2018; Zahangeer Alam et al., 2018). To address air pollution control, the Government of Bangladesh (GoB) had issued a set of limit values for the criteria air pollutants, e.g., PM, Pb, SO2, CO, NOx and O3 in 2005. The notable measures were adopted meanwhile for improved the air quality, the major of which were as lead free gasoline in 1999, introduction of cleaner fuel CNG to transport sector in early 90’s, phase-out of 2-stroke 3-wheeled baby taxis in early 20’s, increased the chimney height for brick kilns, and adoption of new brick burning and control law – 2013 (revised) which prohibits burning fossil fuels in brick manufacturing sector (CASE-DoE, 2019). While these interventions see improved air environment during the time of execution, the sustain benefits hardly go long due to the massive influx of populations in urban centers, increased requirement and use of excessive fuel, lack of action against inappropriate actions until the forced lockdown came as blessing disguise for environment healing due to present COVID-19 pandemic worldwide.

The first case of COVID-19 pandemic was identified in Wuhan, Hubei Province of China at the end of 2019 and then it spread over most countries in the world till to date of writing (IEDCR, 2020). In Bangladesh, first three infections of COVID-19 cases were registered on March 8, 2020 (IEDCR, 2020) and thereafter, country wide complete lockdown came in force on 26 March 2020 as per declaration by the GoB on 16 March 2020. It was then found to be continued in several phases until 26 April 2020 (Shawon, 2020) when government allowed the factories and other economic sectors including garments, export-import zones to be reopened in limited scale maintaining health regulations set by the GoB guided by the WHO. Nevertheless that limited opening causes increased in human activities and business as usual like it was before the shutdown (M. Haque and Ahamad, 2020) and hence, open up the door for infections. While the COVID-19 lockdown reduced the human activities up to 90% due to contagion, the environmental pollution was found to reduce about 30% in Spain, USA, Italy and Wuhan (Muhammad et al., 2020). A few studies further in this domain also reported improved air quality influenced by COVID-19 lockdown from major cities of the world. As for example, the concentration of PM2.5, PM10, SO2, CO, and NO2 in the major three cities of central China have reduced by 30.1%, 40.5%, 33.4%, 27.9% and 61.4%, respectively, during COVID-19 lockdown and subsequent AQI reduction of 32.2%, 27.7% and 14.9% as compared with the concentrations during 2017–19 (Xu et al., 2020). Another study by Sharma et al. (2020) reported maximum reduction of PM2.5 in most of the regions in India. In this align, the concentrations of PM2.5, PM10, CO, and NO2 are seen declined by 41%, 52% and 28%, respectively, in six megacities of India (Jain and Sharma, 2020). A study in Almaty, Kazakhstan by Kerimray et al., (2020) informed 21%, 35% and 49% reduction of PM2.5, NO2 and CO concentrations, respectively, during lockdown period. Furthermore, a similar declined trend in the concentrations of PM2.5, PM10, SO2, CO, and NO2 in major cities of Bazil, Chaina, Spain and Morocco, and an increasing trend for Ozone (O3) in all cases were described by Dantas et al. (2020), Otmani et al. (2020), Tobías et al. (2020), Xu et al. (2020). As appeared, this forced measure gives the impression as blessing disguise for environmental healing; however, changes in air pollutants and its relation of COVID-19 cases and deaths might have different trends in different places influenced by different attributes.

As air pollutants’ health impacts are strongly linked to respiratory diseases like asthma, reduction or difficulties in oxygen supply to blood, sore throat, breathing difficulties etc., and all of which are declared as common symptoms of COVID-19 positive cases by WHO, it is therefore expected that cities with significantly higher air pollution may see the higher number of cases and death tolls. A very limited studies exists that evaluated the link between air quality pollutants and COVID-19 cases and deaths at a regional level in Italy, Spain, France and Germany by Ogen (2020) at Martin Luther University Halle-Wittenberg in Germany. Analyzing the relationship between air quality pollutants and COVID-19 cases and deaths, it appears that the links are yet murky and deemed necessary to explore at different places with different climatic and urban settings to clarify what is still not clear from the available facts and figures. In particular, people living with pollution over the decades like living in urban slums in Dhaka and Chittagong to answer the question whether people living in a densely populated settings is more susceptible to get affected and dying from COVID-19 cases or not. The positive cases in Bangladesh across the major cities to date of 26 April 2020 are 3615 since its first report on 8 March 2020. Among the total cases 95% belongs to the central belt of country, e.g., Dhaka, Gazipur and Narayanganj. This study therefore seeks to characterize the benefits of lockdown on air pollutants at different regions of Bangladesh and their variabilities along with investigation of the relationship exists between COVID-19 registered cases and air pollutants in spatiotemporal scales.
2. Materials and methods

Bangladesh is a promising developing country located in 20°34'N to 26°38'N latitude and 88°01'E to 92°41'E longitude (see Fig. 1) and is housed of about 163 million people in 148,460 km² area including waterbodies, hills, forest. This is one of the most densely populated countries in the world with an average of 1252 people living in a square km area, while the situation is even worst considering urban population in major cities. The country is surrounded by the Bay of Bangl in the south, the Assam Hills in the east and lofty Himalayas to the north. Bangladesh is in the tropical monsoon region where typically warm temperature and high humidity are very common. Although there are six seasons in Bangladesh, the major four seasons are identified as pre-monsoon (March to May), monsoon (June to September), post-Monsoon (October to November) and winter (December to February).

Among the months in a year, the dry period (November to April) generally experienced severe air pollution than other time of a year when relatively low humidity and little or no rain persist. The typical wind speed range 0.5 to 1 ms⁻¹ (primarily northwesterly to east direction) and the temperature is found to vary between 15 °C to 25 °C. In this study the hourly concentration of PM₁₀, PM₂.₅, NO₂, SO₂ and CO were collected from the available 11 continuous air monitoring stations (CAMS) located in 8 major cities in Bangladesh (see Fig. 1) during COVID-19 lockdown (26 March to 26 April 2020). A summary of few attributes of the CAMS and studied cities covering different climatic parameters and characteristics of urban settings is presented in Table 1.

As seen in Table 1, the populations in Dhaka and Chittagong are just few folds higher than the other cities that gives the impression of how these cities are struggling to manage healthy living housing for too many people in urban settings. The reason behind the higher population in Dhaka and Chittagong is due to the job opportunities in public and private sectors as these two cities houses a significant number of industries and commercial hubs, private offices, school and colleges in comparison to other cities in Bangladesh. Considering the climatic parameters, temperature doesn’t show much variability while the monthly average rainfall amount during March and April is found to be varied from as low as 40 mm in Rajshahi to the highest of 261 mm in Sylhet. The relative humidity is found in the range of 64 to 78 within the studied cities. The fact of variation among the sites are confirmed and is even better explained taking range and coefficient of variation in consideration. As Dhaka and Chittagong cities primarily are with commercial and business hubs, the air is seemed to be polluted by emissions from the industries, road traffic sectors, development and constructions activities, household uses of gas as energy, open air burning of waste using fossil fuels etc. Masum and Pal (2020). In a nutshell, the geographical locations, urban settings and regional climate makes the differences in studied cities.

Fig. 1. Location Map of CAMS stations in major cities of Bangladesh.
The influenced of forced lockdown on changed air quality pollutants in Bangladesh was reviewed considering a few perspectives: firstly, spatiotemporal variations of hourly concentration of PM$_{10}$, PM$_{2.5}$, SO$_2$, NO$_x$, CO were evaluated to identify the benefits of COVID-19 lockdown at different sites. The trend analysis was performed using Mann-Kendall (M-K) analysis with their significant level. The magnitude of change in concentration of air pollutants during COVID-19 were determined using Sen’s Slope method. 

In Mann Kendall analysis, the number of sequential values in studied data series is denoted by $n$. If $n$ is 9 or less, the absolute value of $S$ is compared directly to the theoretical distribution of $S$ derived by Mann and Kendall (Gilbert, 1987). The Mann-Kendall test statistic $S$ is calculated by using following equation.

$$ S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(x_j - x_k) $$

Where,

$$ \text{sgn}(x_j - x_k) = \begin{cases} 
1 & \text{if } x_j - x_k > 0 \\
0 & \text{if } x_j - x_k = 0 \\
-1 & \text{if } x_j - x_k < 0 
\end{cases} $$

Table 1

| Latitude | Longitude | Name of the stations | Name of the City | City Code | Population$^a$ (thousands) | Rainfall$^b$ (mm) | Average Temperature$^c$ ($^\circ$C) | R. Humidity$^d$ (%) |
|----------|-----------|----------------------|------------------|-----------|--------------------------|-----------------|-----------------|----------------|
| 23.76 90.38 | CAMS-1 (S-Bhaban) | Dhaka | DHK | 13,798 | 0–318 (101) | 22.2-30.7 | 48–81 |
| 23.76 90.39 | CAMS-2 (BARC) | Dhaka | DHK | 20,157 | 0–318 (101) | 22.2-30.7 | 48–81 |
| 23.78 90.36 | CAMS-3 (D-Salam) | Gazipur | GAZ | 4046 | 0–318 (101) | 22.2-30.7 | (66.5) (0.101) |
| 23.99 90.42 | CAMS-4 (Gazipur) | Narayanganj | NAR | 3490 | 0–318 (101) | 22.2-30.7 | 62–84 |
| 23.63 90.51 | CAMS-5 (Narayanganj) | Chittagong | CTG | 8990 | 0–418 (96) | 23.9-29.6 | 75.5 |
| 22.36 91.80 | CAMS-6 (TV Station, Chittagong) | Dhaka | DHK | 13,798 | 0–1004 (261) | 22.0-28.1 | (72) |
| 22.81 91.81 | CAMS-7 (Agrabad-Chittagong) | Sylhet | SYL | 4408 | (0.057) | 22.0-28.1 | (72) |
| 22.48 89.53 | CAMS-8 (Sylhet) | Khulna | KHU | 2650 | 0–347 (64) | 23.7-32.3 | 57–86 |
| 24.36 88.61 | CAMS-9 (Khulna) | Rajshahi | RAJ | 3000 | 0–102 (40) | 22.8-31.7 | 44–77 |
| 24.89 91.80 | CAMS-10 (Rajshahi) | Sylhet | SYL | 4408 | (0.057) | 23.5-30.4 | (78) |
| 22.71 90.36 | CAMS-11 (Barisal) | Barisal | BAR | 2776 | (0.058) | 22.2 | (78) |

$^a$ population in 2020.  
$^b$ Monthly average of March and April for last three decades.
Table 2
Descriptive statistics of gaseous pollutants in air during COVID-19 lockdown (March – April 2020) and for same period in 2019

| Parameters | DHK | DHK | GAZ | GAZ | NAR | NAR | CTG | CTG | SYL | SYL | KHU | KHU | RAJ | RAJ | BAR | BAR |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| CO (mg m\(^{-3}\)) |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Min        | 1.11 | 0.07 | 0.93 | 0.07 | 0.29 | 0.07 | 0.53 | 0.05 | 0.57 | 0.05 | 0.05 | 0.04 | 0.5  | 0.06 | 0.78 | 0.05 |
| Max        | 43.55 | 0.57 | 66.86 | 0.46 | 19.5 | 0.57 | 16.9 | 0.35 | 23  | 0.32 | 21.1 | 0.59 | 18.3 | 0.38 | 2.7  | 0.29 |
| Mean       | 2.98 | 0.32 | 3.93 | 0.31 | 2.1  | 0.31 | 1.72 | 0.24 | 3.11 | 0.22 | 2.41 | 0.29 | 1.62 | 0.28 | 1.46 | 0.23 |
| Std. dev.  | 5.65 | 0.09 | 10.6 | 0.08 | 3.59 | 0.09 | 2.48 | 0.06 | 3.94 | 0.05 | 4.61 | 0.1  | 3.17 | 0.07 | 0.39 | 0.05 |
| CV         | 1.89 | 0.28 | 2.69 | 0.27 | 1.71 | 0.28 | 1.44 | 0.25 | 1.27 | 0.23 | 1.91 | 0.33 | 1.95 | 0.26 | 0.27 | 0.2  |
| std. value |     | 40  |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| NO\(_2\) (μg m\(^{-3}\)) |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Min        | 3.29 | 4   | 2.68 | 2.63 | 8.64 | 4.31 | 4.83 | 1.51 | 5.3  | 0.64 | 17.9 | 1.83 | 0.96 | 1.85 | 1.64 | 0.83 |
| Max        | 276  | 58.6| 120 | 26.8 | 204  | 62.4 | 152 | 10.9 | 247  | 4.7  | 238  | 27.2 | 147  | 10.3 | 175  | 6.6  |
| Mean       | 129.8| 12.23| 57.3 | 8.64 | 99  | 12.2 | 45.2 | 3.72 | 50  | 1.79 | 91.8 | 4.7  | 84.5 | 3.32 | 33.4 | 1.87 |
| SD         | 67.47 | 10.24| 17.2 | 5.92 | 45.7 | 10.6 | 32  | 2.25 | 42.5 | 1.15 | 57  | 4.57 | 40.6 | 1.9  | 33.6 | 1.13 |
| CV         | 0.98 | 1.59 | 1.07 | 1.28 | 0.87 | 1.64 | 1.34 | 1.13 | 1.6  | 1.21 | 1.17 | 1.83 | 0.91 | 1.08 | 1.89 | 1.15 |
| std. value |     | 100 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| SO\(_2\) (μg m\(^{-3}\)) |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Min        | 6.24 | 6.29 | 1.60 | 5.64 | 12  | 5.87 | 0  | 3.1  | 2.06 | 0.83 | 3.91 | 1.77 | 0  | 1.1  | 1.17 | 0.71 |
| Max        | 127.4 | 31.3 | 85.9 | 23.8 | 87.2 | 31  | 101.8 | 16.7 | 22.5 | 20.9 | 91.35 | 58.5 | 54.3 | 10.44 | 100.8 | 12.19 |
| Mean       | 32.62 | 12.7 | 21  | 13.8 | 39.7 | 11.7 | 17.7 | 8.6  | 9.53 | 7.9  | 24.17 | 12.19 | 15.95 | 5.45 | 21  | 5.38 |
| Std. dev.  | 26.36 | 4.96 | 20.5 | 4.72 | 20.4 | 4.93 | 18 | 3.52 | 5.43 | 5.51 | 24.4 | 11.38 | 14.17 | 2.8  | 23.65 | 3.39 |
| CV         | 2.11 | 1.02 | 2.56 | 0.88 | 1.36 | 1.1  | 1.07 | 1.49 | 1.83 | 2.62 | 2.41 | 2.32 | 1.33 | 2.92 | 1.64 |     |
| std. value |     | 365 |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

DHK – Dhaka; GAZ – Gazipur; NAR – Narayanganj; CTG – Chittagong; SYL – Sylhet; KHU – Khulna; RAJ – Rajshahi; BAR - Barisal.
The values of pollutants under city codes (e.g. DHK) are in normal condition previous year, while these under city codes underlines (e.g. DHK) are lockdown period.

* Bangladesh National Ambient Air Quality Standard (BNAAQS); Values shown in bold exceed the BNAAQS limit values.
Table 3
Descriptive statistics of particulate pollutants in air during COVID-19 lockdown (March – April 2020) and for same period in 2019 *

| Parameters | DHK | DHK | GAZ | GAZ | NAR | NAR | CTG | CTG | SYL | SYL | KHU | KHU | RAJ | RAJ | BAR | BAR |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| PM$_{2.5}$ ($\mu$g m$^{-3}$) | | | | | | | | | | | | | | | | |
| Min | 45.0 | 5.0 | 38.9 | 4.2 | 35.2 | 8.3 | 30.3 | 6.6 | 27.5 | 8.0 | 25.3 | 17.3 | 44.9 | 12.4 | 33.1 | 7.9 |
| Max | 212.7 | 117.3 | 220.9 | 116.5 | 268.2 | 120.6 | 200.0 | 62.6 | 151.7 | 39.9 | 217.0 | 61.7 | 175.1 | 56.4 | 213.2 | 37.8 |
| Mean | 128.4 | 34.7 | 136.0 | 34.0 | 157.9 | 38.1 | 102.3 | 25.5 | 83.1 | 22.1 | 104.4 | 34.4 | 104.6 | 33.5 | 113.4 | 24.2 |
| Std. dev. | 41.8 | 23.3 | 43.8 | 23.3 | 62.3 | 151.7 | 66.6 | 217.0 | 61.7 | 39.9 | 213.2 | 37.8 |
| CV | 0.33 | 0.67 | 0.32 | 0.69 | 0.39 | 0.61 | 0.35 | 0.48 | 0.33 | 0.41 | 0.52 | 0.35 |
| Std. value | 65 | | | | | | | | | | | | | | | |
| PM$_{10}$ ($\mu$g m$^{-3}$) | | | | | | | | | | | | | | | | |
| Min | 97 | 29.5 | 104 | 32.7 | 117 | 25.2 | 82.4 | 14.3 | 58 | 11.6 | 0 | 29.3 | 105 | 20.4 | 67.2 | 11.5 |
| Max | 371 | 75.9 | 319 | 81.6 | 428 | 70.4 | 292 | 103 | 227 | 59.5 | 233 | 93.9 | 330 | 86.3 | 285 | 63 |
| Mean | 214 | 54.6 | 223 | 58 | 296 | 51.1 | 180 | 51.6 | 146 | 35.2 | 131 | 54.3 | 211 | 50.7 | 168 | 39 |
| SD | 63.3 | 13.7 | 59.1 | 14.4 | 78.2 | 12.7 | 47.6 | 18 | 40.4 | 14 | 62.2 | 18.1 | 58.9 | 18.1 | 51.8 | 14.2 |
| CV | 0.3 | 0.25 | 0.27 | 0.25 | 0.26 | 0.25 | 0.26 | 0.26 | 0.28 | 0.4 | 0.47 | 0.33 | 0.28 | 0.36 | 0.31 | 0.36 |
| Std. value | 150 | | | | | | | | | | | | | | | |
| AQI | | | | | | | | | | | | | | | | |
| Min | 97 | 0.32 | 98.9 | 0.31 | 77 | 0.31 | 82.4 | 0.24 | 58 | 0.22 | 29.2 | 0.29 | 105 | 0.28 | 41.3 | 0.23 |
| Max | 353 | 181 | 334 | 180 | 385 | 183 | 441 | 144 | 223 | 98.9 | 354 | 143 | 296 | 132 | 303 | 94.9 |
| Mean | 219 | 83.3 | 216 | 82.5 | 247 | 89 | 202 | 67.4 | 150 | 60.1 | 170 | 85.7 | 194 | 83.7 | 173 | 64.9 |
| Std. dev. | 71.6 | 37 | 73.4 | 36.7 | 86.7 | 36.7 | 84.4 | 28.8 | 45.6 | 23.1 | 94.4 | 28.4 | 56.2 | 28 | 77.8 | 22.1 |
| CV | 0.33 | 0.44 | 0.34 | 0.44 | 0.35 | 0.41 | 0.42 | 0.43 | 0.38 | 0.56 | 0.33 | 0.29 | 0.33 | 0.45 | 0.34 |
| std. value | 100 | | | | | | | | | | | | | | | |

No. of days AQI $\geq$ 100 | 43 |

DHK – Dhaka; GAZ – Gazipur; NAR – Narayanganj; CTG – Chittagong; SYL – Sylhet; KHU – Khulna; RAJ – Rajshahi; BAR – Barisal.
The values of pollutants under city codes (e.g. DHK) are in normal condition previous year, while theses under city codes underlines (e.g. DHK) are lockdown period.

* Bangladesh National Ambient Air Quality Standard (BNAAQS); Values shown in bold exceed the BNAAQS limit values.
x_j and x_k are the sequential data values. When S bears a positive value, it indicates an upward or increasing trend and if the value is negative, it indicates downward trend or decreasing trend. If n is at least 10 or more than 10, the test follows a normal distribution and hence normal approximation test is used with expectation (E) and variance of S as \( \text{VAR}(S) \) using the formulation shown below:

\[
\text{VAR}(S) = \frac{1}{18} \left[ n(n-1)(2n+5) - \sum_{p=1}^{q} t_p (r_p - 1) (2t_p + 5) \right]
\]

Here, \( q \) is the number of tied groups and \( t_p \) is the number of data points in the \( p \)th tied group in the dataset. The standardized test statistic (Z) is calculated as follows:

\[
Z = \begin{cases} 
\frac{S - 1}{\sqrt{\text{VAR}(S)}} & \text{if } S > 0 \\
0 & \text{if } S = 0 \\
\frac{S + 1}{\sqrt{\text{VAR}(S)}} & \text{if } S < 0 
\end{cases}
\]

Where, the value of Z is the Mann-Kendall test statistic which follows a standard normal distribution with mean being 0 and variance being 1. In this study, the confidence intervals of 90%, 95%, 99%, 99.99% (\( p < 0.10, p < 0.05, p < 0.01 \) and \( p < 0.001 \), respectively) were taken to classify the significance of positive and negative trends. Furthermore, the Sen’s slope estimator, is known as the slope of the linear trend, has been estimated using the Theil–Sen estimator (Sen, 1968). It is a nonparametric method used to determine the true slope of an existing trend where the trend can be assumed to be linear (as change per time). The slope (Q) estimates of N pairs of data are first computed by as follows:

\[
Q_i = \frac{x_j - x_k}{j-k} \quad \text{For } i = 1, 2, 3, \ldots \ldots , N
\]

Where \( x_j \) and \( x_k \) are data values at times \( j \) and \( k \) (\( j > k \)) respectively. The median of these N values of Q is the Sen’s estimator of the slope.

A spatial distribution of concentrations for both types of pollutants (particulate and gaseous) were done using ArcGIS version 10.4 statistics. The trends of changes in mean concentrations of the air pollutants presented in map were classified as extreme, high, moderate and mild considering respective confidence interval of 99.99% (**), 99% (**), 95% (*) and 90 (–) as symptom of COVID-19 positive cases initiation takes couple of days to two weeks in many cases. Finally, to evaluate the relationship among air pollutants and the number of COVID-19 registered and published cases during the studied period, Principal Component Analysis (PCA) using statistical software SPSS (Ver. 20) was carried out. In PCA, the factor loadings for each of the member of air pollutants have been taken into consideration for clustering, and grouping of air pollutants are decided based on the variations revealed by the principle components (Mahapatra et al., 2012).

3. Results and discussions

3.1. Descriptive statistics of air pollutants

The descriptive statistics of air pollutants studied during COVID-19 lockdown (March to April 2020) and during the same period in 2019 along with their respective permissible limits set by GoB are presented in Tables 2 and 3. Table 2 illustrate the gaseous pollutants CO, NO\(_2\) and SO\(_2\) concentrations at 8 different sites in Bangladesh. As seen in Table 2, in general gaseous pollutants concentrations are substantially lower than their respective standard concentrations set by GoB for both time periods. However, distinct reduction of the
Daily changes in mean concentration of gaseous air pollutants during COVID-19 lockdown period.

| Pollutants | Dhaka | Gazipur | Narayanganj | Chittagong | Sylhet | Khulna | Rajshahi | Barisal |
|------------|-------|---------|-------------|------------|--------|--------|----------|--------|
| CO         | 0.003 | 0.003   | 0.002       | -0.003     | -0.003 | 0.004  | -0.005   | -0.002 |
| SO₂        | -0.023| 0.021   | -0.046      | -0.057     | -0.181 | -0.126 | -0.055   | -0.086 |
| NO₂        | 0.136 | 0.124   | 0.118       | 0.018      | -0.005 | 0.011  | -0.034   | 0.061  |
Furthermore, the concentrations for gaseous air pollutants during COVID-19 lockdown (March–April) in 8 major cities of Bangladesh were compared with the mean concentrations derived for data of March–April in last 7 years (2013–19) and with March–April of 2019 to check the progressive and immediate changes. The results as obtained is presented in Table 5. As seen Table 5, among the gaseous air pollutants, the maximum reduction in concentration occurs in case of NO$_2$ ranges 75% to 93% across the cities considering 2013 to 2019, while that with 2019, the range is as 80% to 96%. The results yield similar findings of decreasing trends for CO and SO$_2$ (except in Dhaka and Gazipur showing positive compared to 2019 data) across the sites, as discussed earlier illustrating lowest reductions are in the central belt of Bangladesh. A graphical mapping in relation to this can be seen in supplementary file as

Fig. 2. Spatial variability of gaseous air pollutants trends across major cities of Bangladesh during lockdown period (March–April, 2020). In the key-Extreme trend (99.99% confidence level), High trend (99% confidence level), Moderate trend (95% confidence level), Mild trend (90% confidence level or less).
Table 5
Percentage (%) of changes in concentrations of gaseous air pollutants in different cities of Bangladesh.

| Name of the City | March–April (2013–19) Vs COVID-19 Lockdown | March–April (2019) Vs COVID-19 Lockdown |
|------------------|-------------------------------------------|----------------------------------------|
|                  | CO    | SO₂  | NO₂  | CO    | SO₂  | NO₂  |
| Dhaka            | –80   | –33  | –84  | –81   | 38   | –87  |
| Gazipur          | –80   | –9   | –75  | –91   | 10   | –90  |
| Narayanganj      | –46   | –51  | –75  | –76   | –65  | –80  |
| Chittagong       | –81   | –35  | –93  | –79   | –79  | –90  |
| Sylhet           | –88   | –29  | –92  | –68   | –2   | –96  |
| Khulna           | –72   | –51  | –90  | –59   | 137  | –89  |
| Rajshahi         | –67   | –67  | –90  | –72   | –60  | –94  |
| Barisal          | –72   | –67  | –86  | –81   | –75  | –95  |

Fig. S1. Although the magnitude of changes is marginally higher when compared to recent year data (2019), however, no distinct changes in gaseous pollutants are seen for the period of 2013 to 2020, except forced lockdown brought the values down, as expected.

Results of trend analysis for particulate matters in air during COVID-19 lockdown measures in 8 major cities of Bangladesh is shown in Table 6 and Fig. 3. Table 6 presents the rate of change while the graphical representations of changes using map is shown in Fig. 3 with the level of significance of those changes found at 8 different cities under investigation. In addition, Table 6 also present the changes in AQI during several phases along with particulate pollutants. Except PM_{2.5} in Khulna, all cities exhibit statistically significant reduction in particulate pollutants and AQI considering the mean concentrations during COVID-19 lockdown, as seen in Table 6 and Fig. 3. Furthermore, from Table 6, the reduction changes of PM_{2.5} concentrations are substantially higher (see Fig. 3) in the order of Barisal, Chittagong, Rajshahi and Sylhet at a rate of 1.573, 0.813, 0.801 and 0.711 µgm⁻³ day⁻¹, respectively, while the reduction rate are much lower around the central belt e.g., in Dhaka, Gazipur and Narayanganj. Based on PM_{10} changes the standings are found slightly different in order at a rate of –2.995, –1.317, –1.095 and –0.887 µgm⁻³ day⁻¹, respectively, for Barisal, Chittagong, Sylhet and Rajshahi, respectively. The AQI standing follows the PM_{10} trend across the sites. It is noted that the results follow the similar trends of gaseous pollutants as found in Table 5 confirming city-specific urban settings and climatic variabilities.

Furthermore, the concentrations for particulate air pollutants along with AQI during COVID-19 lockdown (March–April) in 8 major cities of Bangladesh were compared with the mean concentrations derived for data of March–April in last 7 years (2013–19) and with March–April of 2019 to check the progressive and immediate changes. The results as obtained is presented in Table 7.

As seen Table 7, both PM_{2.5} and PM_{10} show decreasing trends during COVID-19 lockdown period (March to April 2020) and in comparison, with the previous year data of March to April 2019 yields 31 to 66% reduction across the sites, while that for the same period of 2013 to 2019 are found 13% to 60%. A graphical representation across the site can be found in Fig. S2. Although few differences in changes across the sites are observed as expected and discussed earlier influenced by the city-specific attributes, the distinct changes are hardly seen as reported in the study carried out by Travaglio et al. (2020) taking a greater number of cities in the UK in consideration. The results by analyzing the data and information for this study it is clear that the immediate benefits of air pollutants reduction gained since the government adopted few measures such as introduction to cleaner fuel CNG for motor vehicles, enlarged height of brick kilns and industrial chimneys, phase out of 2 stroke 3 wheeler etc. are suppressed by the unplanned urbanizations, increased number of vehicles, industrializations and lack of control and monitoring schemes by DoE, and hence, at later stages enhanced air pollution around central belts, such as in Dhaka, Gazipur Narayanganj and in commercial and port city Chittagong are evident.

3.3. Correlation between air pollutants and confirm COVID-19 cases

A limited study to date in the UK by Travaglio et al., 2020 and in few cities in Europe by Ogen, 2020 analyzes the relationship between COVID-19 cases with air pollutants, and found poor to weak correlation. However, no such relationship has been found for south Asian countries so far. Moreover, relationship with the COVID-19 cases and time lag of climatic variables by 3, 5 and 7 days on date of positive cases is evaluated considering the fact that people registered today as COVID positive may got affected a week earlier.

Table 6
Daily changes in mean concentration of particulate matters and AQI for the major cities in Bangladesh during COVID-19 lockdown periods (March–April, 2020).

| Pollutants | Dhaka | Gazipur | Narayanganj | Chittagong | Sylhet | Khulna | Rajshahi | Barisal |
|------------|-------|---------|-------------|------------|--------|--------|----------|--------|
| PM_{2.5}   | –0.335 | –0.334  | –0.338      | –0.813     | –0.711 | 0.062  | –0.801   | –1.573 |
| PM_{10}    | –0.636 | –0.455  | –0.642      | –1.317     | –1.095 | –0.001 | –0.887   | –2.995 |
| AQI        | –0.618 | –0.589  | –0.578      | –1.810     | –1.686 | 0.123  | –1.634   | –3.423 |
The greater number of statistically significant correlations are in Dhaka, Sylhet and Barisal, while Gazipur, Narayanganj, Khulna, Rajshahi exhibit couple of significant correlation coefficients, Chittagong revealed none. Based on the standing of the cities the central belt cities e.g., Dhaka, Gazipur and Narayanganj are found with polluted air environment even in lockdown period compared to other cities around the country and in accordance with higher number of positive cases; however, except Dhaka other two cities did not yield positive correlations with COVID-19 positive cases which is unexpected and left an idea that COVID-19 transmission with air may only be harmful for densely living style that is more dominant in Dhaka city. However, positive correlations of SO$_2$, PM$_{2.5}$, PM$_{10}$ and NO$_2$ in Dhaka, PM, SO$_2$, CO and NO$_2$ in Sylhet and similarly in Barisal support the idea of correlations with COVID-19.
positive cases and lethality as reported by Travaglio et al. (2020) and Ogen (2020). While, it is well understood that usually people get affected experienced symptoms within a week or so and thereafter got tested and registered in the data base, therefore 3-, 5- and 7-days lag air pollutants with on date COVID-19 positives cases are evaluated and it has been seen that the 5 days lag air pollutants revealed greater number of statistical relationships. This further indicates that the relationship between air pollutants and COVID-19 cases are not straightforward rather complex and need more data to draw concrete decision.

The limited data of COVID-19 positive cases during the lockdown period studied and its murky relation with air quality reported earlier, it is therefore decided to conduct the principle component analysis (PCA) to identify factor loadings of similar groups taking data with on date COVID-19 cases (see Fig. S3) along with eigen values and PCA loading factors (see Table S1) to get more insight of the relationship or association. It has been seen that the PCA displayed 3D plot with five components, while PC1 and PC4 describing the data with on date COVID-19 cases (see Fig. S3) along with eigen values and PCA loading factors (see Table S1) to get more insight of the relationship or association. It has been seen that the PCA displayed 3D plot with five components, while PC1 and PC4 describing the relationship between air pollutants (on date and 3-, 5- and 7-days lag). As in Bangladesh the gaseous pollutants

Table 7
Percentage (%) of changes in concentrations of particulate matters in air and AQI in Bangladesh.

| Name of the City | March-April (2013–19) Vs COVID-19 Lockdown | March-April (2019) Vs COVID-19 Lockdown |
|------------------|--------------------------------------------|------------------------------------------|
|                  | PM$_{2.5}$ | PM$_{10}$ | AQI  | PM$_{2.5}$ | PM$_{10}$ | AQI  |
| Dhaka            | $-44$      | $-53$     | $-36$ | $-60$      | $-67$     | $-53$ |
| Gazipur          | $-45$      | $-54$     | $-28$ | $-62$      | $-65$     | $-39$ |
| Narayanganj      | $-38$      | $-70$     | $-23$ | $-62$      | $-80$     | $-46$ |
| Chittagong       | $-60$      | $-57$     | $-47$ | $-62$      | $-66$     | $-66$ |
| Sylhet           | $-55$      | $-63$     | $-35$ | $-64$      | $-72$     | $-49$ |
| Khulna           | $-13$      | $-19$     | $-16$ | $-31$      | $-41$     | $-54$ |
| Rajshahi         | $-43$      | $-56$     | $-36$ | $-66$      | $-64$     | $-48$ |
| Barisal          | $-46$      | $-50$     | $-21$ | $-46$      | $-57$     | $-35$ |

Table 8
Correlation coefficients ($r$) among the air pollutants and confirmed COVID-19 patients in Bangladesh.

| Parameters       | Dhaka    | Gazipur | Narayanganj | Chittagong | Sylhet | Khulna | Rajshahi | Barisal |
|------------------|----------|---------|-------------|------------|--------|--------|----------|---------|
| PM$_{2.5}$ (On day) | $0.320$  | $-0.459^*$ | $0.305$     | $0.039$    | $0.346$ | $0.093$ | $0.216$  | $-0.129$ |
| PM$_{2.5}$ (3 days lag) | $0.059$  | $0.239$  | $-0.382$    | $0.061$    | $-0.307$ | $0.210$ | $-0.124$ | $0.077$  |
| PM$_{2.5}$ (5 days lag) | $0.308$  | $-0.164$ | $0.218$     | $0.288$    | $0.598^*$ | $0.379$ | $0.122$  | $0.486^*$ |
| PM$_{10}$ (3 days lag) | $0.512$  | $0.115$  | $0.030$     | $0.145$    | $-0.141$ | $0.121$ | $0.344$  | $0.477^*$ |
| PM$_{10}$ (5 days lag) | $0.448^*$ | $-0.130$ | $0.360^*$   | $0.139$    | $-0.366$ | $-0.147$ | $-0.184$ | $-0.076$ |
| PM$_{10}$ (7 days lag) | $0.568^*$ | $0.025$  | $0.032$     | $0.240$    | $-0.311$ | $0.237$ | $-0.179$ | $0.092$  |
| PM$_{10}$ (5 days lag) | $0.637^*$ | $-0.041$ | $0.415$     | $0.367$    | $0.622^*$ | $0.259$ | $0.193$  | $0.583^*$ |
| CO (On day)       | $0.297$  | $0.133$  | $0.198$     | $0.099$    | $-0.075$ | $0.010$ | $0.388$  | $0.392$  |
| CO (3 days lag)   | $-0.024$ | $0.059$  | $-0.025$    | $-0.097$   | $-0.234$ | $0.061$ | $-0.267$ | $-0.377$ |
| CO (5 days lag)   | $0.069$  | $-0.092$ | $-0.090$    | $-0.085$   | $-0.385$ | $0.410^*$ | $-0.267$ | $0.083$  |
| SO$_{2}$ (On day) | $-0.148$ | $0.072$  | $0.511^*$   | $0.373$    | $0.577^*$ | $0.387$ | $0.328$  | $0.189$  |
| SO$_{2}$ (3 days lag) | $-0.238$ | $0.210$  | $-0.119$    | $0.059$    | $-0.176$ | $0.158$ | $0.291$  | $0.236$  |
| SO$_{2}$ (5 days lag) | $-0.327$ | $0.114$  | $-0.285$    | $0.056$    | $-0.339$ | $-0.203$ | $-0.155$ | $-0.289$ |
| SO$_{2}$ (7 days lag) | $-0.237$ | $0.113$  | $-0.188$    | $0.040$    | $-0.337$ | $0.365$ | $-0.191$ | $-0.051$ |
| SO$_{2}$ (5 days lag) | $0.428^*$ | $0.222$  | $0.555^*$   | $0.352$    | $0.559^*$ | $0.385$ | $0.299$  | $0.370$  |
| NO$_{2}$ (On day) | $0.371$  | $0.166$  | $0.387^*$   | $0.046$    | $0.088$  | $0.179$ | $-0.088$ | $0.271$  |
| NO$_{2}$ (3 days lag) | $0.415^*$ | $0.342$  | $0.086$     | $-0.056$   | $0.145$  | $-0.113$ | $0.549^*$ | $-0.066$ |
| NO$_{2}$ (5 days lag) | $0.119$  | $-0.230$ | $0.373$     | $0.306$    | $0.513^*$ | $0.194$ | $0.372$  | $0.257$  |
| NO$_{2}$ (7 days lag) | $0.046$  | $-0.126$ | $-0.363$    | $0.102$    | $-0.099$ | $0.165$ | $0.018$  | $-0.011$ |

The values kept in bold are the values that are found statistically significant correlations with different confidence levels (as mentioned in the table foot note).

*significant at 95% confidence level (p < 0.05); ** significant at 99% confidence level (p < 0.01).
structures etc. need also to be examined. Nevertheless, this relationship pointed out the health affecting air pollutants may remarkably have increased vulnerability to the COVID-19 positive cases and death tolls.

4. Conclusions

The study evaluates and characterize air pollutants influenced by COVID-19 lockdown for major cities in Bangladesh, and thereafter, examine what is not yet clear whether air quality has some form of relationship with COVID-19 positive cases. The outcomes of the study found that air quality index represents air pollution status in Bangladesh is biased by particulate matters than gaseous pollutants. The investigation revealed that COVID-19 lockdown had substantially reduced air pollutants and thus had positive impact on the air quality in general across the major cities in Bangladesh. Nevertheless, in comparison to air quality data for the same period over 2013 to 2019 as pre-lockdown period, the lockdown exhibit much reduction of CO, SO₂, NO₂, PM₂.₅ and PM₁₀ concentrations accounting 65 to 90%, 30 to 80%, 75 to 95%, 30 to 60% and 20 to 80%, respectively, across the eight major cities. The results confirmed substantial spatial variation across the cities, where cities located in the central belt, such as Dhaka, Gazipur and Narayanganj are in the lower range of reduction than other part of the country. Based on temporal trends during COVID-19 lockdown, both positive and negative trends of the air pollutants are observed: while PM₂.₅, PM₁₀ and SO₂ portray negative trends in general for all the cities, the CO and NO₂ show unexpectedly increasing trends especially in Dhaka, Gazipur and Narayanganj. Correlation coefficients among the air pollutants and COVID-19 cases across the city depict foggy relationship. However, PCA suggests interesting facts of showing greater association with gaseous pollutants notably with NO₂ with COVID-19 positive cases, while no such with particulate pollutants are seen integrated over the major cities in Bangladesh.

Align with studies elsewhere, it is quite clear more work is needed because of significant differences exists in weather pattern, socio-economic environment settings, law and order, virus genome structures and its adaptability with different settings across the countries in the world. Nonetheless, this is clear that health conditions affected by the air pollutants are linked to increase vulnerability to COVID-19.

Declaration of Competing Interest

No potential conflict of interest was reported by the authors. 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.

Acknowledgments

This work was carried out by Md. Mehedi Hassan Masum, PG student in the Department of Civil Engineering at Chittagong University of Engineering & Technology under supervision of Prof. Sudip K Pal with the help of data and information provided by Department of Environment (DoE) that measured data daily basis from its measuring stations located in different locations in Bangladesh set under the Clean Air and Sustainable Environment (CASE) Project.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2021.100952.
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