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Spatio-temporal variability of urban particulate matter using GIS: a lesson from COVID-19 restrictions

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ABSTRACT

BACKGROUND AND OBJECTIVES: Air pollution and its associated health impacts have become a major concern worldwide, particularly in developing countries. Anthropogenic activities were significantly reduced during the COVID-19 pandemic, allowing for the opportunity for source reduction of air pollutants. A number of studies have been conducted in Dhaka, but most of them are concentrated on a single ground-monitoring station, making it impossible to draw a comprehensive pollution scenario for the entire city. In contrast, this study evaluated the spatio-temporal changes of urban Particulate Matters (PM) in 70 locations from five different land use categories. Hence, this study investigated the influence of the COVID-19 pandemic on PM1 (aerodynamic diameter ≤1 µm), PM2.5 (aerodynamic diameter ≤2.5 µm) and PM10 (aerodynamic diameter ≤10 µm) concentration during three specific time frames: November 2019 (Pre-lockdown), April 2020 (During lockdown), and November 2020 (Post-lockdown).

METHODS: The data were collected through portable air quality meter (AEROQUAL 500) during lockdown (April 2020) and post-lockdown (November 2020) period. Data set of pre-lockdowns (November 2019) was collected from Center for Atmospheric Pollution Studies (CAPS). The Tukey's Post Hoc Multiple Comparison Test was conducted using Statistical Package for the Social Sciences (SPSSv26) to address the significant changes in air quality between the periods. Additionally, the GIS (Geographical Information System) platform was used to see the spatial and temporal variations of PMs over the city.

FINDINGS: The study found that average ground level PM1, PM2.5 and PM10 concentration reduced by 75.1, 75.4, 69.6% and 41.1, 32.6, 29.2% respectively during lockdown compared to pre-lockdown and post-lockdown periods. Moreover, the reduction during lockdown was significant at α=0.05 level. The highest reduction was seen in residential areas from the pre-lockdown to lockdown period, whereas in the lockdown to post-lockdown phase that was found in the industrial areas. Interestingly, the northern part of Dhaka city was less polluted than the southern part in all three studied periods. Besides, the Dhaka city dwellers enjoyed comparatively good quality air in lockdown.

CONCLUSION: This study suggested that land use-based source apportionment is required to eliminate the particulate concentration from Dhaka city. Besides, 24 hours continuous data is also important to understand the interaction between particulate concentration and climatic forces. Promoting cleaner transportation options, such as electric vehicles and public transportation is recommended as a means of reducing vehicle emissions. Furthermore, governments could consider implementing emissions regulations, setting limits on emissions, or mandating the use of cleaner fuels and technologies to reduce industrial pollution.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
35	8	5

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INTRODUCTION

Air pollution has become a major threat worldwide in terms of human health risks and economic loss. Since the industrial revolution, the demand for fossil fuels has increased significantly which is the major contributor to the increase in air pollutants in the global atmosphere (Goyal *et al.,* 2023). Most of the south Asian countries (18 out of 20) are suffering from severe particulate pollution while vehicle exhaust and industrial emissions are the dominant sources (Pushpawela *et al.,* 2023; Gunasekara and Waraketiya, 2022). The different sized particulate matter (particularly PM_1, $PM_{2.5}$ and PM_{10}) concentration is more dangerous since it creates severe public health issues (Shang *et al.,* 2018). A number of epidemiological studies have found strong relationships between $PM_{2.5}$ and premature death (Zhao *et al.,* 2017; Shang *et al.,* 2018). Study revealed that each 10 μg/m^3 increase in $PM_{2.5}$ concentration leads to a 0.23% increase in mortality from respiratory diseases (Chen *et al.,* 2019). In 2019, Dhaka was listed as the second most polluted city in the world just after New Delhi in terms of $PM_{2.5}$ exposure (Majumder *et al.,* 2021). A number of sources contribute to airborne particulate matter in Dhaka city where brick kilns are one of them. Most of the kilns are located in the north and west of the city, influencing as a substantial contributor to triggering the $PM_{2.5}$ concentration, particularly during the winter season (Nayeem *et al.,* 2019; Rana *et al.,* 2020). Besides, uncontrolled industrial emission is another major source of $PM_{2.5}$ in several areas of the city (Adhikari *et al.,* 2023). Vehicle exhaust, particularly that emitted by diesel-powered buses and heavy trucks, has also been identified as a significant source (Razib *et al.,* 2020). More recently, another newly added significant source of particulate matter in Dhaka city is the construction of Bus Rapid Transit (BRT) and Mass Rapid Transit (MRT) (Nayeem *et al.,* 2020). Despite the multiple detrimental health and economic consequences of the COVID-19 epidemic, it had encouraging results in lowering air pollution due to restrictions on social and economic activities (Dutheil *et al.,* 2020; Masum and Pal, 2020). COVID-19 lockdown could be inferred as an effective control measure for air pollution in the urban areas from several researches of various parts of the world (both developed and developing countries) (Majumder *et al.,* 2021; Abdullah *et al.,* 2020; Bera *et al.,* 2021). These studies were focused on different air pollutant emissions including $PM_{2.5}$ in lockdown. Most of the studies were conducted through satellite observations (Dutheil *et al.,* 2020; Nakada *et al.,* 2020; Tobías *et al.,* 2020; Nadzir *et al.,* 2020) though very few researchers also utilized ground level data (Kayes *et al.,* 2019). The scopes of these studies were pollution monitoring, source identification, policy recommendation in terms of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and O_3. Xu *et al.,* (2020) recorded 30.1% less air pollution in China during the pandemic lockdown compared to the normal situation. He also mentioned that the Air Quality Index (AQI) in Wuhan, Jingmen, and Enshi decreased drastically in 2020 compared to 2017-2019. Abdullah *et al.,* (2020) showed that $PM_{2.5}$ concentration was reduced by 58.4% in the capital of Malaysia. A sharp reduction of $PM_{2.5}$ had also been observed in Delhi, Kolkata and Kathmandu by 45.44%, 34.08% and 37.42% respectively in 2020 compared to 2019 (Majumder *et al.*, 2021).

Purpose, Objectives and Hypothesis

Several studies worldwide have shown that anthropogenic activities significantly contribute to air pollution, but the COVID-19 pandemic led to a temporary shutdown of these activities resulting in a reduction of air pollutants in the atmosphere. However, most of the ground-based studies (Islam and Chowdhury, 2021; Pal and Masum, 2021; Masum and Pal, 2020) are concentrated on a small number of sampling locations for each city which was unable to draw the holistic pollution scenario of an urban area (Majumder et al., 2021; Hossain et al., 2019). Hence, it is important to consider a large number of sampling locations in a particular city to get a comprehensive pollution status. So, this study focused on 70 locations of Dhaka city and examined the impact of lockdown measures on air pollution levels during three specific time frames: November 2019 (Pre-lockdown), April 2020 (During lockdown), and November 2020 (Post-lockdown). Therefore, the main purpose of this study was to investigate the influence of the COVID-19 pandemic on urban Particulate Matters (PMs) in the context of different land use categories in Dhaka city. The specific objectives to achieve the purpose were; a) To evaluate the status of PM_1, $PM_{2.5}$ and PM_{10} concentration during lockdown compared to pre-lockdown and post-lockdown period, b) To compare the fluctuations in pollution levels among different land use categories during selected time frames, c) To explore the spatio-temporal variability of particulate matter based on 70 locations over the Dhaka city, and d) To examine the AQI and compare it among three different phases of lockdown. The study assumed that the concentration of PM would be significantly lower during the lockdown period compared to pre-lockdown and post-lockdown periods. Additionally, the study predicted that industrial areas might have higher pollution levels compared to other land categories in all time frames. Moreover, the north and south part of Dhaka city might have different pollution scenarios in the studied period. Ultimately, the implementation of lockdown might help to improve the AQI of the city. This study had been carried out in the Dhaka city in 2020.

MATERIALS AND METHODS

Area Selection

The Department of Environment (DoE), had classified Dhaka city into five types of land use including 70 places based on exposure duration to monitor noise levels (in Environment Conservation Rules 1997, Schedule 4), namely: 1. Sensitive area, 2. Residential area, 3. Commercial area, 4. Industrial area, and 5. Mixed area in 2017 under a noise pollution survey in 8 divisional cities of Bangladesh (DoE, 2006). However, DoE identified 10 places for sensitive areas (educational institutions, mosque and hospital) since people stay for a short period of time in these locations. On the other hand, 20 places were chosen for residential areas because individuals spend the majority of their time at home, while 15 places were for commercial areas. Furthermore, 20 locations were selected from mixed areas because those areas were the combination of other two or more land uses. Finally, DoE identified only 5 locations at industrial areas in Dhaka city since all major industrial hubs were outside of the town. This study followed these 70 stations based on land use for the particulate matter sampling (Fig.1).

Data Collection

The Aeroqual 500 series, a laser-based sensor that utilizes the light scattering method to detect particle size and measure concentration, was used to measure particle concentration in the ambient environment. Data was collected for the month of April 2020 (during lockdown) and November 2020 (post-lockdown) for each parameter at each location,

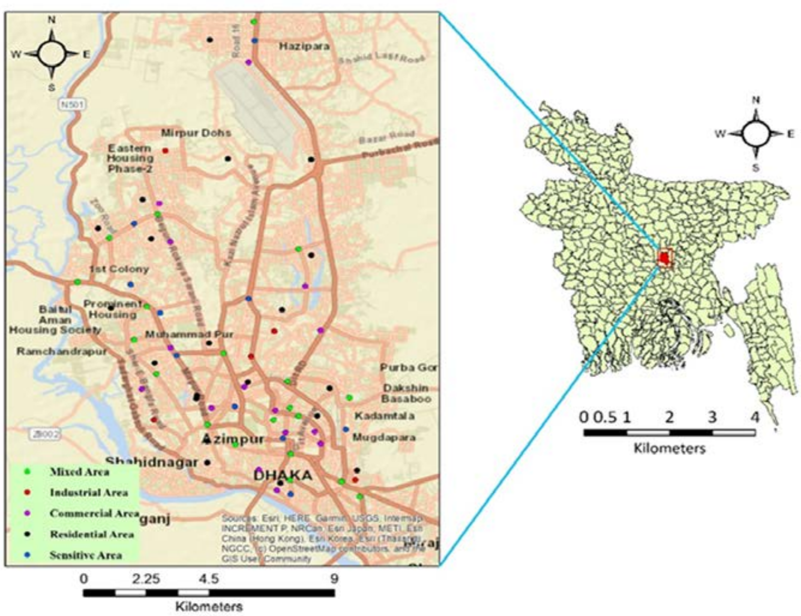

Fig. 1: The map in left side showing the sampling locations in different land use categories of Dhaka city and the index map at the right side showing the location of Dhaka city within a Sub-district map of Bangladesh

and data for November 2019 (pre-lockdown) was obtained from the Center for Atmospheric Pollution Studies (CAPS), Department of Environmental Science, Stamford University Bangladesh. The data collection process was the same for all three-time frames, with the Aeroqual monitor placed on a tripod about 5 feet above the ground, recorded concentration automatically every hour on an SD card, and later exported the data in Comma-Separated Value (CSV) format. The monitor displayed the mean value of each particle size in ppm, which was later converted to micrograms. All three particles were recorded in one sensor, which required a 3-minutes warm-up period before recording data, and the sensor was factory calibrated prior to sampling.

Data Analysis

For the specified time frames, the mean and standard deviation were calculated for each particle size, and a whisker box plot was utilized to visualize the range of the data, outliers, and the symmetry or skewness of the distribution. Tukey's Post Hoc Multiple Comparison test was employed to determine the significance of the differences in PM_1, $PM_{2.5}$, and PM_{10} concentrations between the months in a specific land category, with a p-value of 0.05. All the statistical analysis was conducted using SPSSv26 software. Besides, all attribute data of 70 sampling locations were synchronized in ArcGIS 10.8 which is a professional software popular in the GIS (Geographical Information System) platform. Then, to estimate values at unsampled locations the Inverse Distance Weighting (IDW), a spatial interpolation method, was used. Finally, geo-spatial mapping was done to visualize all spatio-temporal analysis.

AQI Calculation

The Air Quality Index (AQI) typically reflects the degree of air cleanliness and focuses on the assessment of the effects of air pollution on human health and provides recommendations for the portion of the population that might be sensitive to pollution (Xu *et al.*, 2020). This study followed the U.S. Environmental Protection Agency's (EPA) AQI system to categorize air quality (Table 1). To determine the daily (24hr) PM_{10} and $PM_{2.5}$ based AQI for assigning categories the following equation (Eq. 1) (USEPA, 2012) was used.

$$I_P = \frac{(I_{HI} - I_{LO})}{(BP_{HI} - BP_{LO})}(C_P - BP_{LO}) + I_{LO} \quad (1)$$

Where, I_P = Index value for pollutant
C_P = Rounded concentration of pollutant
BP_{HI} = Higher breakpoint value of C_P
BP_{LO} = Lower breakpoint value of C_P
I_{HI} = Index breakpoint value of BP_{HI}
I_{LO} = Index breakpoint value of BP_{LO}

The breakpoints for PM_{10} and $PM_{2.5}$ concentrations along with the ranges of AQI category used in this study have been stated in Table 1.

RESULT AND DISCUSSIONS

Descriptive Analysis

The ground level PM (PM_1, $PM_{2.5}$ and PM_{10}) data were collected in three periods to observe the influence of COVID-19 lockdown on quality of air in Dhaka city. Generally, these pollutants originate from fossil fuel combustion, biomass burning, fires, vehicle emission, construction activities etc. But many of these pollution sources were inactive during lockdown, since Bangladesh imposed strict mobility restrictions to prevent the spread of the COVID-19 outbreak. From this study, it was evident that PM concentration had been reduced drastically during the lockdown period compared to pre-lockdown and

Table 1: Break points of PM_{10} and $PM_{2.5}$ in μg/m³ with AQI category (USEPA, 2012)

Break Points of PM_{10}	Break Points of $PM_{2.5}$	AQI	Category
0-54	0-12	0-50	Good
55-154	12.1-35.4	51-100	Moderate
155-254	35.5-55.4	101-150	Unhealthy for sensitive group
255-354	55.5-150.4	151-200	Unhealthy
355-424	150.5-250.4	201-300	Very unhealthy
425-504	250.5-500.4	301+	Hazardous

post-lockdown (Fig. 2) span. In terms of PM_1, the average concentration was 155.9, 38.2 and 64.80 μg/m³ in November 2019, April 2020 and November 2020 respectively. On the other hand, the $PM_{2.5}$ concentration was 298.2, 73.1 and 108.8 μg/m³ and PM_{10} concentration was 333.4, 98.2, and 141.2 μg/m³ in November 2019, April 2020 and November 2020 accordingly (Table 2).

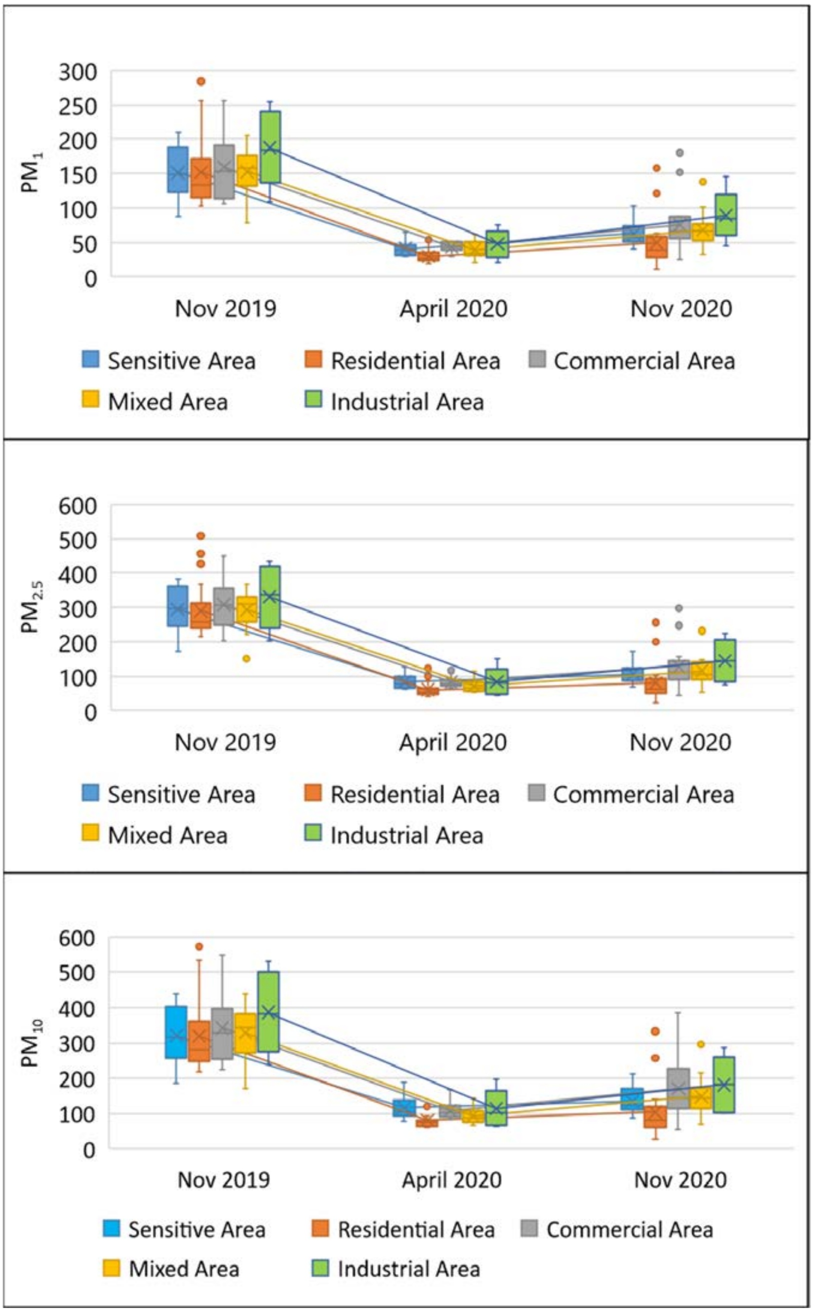

Fig. 2: The deviation of PM_1, $PM_{2.5}$ and PM_{10} concentration (μg/m³) during the three phases of lockdown

Table 2: Descriptive statistics of PM concentration (µg/m^3) in different study period

Year	Statistics	PM_1	$PM_{2.5}$	PM_{10}
	Mean	155.9	298.20	333.4
	Std. Deviation	44	72.3	90.6
November 2019	Minimum	79	151	172
	Maximum	284	507	572
	Range	205	356	400
	Mean	38.2	73.1	98.2
	Std. Deviation	12.7	22.8	30.9
April 2020	Minimum	18	40	61
	Maximum	76	150	198
	Range	58	110	137
	Mean	64.8	108.8	141.2
	Std. Deviation	32.9	54.3	71.3
November 2020	Minimum	12	22	28
	Maximum	180	298	384
	Range	168	276	356

This data reflect considerable changes among the three months of two consecutive years. It could be depicted from table 3 that in April 2020 (during lockdown) the ground level average PM_1, $PM_{2.5}$ and PM_{10} concentration decreased by 75.1, 75.4, and 69.6% compared to pre-lockdown and was 41.1, 32.6, and 29.2% less than post-lockdown. Table 3 shows that during those all three periods the concentrations of PMs were lower in the residential areas than all other land uses and these were even within the permissible limit ($PM_{2.5}$ - 65 µg/m^3 and PM_{10} - 150 µg/m^3 for 24 hours observation), according to the Bangladesh National Ambient Air Quality Standard (BNAAQS) mentioned in the Air Pollution (Control) Rules'22 during the lockdown. In contrast, the industrial areas had polluted air in most of the time. Even in the lockdown, the concentration had exceeded the BNAAQS. However, based on the land use, the average PM_1 concentration reduced by 72.8-80.4%, $PM_{2.5}$ concentration reduced by 71.6-79.2% and PM_{10} concentration reduced by 63.4-74.8% during the lockdown in comparison to the pre-lockdown (November 2019) (Table 3). Meanwhile, the PM's concentrations (34.8-46.4% for PM_1; 21.3-42.2% for $PM_{2.5}$; and 13.1-37.2% for $PM_{2.5}$) were also less during lockdown than the post-lockdown period (November 2020) (Table 3). The main reasons for the decline in the lockdown could have been linked to lower industrial emissions, less mobility, and lower traffic contributions (Nayeem *et al.,* 2021). After the withdrawal of this shutdown in Bangladesh; though the concentration increased, it was still lower than November 2019 probably because of less public movement till that time. Moreover, among three PMs, PM_1 had the highest reduction (72.8-80.4%) in the context of land use-based reduction calculation although $PM_{2.5}$ reduced the most in average concentration (75.4%). Therefore, the concentration range of PM_1 was higher than the other two. In the lockdown period, among all the land uses, the residential areas had seen the highest reduction (74.8% - 80.4%) of all PMs comparing to the pre-lockdown period. This could be attributed to the choice of people to stay at home, depending on online services for daily necessities and use of environmentally friendly transport like bicycle and rickshaw (Sarkar and Khan, 2021). On the other hand, the higher changes (37.2% - 46.4%) were found in the industrial areas from the lockdown to the post-lockdown period due to the activities to return to

Table 3: Mean Concentration of PM_1, $PM_{2.5}$ and PM_{10} (µg/m³) with Relative Changes (%)

Variables	November 2019	April 2020	November 2020	A	B
		Sensitive Area			
PM_1	151	40.8	62.6	-73.0	-34.8
$PM_{2.5}$	293.8	83.3	105.8	-71.6	-21.3
PM_{10}	320.8	117.3	134.9	-63.4	-13.1
		Residential Area			
PM_1	151.7	29.7	49.5	-80.4	-39.9
$PM_{2.5}$	290	60.3	81	-79.2	-25.6
PM_{10}	319.7	80.7	104.2	-74.8	-22.6
		Commercial Area			
PM_1	159.0	43.2	74.9	-72.8	-42.4
$PM_{2.5}$	307.8	81.9	128.0	-73.4	-36.0
PM_{10}	341.7	108.5	171.3	-68.2	-36.6
		Mixed Area			
PM_1	152.5	39.2	67.6	-74.3	-42.0
$PM_{2.5}$	293.2	71.5	114.9	-75.6	-37.8
PM_{10}	328	94.6	148.8	-71.2	-36.4
		Industrial Area			
PM_1	187.2	47.6	88.7	-74.6	-46.4
$PM_{2.5}$	336	83.4	144.3	-75.2	-42.2
PM_{10}	386.2	113.8	181.2	-70.5	-37.2

Note: A= April 2020 vs Nov 2019; B= April 2020 vs Nov 2020

the pre-lockdown production level including the day long operation of the production units along with the movement of heavy transportations in these areas. Furthermore, among all the periods the least reduction has been observed in the sensitive areas (63.4% - 73.0% in the pre-lockdown to lockdown and 13.1% - 34.8% in the lockdown to post-lockdown phases). Though the educational institutions were closed till 12th September 2021, the medical centers and hospitals remained crowded in all those times which might be the reason for less reduction (Nayeem *et al.,* 2020).

Box plots are produced to identify the dispersion nature of the measured concentration of PMs. The first plot shows that the concentration of PM_1 was highly dispersed in industrial areas, commercial areas and mixed areas in the month of November 2019. Mixed areas and residential areas had relatively lower spreading with one outlier in the later one. The overall concentration and dispersion greatly decreased in April 2020 still having a higher dispersion in industrial areas along with mixed areas compared to other land uses like before. The other three land uses showed comparatively compacted concentration with one outlier in residential and industrial areas each. This dispersion pattern of April 2020 is suggesting less movement of regular but sudden traffic. In November 2020 the concentration of PM_1 has increased in all of the studied land uses than that of April 2020 but it was still remarkably less than the concentration of November 2019. However, box plots showed a few outliers in all the studied areas which might happen due to irregular traffic movements. In the context of post-lockdown, the most dispersion has been seen in industrial areas. As it is said earlier, the industries were trying to run fully fledged in this time. However, people were still maintaining social distancing; their movements were basically limited around their residence and working place. For that reason, the other land uses have a compacted concentration of PM_1. A similar scenario was also found in the box plots for $PM_{2.5}$ and PM_{10}; in both cases the higher dispersion was noted in industrial areas and commercial areas in all the studied period. From the location of the median line for the concentration of all PMs in all of the land uses, it is obvious that the changes in the concentration were highly significant between the periods. A few relevant studies have been done in Dhaka city on the COVID-19 outbreak. 28.5-33.5% reduction was also observed in the Moderate Resolution Imaging Spectroradiometer (MODIS) using the Aerosol Optical Depth (AOD) in Dhaka mega city compared to 2016-2019 (Nayeem *et al.,* 2021). Besides, air pollution was also found to be reduced during lockdown in other top polluted megacities. Majumder *et al.,* (2021) found, $PM_{2.5}$ concentration was 36.56% and 45.44% less in Delhi; in Kathmandu 28.32% and 37.42% less; in Kolkata 41.02% and 34.08% less in 2020 than 2018 and 2019 accordingly. In Lahore, it was 44.26% less in 2020 than 2019. Table 4 depicts Tukey's Post Hoc analysis to investigate the significant changes in the average of PMs concentration data based on April 2020 with an equal sample size. The mean differences of PM_1, $PM_{2.5}$ and PM_{10} concentration were significantly lower (at α=0.05) in April 2020 compared to November 2019 pre-lockdown and November 2020 post-lockdown period.

Spatial and Temporal Distribution

The spatial distributions of PMs concentration in different time periods are shown in Figs. 3, 4 and 5. From these figures it is clearly specific that the pollution level was considerably less in all selected locations of Dhaka city during the COVID-19 lockdown period. It could be mentioned that, the southern part of Dhaka city (known as Old Dhaka) was comparatively highly polluted in terms of PM_1, $PM_{2.5}$ and PM_{10} in November 2019. Since November is a dry month, the wind blows from north to south, which

Table 4: Summary of Tukey's Post Hoc Multiple Comparisons between PM concentration and different month

Variables	Month-Year (a)	Month-Year (b)	Difference (a-b)	Significant
PM_1	November 2019	April 2020	117.743*	.00
		November 2020	91.133*	.00
	April 2020	November 2019	-117.743*	.00
		November 2020	-26.610*	.00
	November 2020	November 2019	-91.133*	.00
		April 2020	26.610*	.00
$PM_{2.5}$	November 2019	April 2020	214.871*	.00
		November 2020	179.104*	.00
	April 2020	November 2019	-214.871*	.00
		November 2020	-35.767*	.00
	November 2020	November 2019	-179.104*	.00
		April 2020	35.767*	.00
PM_{10}	November 2019	April 2020	233.471*	.00
		November 2020	190.479*	.00
	April 2020	November 2019	-233.471*	.00
		November 2020	-42.993*	.01
	November 2020	November 2019	-190.479*	.00
		April 2020	42.993*	.01

* The mean difference is significant at .05 level

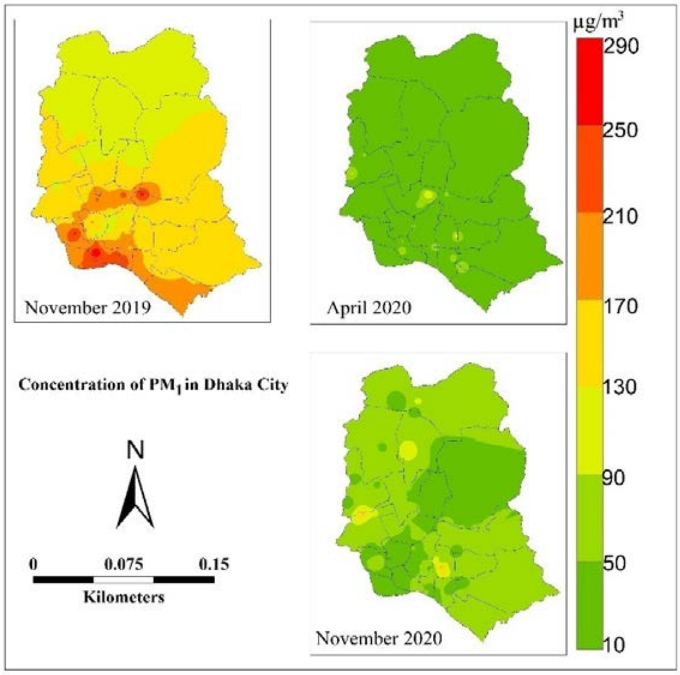

Fig. 3: Spatial and temporal distribution of PM_1 in Dhaka city

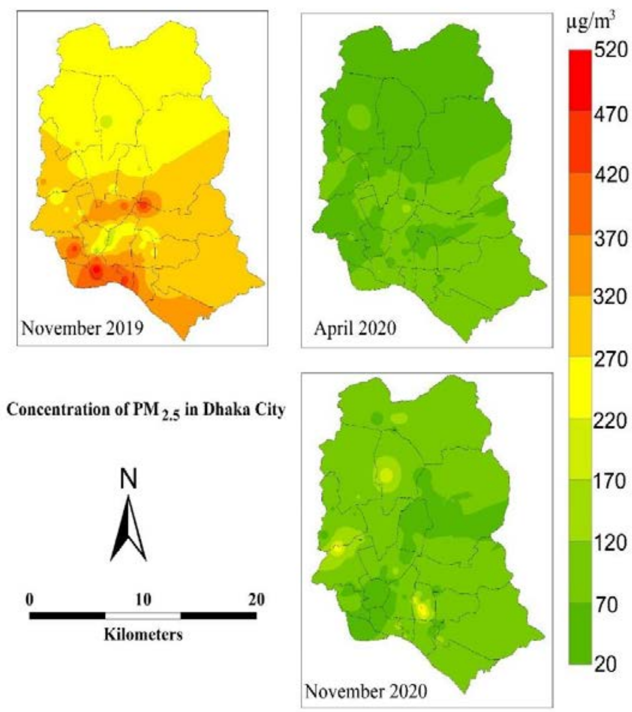

Fig. 4: Spatial and temporal distribution of $PM_{2.5}$ in Dhaka city

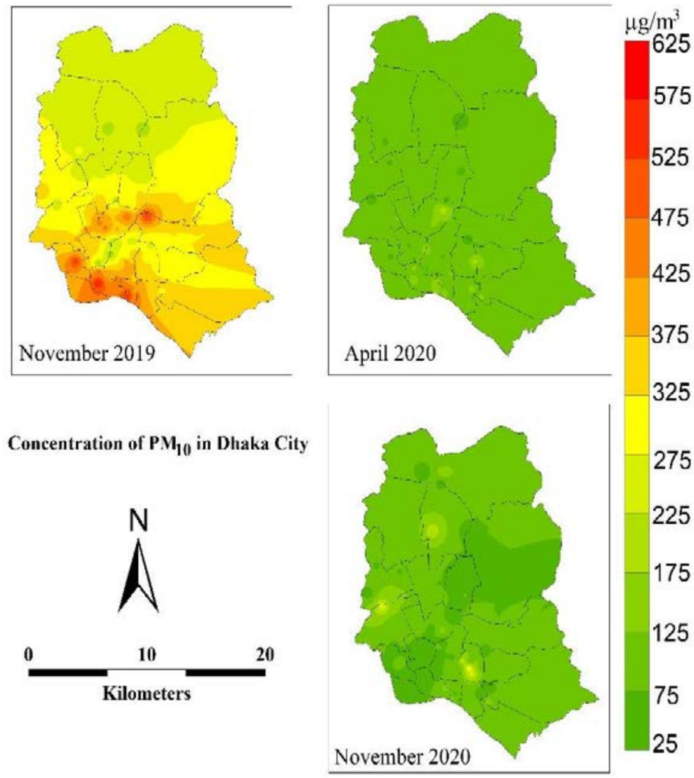

Fig. 5: Spatial and temporal distribution of PM_{10} in Dhaka city

may contribute to the high pollution level in this area (Nayeem *et al.,* 2019). Furthermore, wind speed is too low in Old Dhaka (located in the southern part of Dhaka) due to unplanned building structures, which may also contribute to high PM pollution (Nayeem *et al*., 2020; Tusher *et al.,* 2018). Moreover, a number of illegal brick kilns (situated in the close proximity to Old Dhaka) had started their operation in late October of 2019 which might also be a reason for high pollution in November in that part of Dhaka (Saha *et al.,* 2021; Guttikunda *et al.,* 2012). Eventually, the pollution was a bit lower in the northern part of Dhaka city (e.g., Mirpur Cantonment area) compared to the southern part.

Air Quality Index (AQI) Analysis

Fig. 6 was constructed to visualize AQI categories found for all 70 locations during the months of November 2019, April 2020 and November 2020 in Dhaka city. It is interesting to see that the quality of air was worst in November 2019 (pre-lockdown) in terms of both $PM_{2.5}$ and $PM_{10.}$ In the case of $PM_{2.5,}$ 47 (68%) locations' air quality was 'Hazardous' in November 2019 while 32% were in the 'Very Unhealthy' category. April 2020 exhibits slight improvement of AQI since no sign of 'Hazardous' and 'Very Unhealthy' though the majority of the locations (75%) were in 'Unhealthy' category and 25% locations experienced 'Unhealthy for Sensitive' quality air. In November 2020, with increased $PM_{2.5}$ concentration, categories of 'Hazardous' (3%) and 'Very Unhealthy' (11%) had returned though 52 (74%) locations experienced 'Unhealthy' air. Hence, the quality of post-lockdown air was better than pre-lockdown in Dhaka city. However, an almost similar AQI scenario is observed in terms of PM_{10} concentration. A significant improvement with 'Moderate' and 'Unhealthy for Sensitive Groups' categories rather than 'Hazardous' and 'Very Unhealthy' was observed in Dhaka city during the lockdown period. Even, the considerable

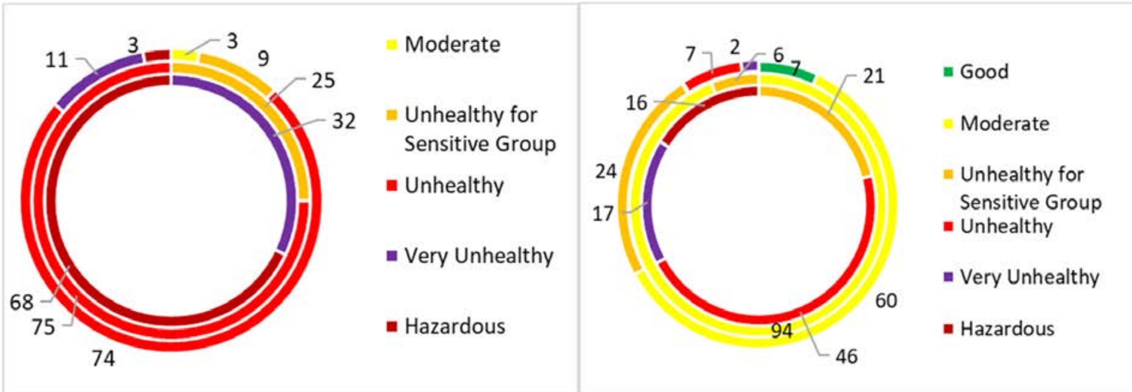

Fig. 6: Category of AQI in November 2019 (Inner), April 2020 (Middle) and November 2020 (Outer) based on $PM_{2.5}$ (left side) and PM_{10} (right side) in selected locations of Dhaka city

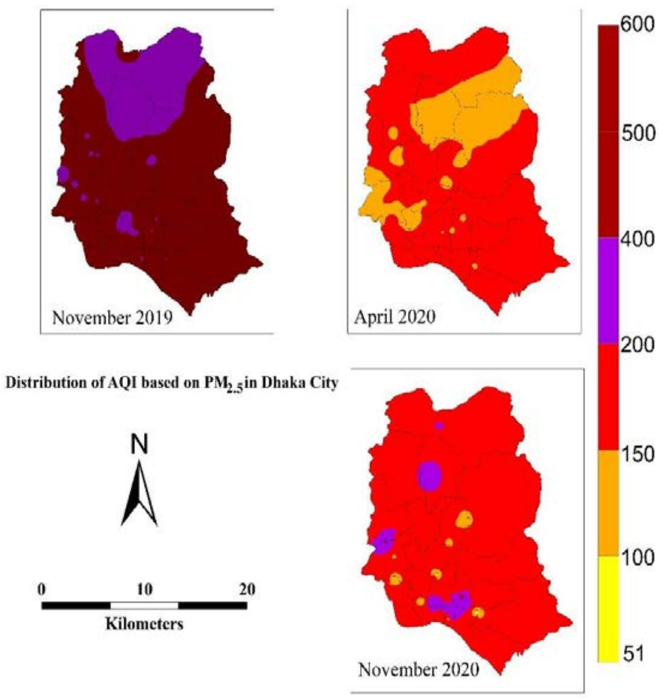

Fig. 7: Spatial and temporal distribution of AQI based on $PM_{2.5}$ concentration in Dhaka city

good air was also found during the post-lockdown period where 5 locations show the 'Good' category of air quality in Dhaka city. This improvement in the AQI was justified by some other studies conducted not only in Dhaka but also in other cities in Bangladesh (Islam and Chowdhury, 2021; Pal and Masum, 2021; Masum and Pal, 2020). The spatial distributions of different AQI categories in different periods are shown in Figs. 7 and 8. Fig. 7 is showing a clear improvement in air quality from pre-lockdown to the lockdown period in all over Dhaka city and again a deterioration from lockdown to post-lockdown. Even the industrial areas returned to old pollution status to some extent. Similarly, Fig. 8 is also illustrating that

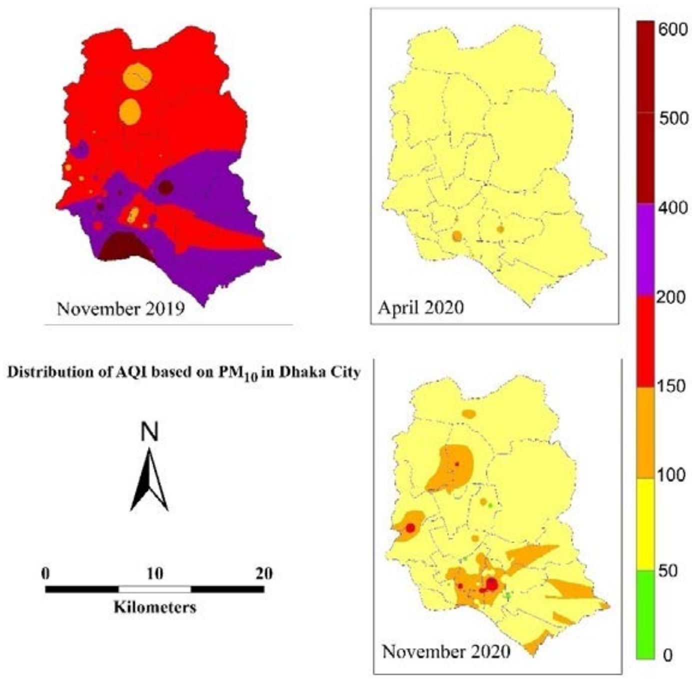

Fig. 8: Spatial distribution of AQI based on PM_{10} concentration in Dhaka city

the AQI of the whole city was improved during the lockdown period. In both figures the southern part had a worse pollution scenario than the northern part. Hence, people living in the southern part of Dhaka are more susceptible to PMs related health risks (Hossain *et al.,*2019).

Since the COVID-19 lockdown provided a unique opportunity to study the changes in air pollution scenario, a good number of studies (Table 5) have also been done in Bangladesh like any other places of the world.

However, all of these studies were based on very few numbers of sampling locations, in most of the cases only one location. To get a clear picture of the pollution status a larger number of scattered sampling locations are needed. Therefore, this study selected 70 locations divided among 5 land use categories scattered over the Dhaka city to understand the comprehensive air pollution status change in pre-lockdown to lockdown and lockdown to post-lockdown periods. This study also considered PM_1 concentration and post-lockdown phase which were absent in previous studies.

Implications

It is apparent that air pollution has significantly decreased on a global scale, including in Bangladesh, although the degree of reduction varied depending on the meteorological factors and pollution sources. Therefore, Bangladesh should take advantage of the lessons learned during the COVID-19 pandemic and implement effective control measures. Despite numerous air pollution regulations implemented in Bangladesh since 1989, pollution levels have not decreased significantly due to a lack of awareness, financial resources, and an increase in population, vehicles, and industries (Islam and Chowdhury, 2021). Consequently, the urgent implementation of a Clean Air Act in Bangladesh is necessary to combat this issue. Many developed and developing countries have already implemented a Clean Air Act, which has ultimately helped to reduce air pollution problems (EPA, 2022). This Act could also be applied in Bangladesh to control emissions from the transportation, industrial, and domestic sectors by enforcing stricter regulations and promoting the use of cleaner technologies in factories. The government

Table 5: The changes of PMs concentration in Bangladesh during COVID-19 lockdown compared to pre-lockdown found in other studies

City	Changes (%)			Total sampling point	Source
	PM_1	$PM_{2.5}$	PM_{10}		
	-	28-57	-	6 locations	Pavel et al., 2020
	-	26	-		Rahman et al., 2021
Dhaka	-	17	-	1 location (US Embassy)	Islam et al., 2021
	-	11	-		Sarkar and Khan, 2021
	-	26	-		Islam and Chowdhury, 2021
	-	33	65		
Gazipur	-	33	45		Pal and Masum, 2021
Narayanganj	-	33	64	1 location (CAMS)	
Rajshahi	-	80	88		
Chattogram	-	32	40		Masum and Pal, 2020

and other organizations could provide incentives for industries and individuals to adopt cleaner air technologies, such as more efficient engines, electric and low-emission vehicles. Furthermore, government and industrialists could invest in research and development to create new technologies and processes that can help reduce pollution, such as developing cleaner fuels, more efficient engines, and improved waste management practices. Educating the public about the negative effects of vehicle and industry-derived pollution can increase awareness and encourage people in promoting sustainable practices like reducing energy consumption, recycling, and utilizing public transportation. Ultimately, creating sustainable cities and communities by reducing air pollution and improving the urban environment can make cities more livable and resilient.

CONCLUSIONS

The current study revealed a significant reduction of PMs concentrations in Dhaka city during lockdown (April 2020) compared to pre-lockdown (November 2019) and post-lockdown (November 2020) period. The ground level average PM_1, $PM_{2.5}$ and PM_{10} concentration reduced by 75.1, 75.4, 69.6% during lockdown compared to the pre-lockdown and were also 41.1, 32.6, 29.2% lower than the post-lockdown. The mean differences between the concentration of November 2019 and April 2020 and again April 2020 and November 2020 were significantly lower (at α=0.05) too. Furthermore, the highest reduction from pre-lockdown to the lockdown (74.8% - 80.4%) was found in the residential areas and from post-lockdown to the lockdown (37.2% -46.4%) was seen in the industrial areas. Less vehicular and public movement and shutting down of industrial activities might be attributed to these reductions. However, the least reduction (63.4%-73.0%, 13.1% - 34.8%) had been observed in sensitive areas for the both periods may be due to higher concentration of people and transportation around medical centers and hospitals. The spatial distribution map of PMs concentration suggested that the northern part of Dhaka city was less polluted than the southern part throughout those three studied time frames. Moreover, air of Dhaka city experienced a good state in the lockdown period since the $PM_{2.5}$ based AQI improved to "Moderate" and "Unhealthy for Sensitive Groups" in April 2020 from "Very Unhealthy" and "Hazardous" categories which again deteriorated in November 2020 as "Very Unhealthy" and "Hazardous" had returned with other categories. Hence, the abatement of PMs concentration occurred due to the restraining measures imposed to reduce population mobility and the closure of numerous commercial establishments and industries. The geo-spatial maps of AQI say that the people of the southern Dhaka city were at more risk of PMs related health implications than the north. Though this study could not represent the 24 hours data for each location (which is important to understand the interaction between air pollution and climatic forces), this is the first ever land use-based study on the influence of COVID-19 on air quality of Dhaka city. Moreover, to explore the overall pollution status of Dhaka city, this study concentrated on 70 locations with an underlying fact that more sampling locations could make the scenario better representative. Besides, scientific study on land use-based source apportionment is also required to eliminate the specific pollutants.

AUTHOR CONTRIBUTIONS

M.T. Islam initiated and contributed to the preliminary concept of the study. Methodology was designed by M.T. Islam and A.K. Majumder. Data was collected by M.T. Islam and A.A. Nayeem under the supervision of A.K. Majumder. M. Islam and A.A. Nayeem did the formal analysis. In manuscript writing, M.T. Islam and A.A. Nayeem prepared the original draft while A.K. Majumder and M. Islam completed all critical revisions and necessary editing of the manuscript. M.T. Islam was involved in the acquisition of research funding.

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CONFLICTS OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

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ABBREVIATIONS

AQI	Air quality Index
BRT	Bus rapid transit
BNAAS	Bangladesh National Ambient Air Quality Standard
CAMS	Continuous Air Monitoring Station
CNG	Compressed natural gas
CSV	Comma Separated Value
DoE	Department of Environment
GDP	Gross domestic product
GIS	Geographic Information System
IDW	Inverse Distance Weighting
MRT	Mass rapid transit
PM_1	Aerodynamic diameter of particles ≤1 µm
$PM_{2.5}$	Aerodynamic diameter of particles ≤2.5 µm
PM_{10}	Aerodynamic diameter of particles ≤10 µm
SPSS	Statistical package for the social sciences
USEPA	United States Environmental Protection Agencies
WHO	World Health Organization
α	Level of significance
$\mu g/m^3$	Microgram per cubic meter

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