ORIGINAL ARTICLE

Prediction of COVID-19 Cases from the Nexus of Air Quality and Meteorological Phenomena: Bangladesh Perspective

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Received: 13 July 2021 / Revised: 13 October 2021 / Accepted: 9 November 2021 / Published online: 28 November 2021
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Abstract

An integrated approach was used to estimate the number of COVID-19 patients related to air quality and meteorological phenomena. Additionally, the air quality during pre-lockdown, lockdown, and post-lockdown stages of the COVID-19 pandemic was assessed to determine the effect of the infection containment measures taken in Bangladesh during the pandemic. The air quality was assessed based on measurements of nitrogen dioxide (NO₂), sulfur dioxide (SO₂), ozone (O₃), carbon monoxide (CO), black carbon, particulate matter (PM_{2.5} and PM₁₀), and aerosol optical depth. Time-averaged maps of these parameters have been generated from NASA's (National Aeronautics and Space Administration) website. Values of these parameters have also been collected from a continuous air monitoring station (CAMS) located in Bangladesh's north-western city Rajshahi. The comparison shows that lockdown during the pandemic has brought significant improvements in air quality. However, the improvement was not sustained, since rapid increases in the air pollutant concentrations were observed in the post-lockdown period. Furthermore, Pearson correlation coefficients between each air quality variable and the daily new COVID-19 case rates were calculated. Different meteorological variables during the same time periods were determined to observe the variation in Rajshahi city. Relationships of these variables with the case rates were also established. Additionally, statistical analyses of the obtained data have been conducted for the measured variables using the Kruskal–Wallis test to assess the differences in the observed data among the pre-lockdown, lockdown, and post-lockdown periods. Dunn's "Q" test was employed to test if the variables showed significance statistical difference during the Kruskal–Wallis test for pairwise comparisons. From the study, it has been observed that both meteorological variables and air quality parameters have significant relationship with daily new COVID-19 case rates. Both positive and negative associations of these parameters with the COVID-19 case rates have been observed. Very high air pollution has been observed in the post-lockdown period. Thus, it is recommended that appropriate authorities undertake corrective measures to protect the environment in cities with large populations. This study provides guidance for decision makers and health officials for future research and potentially reducing the spread of COVID-19.

Keywords COVID-19 · Lockdown · Statistical analysis · Meteorological variable · Time-averaged map · CAMS

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1 Introduction

The COVID-19 pandemic has affected life around the world beginning in December 2019, when it was first reported in China (Gautam 2020; Metya et al. 2020). It was declared as global pandemic on March 2020 by World Health Organization (WHO) (WHO 2020). WHO reported that confirmed cases were maximal in the Americas (44%) and minimal in Western Pacific (1%). About 12% cases are distributed throughout South-East Asia (WHO 2021). Both developed and under-developed countries are facing numerous challenges while dealing with the pandemic. The first COVID-19 case was identified in Bangladesh on March 7, 2020 (Hossain et al. 2020; Shammi et al. 2021). From then on, the pandemic spread exponentially compelling the government to implement a nationwide lockdown beginning on March 26, 2020 (Shammi et al. 2021). Armed forces were deployed to ensure a full lockdown from 24 March 2020 (Akanda and Ahmed 2020). The total confirmed cases in Bangladesh were 1,353,695 and total number of deaths was 22,652 as of 8 August 2021 (Worldometer 2021). Due to the containment actions taken by the government, daily new COVID-19 cases decreased in January and February 2021. However, due to the lack of COVID-19 awareness to maintain social distancing and new viral variants especially the delta variant, daily confirmed cases have started to increase at an alarming rate (IEDCR 2021). Figure 1 illustrates the number of daily confirmed cases, laboratory tests, and case rates (ratio of confirmed cases to the laboratory tests) during April–May 2021 (DGHS 2021).

The city of Rajshahi is one of the six divisional cities of Bangladesh. It is also called the city of education, since a large number of higher education institutions, civil and

military administrative units, and installations are located in this central western Bangladesh city. It has a population around 1 million. The city is well connected with the rest of Bangladesh by road, rail, and air. There are also large industrial units located in this city. Therefore, apart from socio-economic activities, environmental conditions have also been greatly influenced by the various containment actions taken by the government during the pandemic. The most affected regions were first identified and named as red zones. Strict lockdowns were maintained in those regions. All mass gatherings were prohibited during the lockdown period. Both intradistrict and interdistrict transportation was halted except for emergency transportation. Financial aid worth of BDT 1.04 trillion was offered to homeless and poor people (Akanda and Ahmed 2020). Various social-awareness messages were circulated through online platforms and newspapers. Currently, 117 centers are performing COVID-19 tests among which only one is situated in Rajshahi (Rajshahi Medical College Hospital (Corona_Info_Bangladesh 2021). According to the recent report aired on 5 August 2021, 1,154,243 people have recovered from the disease and 146,509 people were in isolation (Corona_Info_Bangladesh 2021).

The virus outbreak has intensely affected the world economy as well as different environmental aspects (Bherwani et al. 2021; Lai et al. 2020; Mostafa et al. 2021; Sohrabi et al. 2020). Different factors affected by this pandemic include air quality, municipal and medical waste generation, noise, ground and river water quality, etc. (Zambrano-Monserrate et al. 2020). Air pollution is currently a major global concern including Bangladesh. Different lung diseases are the result of excessive air pollution. A survey in 2011 by Mahmood revealed that on average, 15,000 people die every year due to lung diseases caused by excessive air pollution in Bangladesh (Mahmood 2011). Particulate matter

Fig. 1 Daily lab tests, confirmed cases, and case rates in recent 30 days (06 April 2021–06 May 2021) in Bangladesh

(PM), sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), and ozone (O_3) are the main pollutants of troposphere that are hazardous to human health (Islam et al. 2021b; Mostafa et al. 2021). Concentration of NO_2 increases in the atmosphere from the automotive exhausts, soil emission, biomass burning, incomplete hydrocarbon fuel combustion, etc. (Cheng et al. 2012; Richter and Burrows 2002). NO_2 undergoes a complex set of reaction with volatile organic compound (VOC) under sunlight to form tropospheric O_3 . Acid rain is the result of excessive NO_2 in the atmosphere. Adverse effects of NO_2 on human health, especially the lung, have been presented by several researchers (Ackermann-Liebrich et al. 1997; Panella et al. 2000; Smith et al. 2000). Direct relationship between mortality rate and NO_2 emission were illustrated also in different works (Burnett et al. 2004; Stieb et al. 2002). Tropospheric ozone is also responsible for a number of lung diseases. Asthma and lung inflammation are the two major outcomes of O_3 in the atmosphere (Brunekreef and Holgate 2002; Holz et al. 1999; McDonnell et al. 1999; Schelegle et al. 2001). PM is the most harmful for human lung and is measured as the concentration of $\text{PM}_{2.5}$ and PM_{10} . Particles having diameter $2.5\text{ }\mu\text{m}$ or lower fall under $\text{PM}_{2.5}$ and particles having the diameter near $10\text{ }\mu\text{m}$ fall under PM_{10} (Pandey et al. 2005). Recent work has shown the effects of $\text{PM}_{2.5}$ on adverse cardiovascular (Rahman et al. 2021a) and respiratory outcomes (Rahman et al. 2021b) in Dhaka. Incomplete combustion is also responsible for the emission of CO in the atmosphere. It is extremely harmful for the health as it replaces oxygen in the hemoglobin. Apart from the lung diseases, CO also affects the human heart considerably (Blumenthal 2001). SO_2 is responsible for asthma, bronchitis, and other lung diseases (Pandey et al. 2005). The main reason for SO_2 emission in the atmosphere is the burning of high sulfur content fuels. Black carbon has high light absorbing capabilities that makes it one of the major climate active components of atmospheric aerosols (GIOVANNI 2021). It also takes part in radiative transfer that causes severe human health problem (GIOVANNI 2021).

All countries are facing severe economic crises due to the pandemic. Environmental degradation is closely related to the economic conditions (Jiang et al. 2020). Although there is uncertainty on how the economic conditions regulate environmental conditions, it is concluded that economic declines initially result in the significant environmental improvement (Akboostancı et al. 2009; Dutheil et al. 2020; Grossman and Krueger 1991; Ozcan et al. 2020; Panayotou 1993; Xu et al. 2016). However, severe environmental pollution emission reductions were expected worldwide such as in the 2007–09 economic decline (Mostafa et al. 2021). Air

pollutant concentrations during COVID-19 lockdown have been assessed in many studies worldwide and comparison with the pre-COVID-19 state has been presented (Collivignarelli et al. 2020; Dantas et al. 2020; Gautam 2020; Mostafa et al. 2021; Muhammad et al. 2020; Nakada and Urban 2020; Sharma et al. 2020; Sicard et al. 2020; Torkmahalleh et al. 2021). This comparison of air quality between lockdown and pre-lockdown stages have been done in Bangladesh, as well (Islam et al. 2021b, c; Masum et al. 2020; Pavel et al. 2020). Islam et al. (2021b) assessed different air quality variables, such as CO_2 , NO_2 , SO_2 , etc. in Dhaka, Bangladesh only during the lockdown period. They also established relationship between meteorological variables with the air pollutants. Multiple linear regression was also performed to establish relationship between COVID-19 cases and air pollution concentrations. No comparison among air qualities during pre-lockdown, lockdown, and post-lockdown was provided. Islam et al. (2021c) compared the air quality during lockdown period with the pre-lockdown period in Bangladesh. However, the post-lockdown period was not taken into consideration. In the Islam et al.'s (2021b, c) work, they relied on only satellite data for the comparison of air quality. Regression model was employed to establish a relationship between COVID-19 cases and air pollution. Pavel et al. in 2020 compared the air quality of Bangladesh during lockdown period with the period before lockdown (Pavel et al. 2020). They established a relationship between the climate variables and COVID-19 mortality and morbidity rate to identify the favorable condition for spreading of the virus. Hridoy et al. (2021) established a relationship between meteorological variables, such as mean temperature, precipitation, wind speed, and relative humidity with the daily COVID-19 cases. Air quality assessments during the pandemic have been done primarily in Dhaka, the capital of Bangladesh. Chattogram and Khulna cities were also assessed.

Therefore, previous works in Bangladesh did not provide any comparisons of air quality with the post-lockdown period. Statistical analyses including nonparametric tests like Kruskal–Wallis test and pairwise Dunn's 'Q' test along with the comparison of air qualities and meteorological properties among pre-lockdown, lockdown, and post-lockdown period, employed in this research, can be very effective to assess the air quality and meteorological conditions in Bangladesh during the three observation periods. This paper presents a systematic comparison between air quality and meteorological variables during pre-lockdown, lockdown, and post-lockdown periods in Rajshahi, Bangladesh by employing different statistical approaches. Also, the relationships between COVID-19 case rates and air pollutants and meteorological variables were estimated.

2 Research Methodology

2.1 Comparison of Air Quality and Meteorological Variables Between Pre-lockdown, Lockdown, and Post-lockdown Periods

For the comparison of air quality, a number of air pollutants and air quality parameters have been taken into consideration. This work relies on two different data sources, i.e., satellite data and ground-based data from the archive of Ministry of Environment and Forests (MEF), Bangladesh. Satellite data have been found very reliable in recent years due to its reliability and their area of observation is not limited to specific regions (Engel-Cox et al. 2004). Therefore, NO₂ and other gases in atmosphere can be reliably monitored using satellite data (Veefkind et al. 2007). From the time-averaged maps generated from satellite data, comparison between air qualities between different timeline of a single region or comparison between two different places can easily be done. There is only one drawback in satellite monitoring, which is the occasional absence of data due to non-covering band in tropics (Engel-Cox et al. 2004; Veefkind et al. 2007). Time-averaged maps of different pollutants in troposphere have been generated from NASA's GIOVANNI platform (GIOVANNI 2021). From 24° 07' to 24° 43' north latitude and from 88° 17' to 88° 58' east longitude has been considered for inspecting the time-averaged maps, which is the geographical location of Rajshahi city (Banglapedia 2021). For satellite data analysis, lockdown period has been considered from April 2020 to June 2020. Pre-lockdown period and post-lockdown periods have been considered from April 2019 to June 2019 and April 2021 to June 2021, respectively. From the satellite data, time-averaged maps of NO₂, SO₂, O₃, CO, PM_{2.5}, AOD, and black carbon emission in Rajshahi city have been generated. Table 1 represents the summary of the satellite data used in this study.

The major advantage of ground-based continuous air monitoring stations (CAMS) is that they provide numerical specific value at different times for a specific location. Therefore, CAMS data along with satellite data analysis

can be a strong air quality monitoring tool. The Ministry of Environment, Forests and Climate Change (MEFC), Bangladesh regularly monitors different air pollutants in the atmosphere through a number of ground-based CAMS, which are located in different regions of the country (Ministry of Environment 2020). There are 16 CAMS situated at different cities of Bangladesh. CAMS-10 situated at 24.38 N latitude and 88.61E longitude monitors air quality in Rajshahi. At this site, O₃, PM_{2.5}, PM₁₀, SO₂, NO₂, and CO are routinely measured (Ministry of Environment 2020). The ambient air quality standards of Bangladesh set by MEFC are presented in Table 2. For ground-based data analysis also, pre-lockdown, lockdown, and post-lockdown periods have been considered April 2019–June 2019, April 2020–June 2020, and April 2021–June 2021, respectively.

Different meteorological variables, such as average daily temperature, average daily dew point temperature, daily precipitation, and daily average wind speed, were calculated for April to June of 2019, 2020, and 2021 from National Centers for Environmental Information (NCEI) under National

Table 2 Standards of air quality of Bangladesh (MEFC 2020)

Pollutant	Objective	Average
Sulfur dioxide	80 µg/m ³ (0.03 ppm)	Annual
	365 µg/m ³ (0.14 ppm)	24 h (a)
Carbon monoxide	10 mg/m ³ (9 ppm)	8 h (a)
	40 mg/m ³ (35 ppm)	1 h (a)
Ozone	235 µg/m ³ (0.12 ppm)	1 h (d)
	157 µg/m ³ (0.08 ppm)	8 h
Lead (Pb)	0.50 µg/m ³	Annual
NO ₂	100 µg/m ³ (0.053 ppm)	Annual
PM _{2.5}	15 µg/m ³	Annual
	65 µg/m ³	24 h
PM ₁₀	50 µg/m ³	Annual (b)
	150 µg/m ³	24 h (c)

(a) Should not exceed more than once per year. (b) Arithmetic mean should not exceed 50 µg/m³, annually. (c) The number of days per calendar year with a 24 h average of 150 µg/m³ should be less than or equal to one. (d) Number of days per annum with 0.12 ppm maximum hourly average should not exceed one

Table 1 Summary of the air pollutants monitored using the satellite database in this research (GIOVANNI 2021)

Time-averaged maps	Unit	Description
NO ₂ tropospheric column	1/cm ²	30% cloud screened. Daily 0.25 degree, OMI OMNO2d v003
AOD	N/A	Monthly 0.5×0.625 degree, MERRA-2 model M2IMNXGAS v5.12.4
PM _{2.5} column mass density	kg/m ²	Monthly 0.5×0.625 degree, MERRA-2 model M2TMNXAER v5.12.4
O ₃ total column	DU	Daytime/ascending, daily 1 degree, AIRS AIRS3STD v006
CO surface concentration	ppbv	Monthly 0.5×0.625 degree, MERRA-2 model M2TMNXCHM v5.12.4
SO ₂ column mass density	kg/m ²	Monthly 0.5×0.625 degree, MERRA-2 model M2TMNXAER v5.12.4
Black carbon column mass density	kg/m ²	Monthly 0.5×0.625 degree, MERRA-2 model M2TMNXAER v5.12.4

Oceanic and Atmospheric Administration (NOAA) (NOAA 2021). Variation of these meteorological variables throughout the observed periods (lockdown period from April 2020 to June 2020, pre-lockdown period from April 2019 to June 2019, and post-lockdown period from April 2021 to June 2021) have also been observed in this research.

2.2 Statistical Analysis of the Observed Data

Summary statistics have been calculated for the obtained dataset. Mean, standard deviation, 25th percentile, 75th percentile, skewness, kurtosis, coefficient of variation (CV), minimum value, maximum value, range, and median of the data during the pre-lockdown, lockdown, and post-lockdown periods have been determined. The nonparametric Kruskal–Wallis ANOVA on ranks was applied to the air quality and meteorological variables to decide on accepting or rejecting the null hypothesis. Null hypothesis in this analysis states that the means can be considered the same. After performing the Kruskal–Wallis tests, the variables for which statistical differences were observed were further analyzed through Dunn's Q test. This test illustrated which pair of each variable is responsible for significant statistical difference between the periods. In this test, the null hypothesis was that the means of the selected pairs are same.

2.3 Relationship Between Daily COVID-19 Case Rates and the Observed Variables

Daily COVID-19 case rates have been obtained from the website of Directorate General of Health Services, Bangladesh (DGHS 2021). These daily case rates are the ratio of daily confirmed COVID-19 cases and daily conducted laboratory tests. Daily case rates in spite of daily confirmed cases have been taken for better accuracy in analysis. Only the lockdown (April 2020–June 2020) and post-lockdown (April 2021–June 2021) data of the observed variables were taken into consideration for establishing the relationship with the case rates, as no COVID-19 case was there in the pre-lockdown period. Linear regression models were established for each variable, and corresponding coefficients of determination (R^2) and Pearson correlation coefficients (r) were determined.

3 Results and Discussion

3.1 Comparison of Air Qualities and Meteorological Variables

3.1.1 Variation in NO₂ Emissions

Major sources of NO are automotive and industrial emissions (Verma and Kamyotra 2021). Time-averaged maps

of NO₂ total column for pre-lockdown (April 2019–June 2019), lockdown (April 2020–June 2020), and post-lockdown periods (April 2021–June 2021) in Rajshahi, Bangladesh are illustrated in Fig. 2a (GIOVANNI 2021). It can be seen that minimum tropospheric NO₂ has been recorded in Rajshahi during the lockdown period. During both pre-lockdown and post-lockdown periods, the tropospheric NO₂ columns were higher than the lockdown period. Therefore, the improvement in air quality during the lockdown period was not sustainable as NO₂ concentration in atmosphere increased during the post-lockdown period. Mostafa et al. predicted this drastic increase in air pollutant after the lockdown period (Mostafa et al. 2021). Similar increases in air pollution during post-lockdown state in China have been observed (Abnett 2020). In different cities of Bangladesh, considerable reductions of atmospheric NO₂ have been observed in a number of studies (Islam et al. 2021b, c; Metya et al. 2020; Mishra and Kulshrestha 2021; Pavel et al. 2020). Similar situations have been reported worldwide, such as in India (Gautam 2020; Sharma et al. 2020; Verma and Kamyotra 2021), China (Wang and Su 2020), Brazil (Dantas et al. 2020), Egypt (Mostafa et al. 2021), Milan in Italy (Collivignarelli et al. 2020), etc. Similar situations have been observed in the CAMS data. Figure 3a represents mean and standard deviation of 24 h average NO₂ emission in Rajshahi during pre-lockdown (April 2019–June 2019), lockdown (April 2020–June 2020), and post-lockdown periods (April 2021–June 2021) (CASE 2021). It is clear that NO₂ emissions across Rajshahi gradually decreased to a minimum in the lockdown stage and started to increase after the lockdown was lifted. A minimum of 9.37 ppb NO₂ emission has been observed during the lockdown period and then started to increase in the post-lockdown period. Therefore, CAMS data correspond to the time-averaged maps generated from the available satellite data, which has been illustrated earlier.

3.1.2 Variation in Tropospheric Ozone Concentration

Ozone can be found in both stratosphere and troposphere. However, stratospheric ozone is beneficial for human being by preventing harmful UV rays from sun from reaching the earth surface, where tropospheric ozone is harmful to human health. Time-averaged maps of ozone total column in troposphere during lockdown, pre-lockdown, and post-lockdown periods are illustrated in Fig. 2b (GIOVANNI 2021). As the color in the figure shifts from blue to red in the figure, the higher is the tropospheric ozone concentration. Considerable improvement of air quality in terms of ozone in Rajshahi city was observed during the lockdown period as seen in figure (275.8–277.8 DU). No significant variations in ozone concentrations were observed between

Fig. 2 Time-averaged maps of pollutants **(a)** NO₂ total column (cm⁻²), **(b)** O₃ total column (DU), **(c)** CO mass concentration (kg·m⁻²·s⁻¹), **(d)** SO₂ column mass density (kg m⁻²), **(e)** PM_{2.5} column mass density

(kg m⁻³), **(f)** AOD, and **(g)** black carbon column mass density (kg m⁻²) over Rajshahi, Bangladesh during pre-lockdown, lockdown, and post-lockdown periods (GIOVANNI 2021)

Fig. 2 (continued)

pre-lockdown and post-lockdown period. In each period, the values varied from 279.7 DU to 283.6 DU. Therefore, the improvement during lockdown was not sustained. Mean and standard deviation of 8 h average ozone concentration (ppb) over Rajshahi obtained from CAMS are illustrated in Fig. 3b (CASE 2021). O_3 concentrations were also minimal during lockdown period with a mean value of 5.58 ppb. This finding is in contract to most other locations that have been reported in the literature where they

found that O_3 increased during the lockdown period due to the reduced NO emissions and resulting titration (e.g., Santoso et al. 2021). During the post-lockdown period, O_3 concentrations started to increase and produced a mean of 24.47 ppb in post-lockdown stage. These results correspond with the satellite data and the same conclusion can be drawn. As formation of O_3 is closely related to NO_2 , the scenarios for both NO_2 and O_3 have been observed

Fig. 3 Variation of each pollutant **(a)** 24 h average NO₂ emission (ppb), **b** 8 h average ozone concentration (ppb), **c** 8 h average CO emissions (ppm), **d** 24 h average SO₂ concentration (ppb), **e** 24 h

average PM_{2.5} concentration (μg/m³), and **f** 24 h average PM₁₀ concentration (μg/m³) (CASE 2021)

in similar fashion, suggesting that Rajshahi is likely in a NO_x-limited regime (Seinfeld and Pandis 2016).

3.1.3 Variation in Carbon Monoxide Concentrations

Vehicle exhaust is a major source of CO in atmosphere (Pérez-Martínez et al. 2014). It was expected that reduction

in CO emissions would occur, since vehicles were not in operation during the lockdown period. Time-averaged maps of CO mass concentration during pre-lockdown, lockdown, and post-lockdown periods in Rajshahi are presented in Fig. 2c (GIOVANNI 2021). The more the color of the figure shifts from blue to red, the higher the CO concentration is in the atmosphere. It is clear from the figure that CO

concentrations were minimum during the lockdown period and maximum in post-lockdown period. Thus, similar to the previous results, the improvement in air quality in terms of CO was not sustained.

The CAMS 8-h average CO concentrations (mean and standard deviation) in Rajshahi during the lockdown, pre-lockdown, and post-lockdown periods are illustrated in Fig. 3c (CASE 2021). CO concentrations were reduced during the lockdown and reached a minimum value of 0.38 ppb during the lockdown stage. However, emissions started to increase in the post-lockdown period similar to the satellite data. Considerable reductions of CO were observed in different cities of Bangladesh and in other countries of the world (Collivignarelli et al. 2020; Dantas et al. 2020; Nakada and Urban 2020; Sharma et al. 2020; Wang and Su 2020).

3.1.4 Variation in Sulfur Dioxide Concentrations

Figure 2d shows time-averaged maps of SO₂ mass column density over Rajshahi during the pre-lockdown, lockdown, and post-lockdown periods (GIOVANNI 2021). As the color shifts from blue to red in the figure, atmospheric concentrations of SO₂ increase. Slight reductions of SO₂ concentration in atmosphere during lockdown were observed. Although the differences among the three stages were not significant, the reduction in SO₂ concentration during lockdown was observable, and increased pollution during post-lockdown period was also seen. Therefore, the improvement in air quality was not permanent.

CAMS SO₂ data during the observed period were not consistently available. Like other parameters, a minimum SO₂ concentration of 1.9 ppb was observed in the lockdown period, and then, the concentration increased in post-lockdown period, as shown in Fig. 3d. Reduction of SO₂ during lockdown has been observed in several researches worldwide (Collivignarelli et al. 2020; Mahato et al. 2020; Wang et al. 2019).

3.1.5 Variation in Particulate Matter Concentrations

The largest source in Rajshahi is brick kilns (40.2%) with a substantial contribution from biomass burning (Begum et al. 2014) including transboundary pollution from across the IGP (Omami et al. 2017). Lockdown resulted in the reduction of automobile operation, local brick making, and some other industries producing an expected reduction in PM. Time-averaged maps of PM_{2.5} column mass density over Rajshahi during pre-lockdown, lockdown, and post-lockdown periods are illustrated in Fig. 2e (GIOVANNI 2021). The more the color in the figure shifts from blue to red, the higher the concentration of PM_{2.5} is in the atmosphere. Lockdown is clearly responsible for substantial reductions in PM_{2.5} in the atmosphere. Similar to the cases for the other pollutants,

dark reddish spots were visible in the post-lockdown period indicating the maximum concentration of PM_{2.5} in the post-lockdown period. Therefore, the improvement in air quality during lockdown was not sustained and the concentration in post-lockdown period became even higher than the pre-lockdown period.

CAMS data for both PM_{2.5} and PM₁₀ were available in Rajshahi. Figure 3d and Fig. 3e present the mean and standard deviation of PM_{2.5} and PM₁₀ concentration, respectively, in Rajshahi city during the pre-lockdown, lockdown, and post-lockdown periods (CASE 2021). In case of both PM_{2.5} and PM₁₀, reduction of the PM concentrations was observed during the lockdown stage, but they increased in the post-lockdown stage. In the post-lockdown stage, the maximum PM concentration was observed, and higher than the pre-lockdown stage just like the satellite data. The average PM_{2.5} concentration was 26.33 µg/m³ in lockdown, while the average PM₁₀ concentration was 69.60 µg/m³ during the lockdown period. The highest average PM_{2.5} of 88.67 µg/m³ and 201.70 µg/m³ for the average PM₁₀ were measured during the post-lockdown period. Therefore, both the satellite and CAMS data showed that the air quality improvement during the lockdown period was not sustained. Similar results have been observed in different cities throughout the world (Bao and Zhang 2020; Collivignarelli et al. 2020; Dantas et al. 2020; Mahato et al. 2020; Qin et al. 2004; Sharma et al. 2020; Tobías et al. 2020).

3.1.6 Variation in Aerosol Optical Depth (AOD)

The more particles that are present in the atmosphere, the greater will be the blockage of solar radiation. AOD measures this amount of solar radiation intensity being blocked by the particles (ESRL 2021). Therefore, higher AOD reflects higher PM concentrations and will be injurious to human health, visibility, and the ecosystem. Time-averaged maps of AOD over Rajshahi during the pre-lockdown, lockdown, and post-lockdown stages are presented in Fig. 2f (GIOVANNI 2021). The more the color in the figure shifts from blue to red, the higher the AOD is. The minimum AOD was observed during the lockdown stage (0.70–1.75). Comparatively high values of AOD were observed in post-lockdown stage, and they were higher than in the pre-lockdown period (1.40–2.80). Thus, in this case, the improvement was also not permanent. Reductions in the atmospheric aerosol has also been observed in different studies around the world (Bao and Zhang 2020; Collivignarelli et al. 2020; Dantas et al. 2020; Sharma et al. 2020). Due to the unavailability of CAMS data, this work only relies on satellite data for AOD monitoring.

3.1.7 Variation in Black Carbon Concentrations

Time-averaged maps of the black carbon column mass density over Rajshahi during the lockdown, pre-lockdown, and post-lockdown are presented in Fig. 2g. Minimum black carbon concentrations were observed in the lockdown period. However, severe dark reddish spots were clearly visible in post-lockdown period indicating rapid rise of the black carbon concentrations in this period. Thus, the improvement in lockdown was not sustained as was the situation with the other air pollutants in Rajshahi.

3.1.8 Changes in Meteorological Variables

Variations of average temperature, average dew-point temperature, wind speed, and precipitation during the pre-lockdown, lockdown, and post-lockdown periods are shown in Fig. 4 (NOAA 2021). Considerable variation of these meteorological parameters was observed throughout the study. Average temperature was lowest in the lockdown period (83.08°F) and maximum in post-lockdown period (85.84°F) (Fig. 4a). Average dew-point temperature was also minimum in the lockdown period (75.01°F). Variations of average

dew-point temperature are shown in Fig. 4b. Minimum wind speed was observed in the pre-lockdown period (1.895 m/s); while maximum wind speed was observed in the lockdown period (2.07 m/s) (Fig. 4c). Finally, the minimum precipitation was observed in the lockdown stage (average 0.216 cm) and maximum in post-lockdown stage (0.369 cm on average) (Fig. 4d).

3.2 Statistical Analyses

Statistical analyses were performed to assess the characteristics of the obtained data during the pre-lockdown, lockdown, and post-lockdown periods. Mean, standard deviation, 25th percentile, 75th percentile, skewness, kurtosis, coefficient of variation (CV), minimum value, maximum value, range, and median were calculated for the air pollutants and meteorological variables during the pre-lockdown, lockdown, and post-lockdown stages. A summary of the statistical data analysis for the air quality parameters and meteorological variables are presented in Tables 3 and 4, respectively. To determine if the variations of the observed data among the observed periods were statistically different from one another, Kruskal–Wallis ANOVA on rank analyses have been done for each air pollutant and meteorological

Fig. 4 Variation of (a) average temperature (°F), b dew-point temperature (°F), c average wind speed (m/s), and d precipitation (cm) during pre-lockdown, lockdown, and post-lockdown period (NOAA 2021)

Table 3 Summary of the statistical data of the air pollutants during the observed periods

Observed period	Statistical parameters	NO ₂ (ppb)	O ₃ (ppb)	CO (ppm)	SO ₂ (ppb)	PM _{2.5} (µg/m ³)	PM ₁₀ (µg/m ³)
Pre-lockdown period (April 2019–June 2019)	Mean	12.97	30.80	0.76	3.03	74.07	98.67
	Standard deviation	2.51	1.73	0.04	0.57	4.38	8.5
	25th percentile	11.9	29.9	0.74	2.8	72.1	95.5
	75th percentile	14.4	31.6	0.78	3.4	76.4	103.5
	Skewness	−1.06	0.98	1.29	−1.28	−0.64	−1.49
	Kurtosis	N/A	N/A	N/A	N/A	N/A	N/A
	Coefficient of variation, CV (%)	19.36	5.63	5.45	18.9	5.92	8.62
	Min value	10.2	29.3	0.73	2.4	69.4	89.0
	Max value	15.1	32.7	0.81	3.5	78.1	105.0
	Range	4.9	3.4	0.08	1.1	8.7	16.0
	Median	13.6	30.4	0.75	3.2	74.7	102.0
Lockdown period (April 2020–June 2020)	Mean	9.37	5.58	0.38	1.90	26.33	69.60
	Standard deviation	0.99	1.4	0.16	0.13	4.05	15.3
	25th percentile	9.1	4.8	0.32	1.8	24.1	60.8
	75th percentile	9.9	6.2	0.47	2.00	28.1	74.7
	Skewness	−1.68	0.68	−1.26	−0.67	1.07	1.68
	Kurtosis	N/A	N/A	N/A	???	N/A	N/A
	Coefficient of variation, CV (%)	10.5	25.50	42.35	6.90	15.38	21.98
	Min value	8.2	4.3	0.20	1.76	22.9	59.5
	Max value	10.0	7.1	0.51	2.02	30.8	87.2
	Range	1.8	2.8	0.31	0.26	7.9	27.7
	Median	9.9	5.4	0.43	1.92	25.3	62.1
Post-lockdown period (April 20, 201–June 2021)	Mean	14.47	24.47	1.23	3.39	88.67	201.70
	Standard deviation	3.30	2.58	0.09	0.57	3.75	19.59
	25th percentile	12.8	23.2	1.18	3.1	87.3	192.3
	75th percentile	16.1	25.9	1.27	3.7	90.8	211.8
	Skewness	0.09	−0.74	0.84	0.29	−1.54	−0.35
	Kurtosis	N/A	N/A	N/A	N/A	N/A	N/A
	Coefficient of variation, CV (%)	22.81	10.53	7.03	16.71	4.23	9.71
	Min value	11.2	21.7	1.15	2.8	84.4	181.4
	Max value	17.8	26.8	1.32	4.00	91.4	220.5
	Range	6.6	5.1	0.17	1.2	7.0	39.1
	Median	14.4	24.9	1.21	3.4	90.2	203.2

variable. The null hypothesis in this analysis states that the means of the data taken at different stages can be considered equal. Therefore, from these nonparametric tests, decision on accepting or rejecting null hypothesis were taken. The Kruskal–Wallis tests for air quality parameters and meteorological variables are summarized in Table 5. After performing the Kruskal–Wallis tests, the variables which showed significant statistical difference among the observed periods were analyzed for pairwise differences using Dunn's method (Dunn 1964). In this work, O₃, CO, PM_{2.5}, PM₁₀, average temperature, and average dew-point temperature showed significant statistical difference between the observed periods in the Kruskal–Wallis tests. The null hypothesis in the Dunn test was that the rank sums of the selected pair are the same.

The Dunn's test results are presented in Table 6. From these analyses, the pre-lockdown and lockdown pair for ozone and lockdown and post-lockdown pairs for CO, PM_{2.5}, PM₁₀, average temperature, and average dew-point temperature are the main pairs showing statistically significant differences.

3.3 Relationship Between COVID-19 Case Rates and Air Pollution Parameters, as well as Meteorological Variables

Since COVID-19 directly affects the human lung, it was expected that high air pollution would be associated with higher daily COVID-19 case rates (Islam et al. 2021b). Instead of using the daily confirmed case numbers, the ratio

Table 4 Summary of the statistical data of the meteorological properties during the observed periods

Observed period	Statistical parameters	Average temperature (°F)	Dew-point temperature (°F)	Average wind speed (m/s)	Precipitation (cm)
Pre-lockdown period (April 2019–June 2019)	Mean	85.73	79.07	1.89	0.32
	Standard deviation	3.34	2.09	0.68	0.98
	25th percentile	83.8	77.9	1.40	0
	75th percentile	88.1	80.4	2.30	0
	Skewness	−0.77	−0.39	−0.08	4.21
	Kurtosis	0.26	0.03	−0.37	19.54
	Coefficient of variation, CV (%)	3.90	2.64	35.8	302
	Min Value	76.7	73.6	0.70	0
	Max Value	90.4	82.8	3.40	5.28
	Range	13.7	9.20	2.70	5.28
	Median	86.4	79.0	1.90	0
Lockdown period (April 2020–June 2020)	Mean	83.08	75.01	2.07	0.22
	Standard deviation	3.64	5.69	1.28	0.49
	25th percentile	80.6	72.15	1.50	0
	75th percentile	86.0	79.45	2.28	0.20
	Skewness	−0.52	−1.07	4.65	3.27
	Kurtosis	−0.59	0.74	31.37	12.29
	Coefficient of variation, CV (%)	4.38	7.58	61.91	228
	Min value	74.5	59.2	0.70	0
	Max value	89.2	82.0	11.40	2.9
	Range	14.7	22.8	10.70	2.9
	Median	84.1	76.3	1.80	0
Post-lockdown period (April 2021–June 2021)	Mean	85.84	79.10	1.90	0.37
	Standard deviation	3.37	2.20	0.68	0.98
	25th percentile	82.2	77.6	1.50	0
	75th percentile	88.5	80.7	2.50	0.26
	Skewness	−0.69	−0.31	−0.05	4.12
	Kurtosis	−0.26	0.09	−0.57	19.36
	Coefficient of variation, CV (%)	3.93	2.78	35.81	264.74
	Min value	77.8	73.4	0.60	0
	Max value	90.4	83.2	3.30	5.35
	Range	12.6	9.8	2.70	5.35
	Median	86.3	79.1	1.80	0

of daily confirmed cases to the number of daily laboratory tests were used to provide better accuracy in the regression model. The relationships between NO_2 , O_3 , CO , SO_2 , $\text{PM}_{2.5}$, and PM_{10} with the confirmed COVID-19 case rates in the form of linear regression are shown in Fig. 5. Very weak relationships were observed between case rates and the different air pollutants. Positive association of case rates with PM_{10} were observed in Fig. 5f ($R^2=0.0016$). Positive associations with case rates have also been reported in previous studies (Islam et al. 2021b; Martelletti and Martelletti 2020; Ogen 2020). However, negative relations were observed for NO_2 ($R^2=0.0842$), O_3 ($R^2=0.016$), CO ($R^2=0.0566$), SO_2 ($R^2=0.0285$), and $\text{PM}_{2.5}$ ($R^2=0.0292$). Although the

government declared the nationwide lockdown from April 2020 to June 2020, different containment actions continued to be implemented up to December 2020. Thus, case rates became lower in the months of January 2021 and February 2021. However, in that period, air pollution was very high similar to when the lockdown was lifted. Additionally, a new variant of COVID-19 was observed in Bangladesh in March 2021 (IEDCR 2021). People began to no longer maintaining social distancing. Hence, COVID-19 case rates again started to increase as well as the mortality rate, although the pollution levels were consistent with the previous months. For these reasons, negative slopes were obtained for rest of the variables. Summary of the slopes, intercepts, coefficient

Table 5 Kruskal–Wallis test results for different air pollutants and meteorological variables

Pollutant	Period	Sample size	Sum of rank	Average rank	H-statistic Value	Chi-square	<i>p</i> value	Decision on null
NO ₂	Pre-lockdown	3	18	6	5.60	5.99	0.061	Fail to reject
	Lockdown	3	6	2				
	Post-lockdown	3	21	7				
O ₃	Pre-lockdown	3	24	8	7.20	5.99	0.027	Reject null
	Lockdown	3	6	2				
	Post-lockdown	3	15	5				
CO	Pre-lockdown	3	15	5	7.20	5.99	0.027	Reject null
	Lockdown	3	6	2				
	Post-lockdown	3	24	8				
SO ₂	Pre-lockdown	3	18	6	5.60	5.99	0.061	Fail to reject
	Lockdown	3	6	2				
	Post-lockdown	3	21	7				
PM _{2.5}	Pre-lockdown	3	15	5	7.2	5.99	0.027	Reject null
	Lockdown	3	6	2				
	Post-lockdown	3	24	8				
PM ₁₀	Pre-lockdown	3	15	5	7.20	5.99	0.027	Reject null
	Lockdown	3	6	2				
	Post-lockdown	3	24	8				
Average temperature	Pre-lockdown	37	3719	100.51	21.54	5.99	2.10×10^{-5}	Reject null
	Lockdown	90	6021.5	66.91				
	Post-lockdown	37	3789.5	102.42				
Dew-point temperature	Pre-lockdown	37	3767.5	101.82	23.01	5.99	1.01×10^{-5}	Reject null
	Lockdown	90	5973.5	66.37				
	Post-lockdown	37	3789	102.41				
Average wind speed	Pre-lockdown	37	3107	83.97	0.05	5.99	0.975	Fail to reject
	Lockdown	90	7369.5	81.88				
	Post-lockdown	37	3053.5	82.53				
Precipitation	Pre-lockdown	37	2761	74.62	1.56	5.99	0.459	Fail to reject
	Lockdown	90	7751	86.12				
	Post-lockdown	37	3018	81.57				

of determination, and Pearson coefficient ‘*r*’ for different pollutants and the meteorological variables (average temperature, dew-point temperature, average wind speed, and precipitation) obtained during regression analysis are presented in Table 7.

The relationships between meteorological variables and COVID-19 case rates are shown in Fig. 6. All the meteorological variables showed weak positive correlations with COVID-19 case rates. Coefficient of determinations for temperature, wind speed, dew-point temperature, and precipitation have been observed 0.0646, 0.0098, 0.5323, and 0.0138, respectively. Positive correlations for the different meteorological variables with COVID-19 transmission rates have been found in the previous studies throughout the world (Bashir et al. 2020; Islam et al. 2021a; Kafieh et al. 2020; Pedrosa 2020; Tosepu et al. 2020), although some exceptions were also observed (Liu et al. 2020; Zhu et al. 2020). Therefore, there exists a weak relationship between

meteorological variables in Rajshahi and daily confirmed COVID-19 case rates.

3.4 Influence of COVID-19 on Different Factors in Bangladesh

The most important sector that has been greatly affected by the pandemic is the economy. All countries have experienced severe economic crises during the pandemic (Kumar et al. 2020; Mostafa et al. 2021). Reduction in the operation of industries, transportation of workers and goods, etc. are the prime reasons for the economic crisis worldwide (Fernandes 2020; McKibbin and Fernando 2020). Like other countries, Bangladesh has been facing several challenges due to the reduction of industrial activities during the lockdown. Since travel to and from China was stopped during the lockdown, some large projects requiring the aid of China (Padma rail link, Karnaphuli road tunnel, Padma bridge) were halted

Table 6 Dunn's Q-test results for the variables that showed significant statistical difference

Variables	Pair	Q value	Critical value for $\alpha = 0.05$	Decision on null
O_3	Pre-lockdown and lockdown	2.683	2.394	Reject null
	Lockdown and post-lockdown	1.342	2.394	Fail to reject
	Pre-lockdown and post-lockdown	1.342	2.394	Fail to reject
CO	Pre-lockdown and lockdown	1.342	2.394	Fail to reject
	Lockdown and post-lockdown	2.683	2.394	Reject null
	Pre-lockdown and post-lockdown	1.342	2.394	Fail to reject
PM _{2.5}	Pre-lockdown and lockdown	1.342	2.394	Fail to reject
	Lockdown and post-lockdown	2.683	2.394	Reject null
	Pre-lockdown and post-lockdown	1.342	2.394	Fail to reject
PM ₁₀	Pre-lockdown and lockdown	1.342	2.394	Fail to reject
	Lockdown and post-lockdown	2.683	2.394	Reject null
	Pre-lockdown and post-lockdown	1.342	2.394	Fail to reject
Average temperature	Pre-lockdown and lockdown	3.623	2.394	Reject null
	Lockdown and post-lockdown	3.829	2.394	Reject null
	Pre-lockdown and post-lockdown	0.173	2.394	Fail to reject
Average dew-point temperature	Pre-lockdown and lockdown	3.823	2.394	Reject null
	Lockdown and post-lockdown	3.886	2.394	Reject null
	Pre-lockdown and post-lockdown	0.053	2.394	Fail to reject

(Begum et al. 2020). Vital economic lifelines in Bangladesh, such as agriculture, service sector, and industrial sector, were greatly affected by the lockdown. About BDT 570 million (7 million USD) loss incurred daily in the dairy industry alone as millions of liters of milk were left unsold during the lockdown (Begum et al. 2020). China annually imports about 70% of Bangladesh's crabs, and these shipments were stopped during the pandemic (Khaled 2020). The garment sector experienced losses of USD 2.6 billion during the lockdown period (Begum et al. 2020). Raw materials for pharmaceutical production are generally imported from India and China, which were hampered during the pandemic. Therefore, shortages of various medicines were observed during the lockdown. The price of hand sanitizers and face masks increased about 400% in the lockdown that caused great problems to the mass of people (Dhaka-Tribune 2020). A reduction of USD 3 billion in GDP (Gross Domestic Product) was predicted by Asian development bank (Begum et al. 2020). Tourism also contributes a significant portion of country's GDP (about 4.4%) (World_Bank 2019). The government closed all the tourist spots in the country during the lockdown. As a result, in April 2020 alone, the tourism industry lost BDT 15 billion (180 million USD) and about 5000 people have lost their job in this sector (TOAB 2020).

Bangladesh declared an educational vacation on March 16, 2020 shutting all schools, colleges, and universities with an expectation to start 5 April, 2020 (MOE 2021). However, as the COVID scenario worsened, educational institutions were still closed as of 27 July 2021. Limited classes were

conducted through online platforms to keep the students up to date. The government also allocated funds for poor people, so that they can also take part in online classes. A recent study by Begum et al. (2020) revealed that large numbers of students at the graduate level were suffering from excessive stress and anxiety issues as their graduation completion has been delayed. Huge social impacts have been observed in Bangladesh during the lockdown stage. Social panic and hatred were transmitted throughout the country through social media due to the transmission of different false or fake information. People stayed most of the time in their home enjoying leisure, which triggered greater use of social media. Therefore, rumors were rapidly transmitted creating havoc. A surge in crime and poverty were also noted in the lockdown period. Research showed that domestic violence against women increased drastically during the lockdown period and many women were suffering from anxiety disorder (Banna et al. 2020).

The lockdown period triggered the consumption of more food as observed by different studies (Mostafa et al. 2021; Nile 2020). The high food consumption is responsible for high waste generation and obesity. The authority took necessary steps by decreasing the waste collection interval time. However, both affected patients who did not test for the disease and normal people dumped the waste in the same site. This co-mixing of material was harmful for the waste collector and many workers were affected while handling these wastes. Again, generation of medical wastes increased drastically during the

Fig. 5 Correlation between COVID-19 case rates and each pollutant: (a) 24 h average NO₂ emission (ppb), b 8 h average ozone concentration (ppb), c 8 h average CO emissions (ppm), d 24 h average SO₂

concentration (ppb), e 24 h average PM_{2.5} concentration (μg/m³), and f 24 h average PM₁₀ concentration (μg/m³), obtained from CAMS over Rajshahi city, Bangladesh

pandemic. Improper biomedical waste management is responsible for around 5.2 million deaths in Bangladesh every year (Rahman et al. 2020). In Dhaka alone, 206 tons of medical wastes are being generated daily (Rahman et al. 2020). These wastes are being handled improperly and by untrained workers without any safety gears, leading to increased virus transmission among workers. These wastes are sometimes dumped in unauthorized and unprotected areas, affecting human health, and increasing the COVID-19 transmission rate. Therefore, a proper

waste management strategy is necessary to overcome this situation. High environmental noise is detrimental to human health, and can be responsible for cardiac arrest, hypertension, and other diseases (Mostafa et al. 2021; Muzet 2007; Zambrano-Monserrate et al. 2020). During the lockdown period, many industries and transportation were not in operation. Thus, considerable reduction of noise was observed. Similar cases were observed in different countries during the lockdown (Ahramonline 2020; Masrawy 2020).

Table 7 Summary of intercepts, slopes, coefficients of determination, and Pearson 'r' for different pollutants and meteorological variables from regression analysis

Pollutants	Intercept	Slope	Coefficient of determination (R^2)	Pearson 'r'
NO ₂	19.5740	-0.4256	0.0842	0.2901
O ₃	15.4400	-0.0625	0.0160	0.1264
CO	16.5790	-2.5855	0.0566	0.2378
PM _{2.5}	15.9890	-0.0259	0.0292	0.1709
PM ₁₀	14.1240	0.0028	0.0016	0.0397
SO ₂	17.0950	-0.9810	0.0285	0.1687
Average temperature	-17.9660	0.3839	0.0646	0.2542
Dew-point temperature	-45.8410	0.7884	0.5323	0.7296
Average wind speed	13.2420	0.4930	0.0098	0.0988
Precipitation	13.9790	0.9968	0.0138	0.1176

Fig. 6 Correlation between COVID-19 case rates and meteorological phenomena: **(a)** average temperature (°F), **(b)** dew-point temperature (°F), **(c)** average wind speed (m/s), and **(d)** precipitation (cm) over Rajshahi city, Bangladesh

4 Conclusions

This study found that air quality and other socio-economic factors have been greatly affected by COVID-19 lockdown period. These other factors included the economy, waste management scenario, environmental noise, etc. Both positive and negative impacts of the viral spread containment

actions taken by the government have been observed. Negative impacts of the lockdown included economic losses, educational vacation for prolonged periods, difficulties in handling municipal and medical wastes, etc.

Conversely, positive impacts have been observed for environmental pollution, especially air pollution. Considerable improvements of different air quality parameters, such as NO₂, O₃, CO, SO₂, PM_{2.5}, PM₁₀, AOD, and black carbon

emissions, have been observed during lockdown period. To assess changes in these variables, satellite data and CAMS data from Rajshahi were used. However, the air quality improvements were not sustained with substantial increases in all the air pollutants being observed in the post-lockdown period. The lockdown period resulted in large economic crises in Bangladesh. Thus, the government was unable to invest more for clean air development and the gains during the lockdown were lost. Statistical analyses showed statistically significant differences in the measured variables among the lockdown, pre-lockdown, and post-lockdown stages.

Relationships between daily confirmed case rates and the different air pollutants were estimated using linear regression. PM_{10} had a weak positive association with case rates, while the others showed weak negative associations. Variations of different meteorological variables, such as average temperature, dew-point temperature, average wind speed, and precipitation with daily COVID-19 case rates, were also presented in this study. All the meteorological variables showed weak positive correlations with the COVID case rates. A drastic deterioration of air quality in Rajshahi city was observed in post-lockdown stage. Thus, it is recommended that the government takes necessary steps and applies strict laws to protect the environment, and provides a balance between economic growth and a sustainable environment. It is expected that this study could serve as the basis for future research of the assessment of environmental and meteorological behavior in relation to COVID-19 for other parts of the world.

Acknowledgements Authors would like to acknowledge the Department of Mechanical Engineering, Rajshahi University of Engineering & Technology, Bangladesh for supporting the research work. The authors are also thankful to the Ministry of Environment, Forests and Climate Change, Bangladesh for providing the air quality data.

Author Contributions All the authors have contributed substantially to the work reported. All authors have read and agreed to the published version of the manuscript. MMA: conceptualization, literature review, writing (original draft), writing (review and editing), and visualization. MEH: conceptualization, data analysis, writing (original draft), writing (review and editing), and supervision. SR: data curation and writing (review and editing). PKR: writing (original draft) and data curation. FA: conceptualization, data analysis, and writing (review and editing). MMR: conceptualization, data analysis, and writing (review and editing). MMR: data analysis and writing (review and editing). PKH: conceptualization, data analysis, supervision, and writing (review and editing).

Funding This research received no external funding.

Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflicts of Interest The authors declare no conflict of interest.

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