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# Assessment of temporal shifting of $PM_{2.5}$, lockdown effect, and influences of seasonal meteorological factors over the fastest-growing megacity, Dhaka

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**Abstract** Dhaka is subjected to high pollution levels throughout the year, holding some relatively high amounts of pollution readings, making its air unhealthy to breathe. The study examined hourly, shifting, seasonal fluctuations in particulate matter ($PM_{2.5}$), the effects of seasonal meteorological variables, and the lockdown effect over the megacity of Dhaka from 2019 to 2021 using data from AirNow. The results indicate the daily average $PM_{2.5}$ concentration between 2019 and 2021 was 112.49 μg/m$^3$, about four times higher than the WHO limit and two times higher than the Bangladesh standard. Daily $PM_{2.5}$ concentrations was high during morning and evening pick-up hours, reaching a maximum hourly concentration of 472.9 μg/m$^3$ in February 2020. The maximum average $PM_{2.5}$ concentration was 211.23 μg/m$^3$ in March 2021 (winter season), and the lowest average was 27.58 μg/m$^3$ in August 2020 (rainy season). The Pearson correlation coefficient (r) between the $PM_{2.5}$ and meteorological variables were inverse with rainfall (− 0.62), temperature (− 0.73), humidity (− 0.82), but positive with wind (0.09). Daily average Air Quality Index (AQI) concentrations improved from 108.53 to 67.99 μg/m$^3$ during the lockdown period. Finally, the study recommended many mitigation strategies that might assist accountable authorities in lowering the number of life-threatening components in the air.

**Keywords** $PM_{2.5}$ concentration · Meteorological variables · Lockdown period · AQI level · Mitigation strategies

## 1 Introduction

The clean and safe air is the most important element of the environment for all living beings to survive. In the 21st century, ambient air quality has become a major concern

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for an urban population for its substantial impact on the environment, health, and climate change. The economic development and the rise in energy consumption in Bangladesh have caused fine particulate matter ($PM_{2.5}$) to become the major air pollutant [1]. Air pollution has become a leading cause of many severe diseases and early deaths around the world. Along with reducing the atmospheric visibility, $PM_{2.5}$ also increases the cardiovascular and respiratory diseases as well as mortality rates. Anthropogenic activities are a primary source of ambient air pollution, as they emit a variety of hazardous pollutants in high concentrations that are deleterious to human health [39]. Besides economic development, urbanization, industrialization, energy consumption and motorization, etc. extreme climatic events including heatwaves, rainfall, temperature, and tropical cyclones have influences on urban air pollutions [2, 3]. Notably, Dhaka is the capital city of Bangladesh and one of the fastest growing megacities, having caught global attention due to excessive air pollution [40, 41]. In recent years, the concentration of air pollutants, especially $PM_{2.5}$, in Dhaka has increased multiple times, which poses a serious threat to public health as well as the urban landscape [4].

PM is one of the dangerous air pollutants emitted from residential, industrial, energy, vehicles, and dust. Many studies have shown that particle and gaseous air pollution are harmful to human health. PM causes respiratory infections, lung problems, and, most critically, a weakened immune system. $PM_{2.5}$, in particular, affects as it goes through the respiratory system, with a significant likelihood of being deposited in the lungs. Asthma, rhinitis, wheezing, eczema, allergic illness, etc. are all exposure to air pollution [5]. Continuous exposure to polluted air has been linked to alterations in numerous neurobehavioral functions in youngsters, as well as signs of depression and cognitive impairment in the elderly. The concentrations of air pollutants and problems associated with air pollution have been increasing, especially in the urban areas because of rapid urbanization, industrialization, increase of transportation activities, economic development, land cover change, deforestation, excessive use of plastics, and so on. However, in 2020, a vivid number of studies have found a decreasing trend of air pollutant concentrations in the air due to the COVID-19 lockdown effect in different cities around the world [6, 7]. For example, during the COVID-19 lockdown scenarios, megacities such as Bangkok, Kualalumpur, and Quezon City reported a reduction in $PM_{2.5}$ emissions resulting from vehicle use and industrial emissions of up to 80% [8].

In 2020, excessive air pollution resulted in the death of more than 2.1 million people in the South Asian region, where 1,667,000 cases accounted for in India, 235,700 in Pakistan, 173,500 in Bangladesh, and 42,100 in Nepal. Bangladesh is ranked ninth among the top ten countries with the most outdoor Ambient Particulate Matter. In addition, Bangladesh ranked fourth among the top ten countries with the highest ozone exposure and eleventh among the top seventeen countries with high exposure to household air pollution. In recent years, Bangladesh has seen an alarming spike in mortality due to air pollution. In 2019, the country recorded a total of 173,500 deaths due to air pollution, an increase of more than half lakh than the previous year [9]. In 2020, the total death respiratory problem was accounted for 74,000. Several studies have revealed that poor air quality increased mortality in Dhaka in recent studies including [10]. Besides other diseases and deaths in Bangladesh, the presence of PM in the air reducing the expectancy by seven years. The air quality of Dhaka City is getting worse day by day, which has become a major concern of the urban policymakers and responsible authorities.

Of course, climate change and air quality are inextricably interconnected with each other due to intricate atmospheric dynamics. Regarding the influences of temperature, rainfall, wind speed, and humidity on air pollutant dynamics, few discussions were addressed in some research. Liu et al. [11] assessed the association between temperature variations and ozone concentrations of Taiwan using multiple regression models. Dong et al. [12] investigated the seasonal impacts of meteorological changes on air pollutants concentrations of Beijing, China, also in different cities of China [2] for the urban areas of India [13]. Trinh et al. [14] investigated the impacts of temperature inversion on air pollutants and its effects on public health in a city in Vietnam. Although meteorological factors are generally considered to play a role in air pollution events, they are frequently consigned to the background. The associations between air pollutants and meteorological factors in the previous studies have been found different for different study areas. Some studies found positive correlations for some meteorological factors, while others found inverse correlations because of different topographical and seasonal characteristics.

Recently, a great number of research devoted attention to air-suspended PM, notably $PM_{2.5}$, including emission sources, physical properties, and chemical disintegration [15, 16]. A better knowledge of the spatial and temporal fluctuations of $PM_{2.5}$ can aid in deploying efficient air pollution-reduction measures. Most of the researches focused on either the spatial distribution of $PM_{2.5}$ concentrations or monthly temporal variations of $PM_{2.5}$ and many of the researches are based on the air pollutants of China. Though few studies illustrated the $PM_{2.5}$ dynamics in response to meteorological factors of the Indian cities [17], it is still a research gap for Bangladesh. Rana et al.

[18] have discussed the atmospheric $PM_{2.5}$ trends in Dhaka from 2012 to 2015. Rahman [6] showed the variations of air pollutants of Dhaka City during the lockdown in Bangladesh (from March 1, 2020 to May 15, 2020). Besides, the change in air quality patterns in Bangladesh in recent years has not been focused. This study (i) Addressed hourly, daily, monthly and seasonal $PM_{2.5}$ variations (ii) Analyzed the nexus between $PM_{2.5}$ concentrations and meteorological factors such as temperature, rainfall, wind speed, and humidity (iii) Health impacts of $PM_{2.5}$ concentrations, and (iv) Variations of $PM_{2.5}$ concentration levels during the different phases of lockdown in Dhaka City with the goal of better and more comprehensively informing the next stage of policymaking for the sustainable air quality management regarding public health and environmental protection.

## 2 Methods and materials

### 2.1 Study area

Dhaka is one of the fastest-growing megacities in the world and the capital of Bangladesh. The city is a densely populated city with high ambient air pollution resulting from the smoke from brick kilns, industrial activities, car and traffic exhaust containing high sulfur levels, and re-suspended dust from roads, etc. [18]. Higher population growth rate, uncontrolled urbanization and industrialization, higher motorized vehicular increasing rate, and transport activities resulted in massive air pollution in Dhaka City. Moreover, Dhaka City has been identified as the second highest $PM_{2.5}$ emitter in the world [9]. The mean atmospheric concentration of $PM_{2.5}$ (80 $\mu g/m^3$) in Dhaka City exceeds the Bangladeshi standard by five times and the WHO standards by more than eight times [19], which is threatening the lives of 21 million people living in an area of just 306.4 $km^2$. Furthermore, due to the current environmental disturbance, Dhaka city people are suffering from a variety of maladies such as eye irritation, severe headaches, disruption of blood circulation, respiratory problems, and even premature mortality [6]. Bangladesh saw a total of 173,500 deaths due to air pollution in 2019, which is over 50,000 deaths in 2017 and this death rate has been increasing every year with the increase of pollutant emissions [9]. World Bank (2015) reported that 26% of total death in Dhaka are caused by air pollution. In this regard, the study of air pollution in Dhaka City will not only assist concerned authorities and decision-makers in improving air quality but will also demonstrate its usefulness as a substitute measure for inhaling clear air quality in Dhaka in the coming years with public participation.

### 2.2 $PM_{2.5}$ satellite-based country data

The $PM_{2.5}$ satellite data and related services were provided by the Socioeconomic Data and Applications Center (SEDAC) that is managed by the NASA Earth Science Data and Information System (ESDIS) project [20]. Its purpose was to provide an annual global surface of concentrations ($\mu g/m^3$) of mineral dust and sea salted fine particular matter of $\leq 2.5$ µm. These data sets can be used for large-scale health and environmental research. These datasets use grids from MODIS, MISR, and SeaWiFS Aerosol Optical Depth (AOD) with GWR from 1998 to 2016 [21]. Urban areas were derived from the Global rural–urban mapping project, V01, Urban Extent Polygons, revision 02 of the same times series. Country averages are counted by population weights, i.e., concentration in populated areas was counted more toward the country average compared to the concentration in less populated areas. It had a times series from 2008 to 2015 [20].

### 2.3 $PM_{2.5}$ hourly data

The United States (US) Embassy in Dhaka, Bangladesh, has regularly collected real-time atmospheric data monitoring from the rooftop and shared those data publicly on the AirNow Department of State (AirNow DOS). Being evaluation of Air Quality Index (AQI) the main concern, the organization also collects hourly $PM_{2.5}$ data [22]. The installed instrument of US Ambassy uses a beta annulation monitor (BAM)—1020, PM Coarse System, and derives results on an hourly basis and local level. For uninterrupted monitoring of $PM_{2.5}$ and its' extensive uses, the BAM—1020 is built. Larger particles (> 2.5 µm diameter) are filtered, letting air pass through a chamber heated up to 20 °C impacting on a filter tape and in the exposure of beta radiation [23]. The degree of absorption of the radiation by the particulate matter found in the filter tape is an essential part of $PM_{2.5}$ calculation by following sensitive calibration procedures. All the collected datasets are analyzed and graphically represented separately for better visualization.

### 2.4 Nexus between $PM_{2.5}$ concentrations and meteorological factors

In air pollution events, meteorological conditions have a direct impact on emission control. This study utilized daily average $PM_{2.5}$ concentrations data and daily average meteorological data such as rainfall, temperature, humidity, and wind speed to analyze the influences of climatic factors on $PM_{2.5}$ concentrations in Dhaka City over the study period. The data were collected from NASA Prediction Of Worldwide Energy Resources—The POWER Project. The POWER Data Services are a collection of restful Application Programming Interfaces (APIs), geographic image services, and Open-source Project for a Network Data Access Protocol (OPeNDAP) services. These three distinct service offerings facilitate data discovery, access, and dissemination to our user base in the form of Analysis Ready Data (ARD) and as direct application inputs to decision-support tools. In this regard, the hourly $PM_{2.5}$ data were converted to daily mean $PM_{2.5}$ data. After that, the linear regression (Eqs. 1–3) and Pearson's correlation (Eq. 4) analysis were performed [24].

The primary equation of linear regression is given in Eq. 1.

$$y = a + bx \quad (1)$$

Here, a and b can be estimated from Eqs. 2 and 3.

$$a = \frac{(\sum y)(\sum x^2) - (\sum x)(\sum xy)}{n(\sum x^2) - (\sum x)^2} \quad (2)$$

$$b = \frac{n(\sum xy) - (\sum x)(\sum y)}{n(\sum x^2) - (\sum x)^2} \quad (3)$$

In addition, the equation of Pearson's correlation is given in Eq. 4.

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad (4)$$

where r = correlation coefficient, $x_i$ = values of the x—variable in the sample, $\bar{x}$ = mean of values of the x—variables in the sample, $y_i$ = values of the y—variable in the sample, $\bar{y}$ = mean of the values of the y—variables in the sample.

## 3 Results and discussion

### 3.1 $PM_{2.5}$ in Bangladesh

Over the years, Southern Asia has been identified as the most critical zones in terms of air quality issues. China, India, and Bangladesh are listed at the top by becoming the most vulnerable zones due to having the lowest air quality in several years [17, 18]. Bangladesh is facing continuous atmospheric degradation as the $PM_{2.5}$ particles have been increasing at a constant rate over the last decade. Where in 1998, the annual $PM_{2.5}$ value had a maximum of 47.6 μg/$m^3$ that increased at a steady rate to 52.1 μg/$m^3$ in the year 2000, 55 μg/$m^3$ in 2002, 57.1 μg/$m^3$ in 2004, 60.1 μg/$m^3$ in 2006. During 2006–2016, the value faced more increment rate as in 2012 and 2016, the values were 66 and 66.2 respectively (Fig. 1).

The locational overview shows in all years, the Dhaka division, the home of the capital of Bangladesh, faced the highest concentration of $PM_{2.5}$ particles. As the years passed, Rangpur and Rajshahi divisions also met higher concentrations of $PM_{2.5}$ particles. The lowest concentration of $PM_{2.5}$ particles was noticed at the Chittagong division, mostly because of hilly regions and increased greeneries. A lower concentration of $PM_{2.5}$ particles was also detected in the Sylhet division as the climate is mostly rainy and green concentration is also present.

### 3.2 Hourly variation of $PM_{2.5}$ in Dhaka

This study decomposed the observed concentration of $PM_{2.5}$ to examine the day to day variations of $PM_{2.5}$ concentrations for each month during the study period. The annual average, minimum and maximum concentration of $PM_{2.5}$ in Dhaka City are presented in Fig. 2. The daily average concentration of $PM_{2.5}$ in Dhaka from 2020 to 2021 was found 112.49 μg/$m^3$ which was about four times higher than the WHO standard and two times higher than the Bangladeshi standard. Results show that the concentration of $PM_{2.5}$ increases and drops rapidly, increases during peak hours (both morning and evening peak hours). The maximum hourly concentrations of the pollutants were found 472.9 μg/$m^3$ during February 2020, about seven times higher than the BD limit and 19 times higher than the WHO standard, while the minimum concentration was observed 2.8 μg/$m^3$. Figure 2 shows that even at the minimum concentration, it exceeds the limit of the WHO standard. Though the concentration of $PM_{2.5}$ decreases during the off-peak hours of the day, it increases at night. According to Iqbal (2016) and Labib et al. (2018), heavy vehicles (trucks, large buses, and lorry) are one of the primary pollutant emissions sources in Dhaka City, which are allowed to operate on the roads of Dhaka City from 10.00 pm to 5.00 am. As a result, thousands of heavy vehicles use the roads of Dhaka City to transport goods and people every day. This accelerates the $PM_{2.5}$ concentration in the air of Dhaka City at night.

### 3.3 Shifting variation of $PM_{2.5}$ in Dhaka

The concentration of $PM_{2.5}$ was analyzed in different parts of the time in a day. As Dhaka is the busiest city in Bangladesh, the situation changes at different times of the day. Four different periods were selected for this assessment such as late-night (00:01–06:00), morning (06:01–12:00), afternoon (12:01–18:00) and night (18:01–00:00). $PM_{2.5}$ extensively fluctuated over different periods.

During the study period, daily mean concentration of $PM_{2.5}$ in Dhaka indicates a seasonal variation (Fig. 4). The fluctuation is clearly visible during the peak hours of the daytime and the after 10.00 am of the night time, and varied depending on the season. It can also be related to the

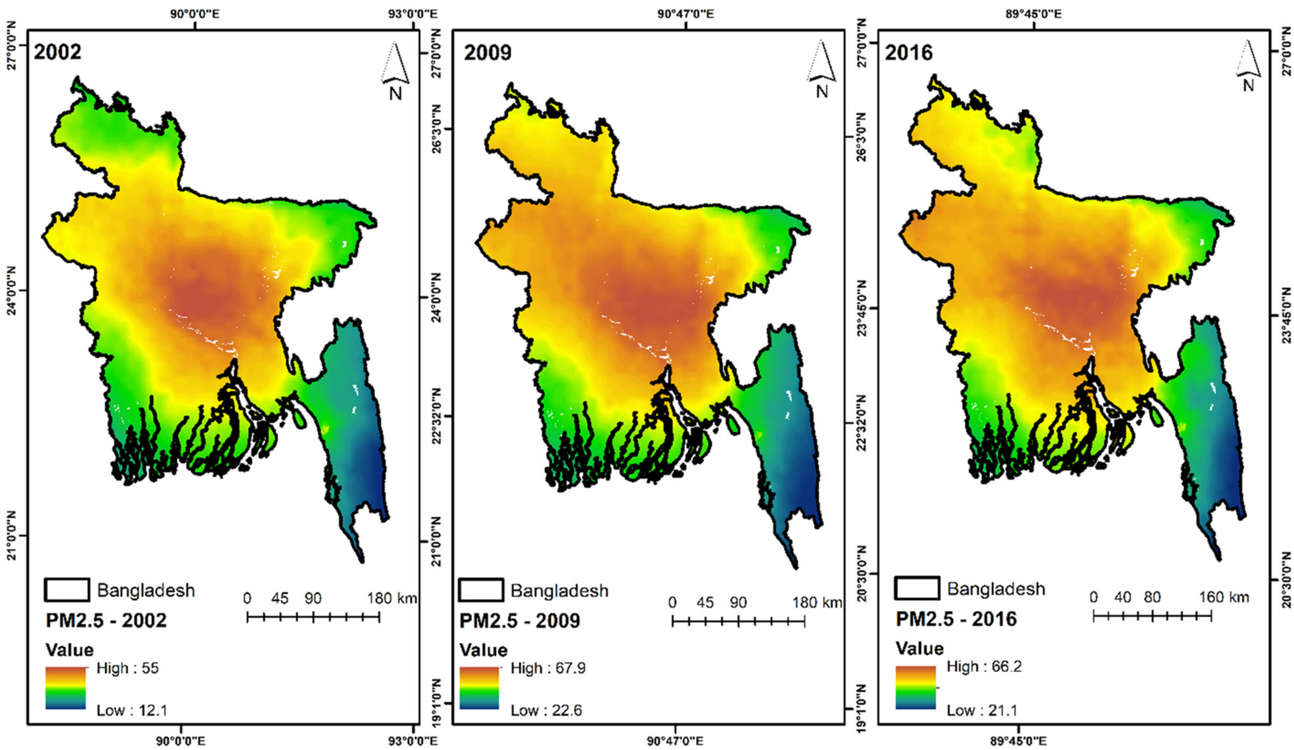



**Fig. 1** Level of $PM_{2.5}$ in Bangladesh from 1998 to 2016

working hours and the running hours of the industries and the brickfields The morning session has the most rate of fluctuation among the four time periods. Afternoon sessions have relatively less fluctuation of $PM_{2.5}$ in the atmosphere. Seasonal variation plays a key role in the variation because, during the rainy seasons, particulates have less chance of free movement. The rate of deviation remains unstable in the winter season most. In February 2019, all the shifts had deviations ranging above 80 $\mu g/m^3$. During the time period 2019–2021, the deviation rate increased rapidly creating greater risk to urban health. For example, March 2019 had the average $PM_{2.5}$ value of $131.52 \pm 81.58$ whereas, in 2021, it was found $186.37 \pm 133.45$, almost twice as before. Also, significant high deviation (above 200) was also monitored during the last two winter seasons (2020 and 2021) (Table 1).

This study significantly identified the winter nights and mornings as the periods having the most deviated $PM_{2.5}$ situation. One of the major sources of $PM_{2.5}$ emissions in Dhaka City is the transportation sector, especially trucks and buses. The trucks and long-distance buses are permitted to operate from 10 p.m. to 8 a.m. inside of the city. That is why the emission levels and concentration of $PM_{2.5}$ remain higher during this time. Still, it is a matter of agitation that 2021 had the most worsening status of deviation from the standard average value. From the pattern analysis of the previous years, the deviation of $PM_{2.5}$ is increasing at a compounding rate.

### 3.4 Monthly variation of $PM_{2.5}$ in Dhaka

Different monthly $PM_{2.5}$ concentrations in Dhaka City were observed from 2019 to July 2021. The monthly variations of $PM_{2.5}$ during the study period are shown in Fig. 3. Seasonal statistics of the pollutants were also calculated. Analysis shows that $PM_{2.5}$ dangerously worsened during the winter season and exceeded Bangladesh standards multiple times, while the average concentration level remained within the Bangladesh standard during the rainy season. The average summertime concentration was found 28.275 $\mu g/m^3$ (ranges between 3.9 and 575.50 $\mu g/m^3$), whereas during the rainy season 37.79 $\mu g/m^3$ (ranges between 2.83 and 220.30 $\mu g/m^3$), and 152.65 $\mu g/m^3$ (ranges between 98 and 472.9 $\mu g/m^3$) during the winter season. However, the values were significantly higher than the WHO limit of $PM_{2.5}$ concentrations. The highest average concentration was calculated 211.23 $\mu g/m^3$ in March 2021, while the minimum average 27.58 $\mu g/m^3$ in August 2020 (Table 1).

This study identified winter as the most polluted season and the rainy season as the least polluted season which is consistent with the outcomes of [18, 25]. The seasonal brick burning in the brick kilns during winter and summer

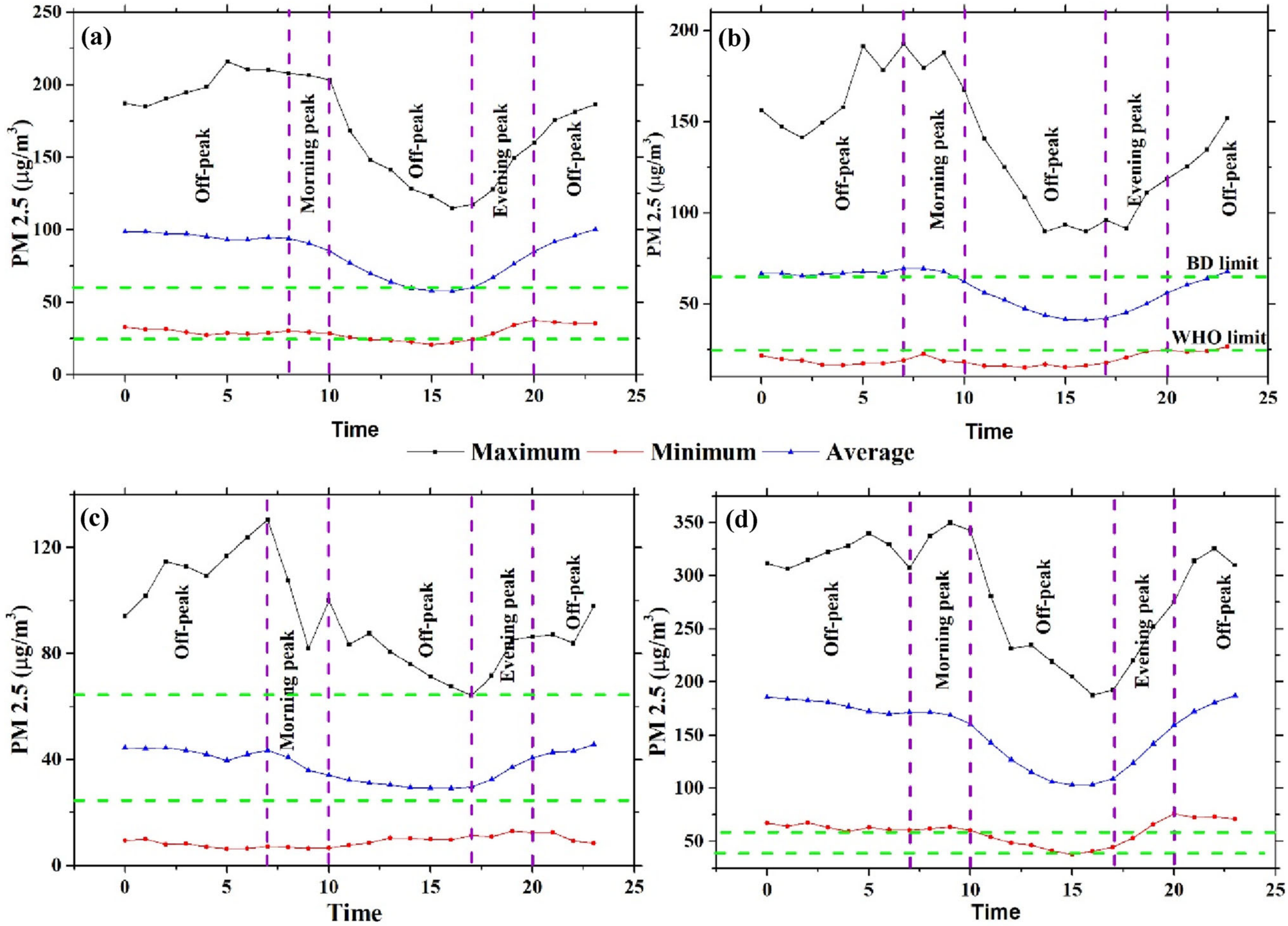



**Fig. 2** Hourly variations of $PM_{2.5}$ **a** average annual hourly and **b** summertime variations **c** rainy season **d** winter season in Dhaka City3.3 Shifting variation of $PM_{2.5}$ in Dhaka

could be the potential influencing factors to higher $PM_{2.5}$ concentration in Dhaka City. The wet deposition of PM due to frequent rain in the rainy season may decrease the PM concentrations in the air during the rainy season. Moreover, the reduction of construction activities and dust during the rainy season may decrease the PM concentrations.

### 3.4.1 *Nexus between $PM_{2.5}$ concentrations and rainfall in Dhaka*

Meteorological factors such as rainfall, temperature, wind speed, and relative humidity have significant impacts on air pollutants dynamics [17]. Figure 2, 3 shows the clear variations in the monthly average concentrations of $PM_{2.5}$ in Dhaka City. To assess the influences of meteorological factors on the concentrations of $PM_{2.5}$ in the air, this study analyzed the relationship between $PM_{2.5}$ concentrations and meteorological factors and presented in Fig. 4. The Pearson's correlation test was also analyzed. Figure 4a shows the negative correlation between $PM_{2.5}$ concentrations and rainfall with the moderate $R^2$ value 0.38179 and Pearson's correlation value $-0.61789$. The $PM_{2.5}$ concentrations were observed higher in the days when rainfall recorded 0.00 mm. This implies that the increase of water in the atmospheric environment reduces pollutant concentrations. Thus, rainfall acts as a natural scrubber, lowering pollutant levels by reducing pollutant concentrations in the atmosphere due to erosion and diffusion dilution generated by rain.

The evidence for the association between pollutant concentrations and rainfall is contradictory. According to Rosenfeld and Woodley [26], the number of cloud condensation nuclei in contaminated air is nearly ten times larger than the number in clean air. As a result of the air pollution, little droplets would form, which would be difficult to expand to the size of precipitation. This impact was found by Jirak and Cotton [27] at elevation places west of Denver and Colorado Springs, Colorado. Rosenfeld et al. [28] explained both the decrease and increase in rainfall caused by air pollution as a result of a combination of radiative impacts on surface heating and microphysical effects on energizing convection. Most of the recent studies

**Table 1** Shift-wise average $PM_{2.5}$ in different time

| 2019 | | | | | 2020 | | | |
|---|---|---|---|---|---|---|---|---|
| Time | Late night | Morning | Afternoon | Night | Late night | Morning | Afternoon | Night |
| Jan | 215.26 ± 58.08 | 201.82 ± 62.91 | 113.09 ± 56.09 | 204.49 ± 67.56 | 207.86 ± 77.31 | 170.61 ± 65.15 | 132.95 ± 51.09 | 208.04 ± 73.45 |
| Feb | 207.03 ± 103.7 | 198.02 ± 129.66 | 126.3 ± 82.93 | 177.75 ± 82.97 | 188.45 ± 69.65 | 179.13 ± 70.8 | 107.19 ± 34.25 | 165.25 ± 41.99 |
| Mar | 131.52 ± 81.58 | 130.7 ± 72.21 | 95.53 ± 53.44 | 132.72 ± 54.73 | 127.08 ± 61.4 | 106.21 ± 52.12 | 65.26 ± 24.59 | 107.04 ± 41.5 |
| Apr | 71.58 ± 52.2 | 81.59 ± 52.93 | 59.69 ± 31.38 | 71.11 ± 34.69 | 54.34 ± 29.42 | 58.79 ± 36.84 | 42.17 ± 19.91 | 53.65 ± 28.22 |
| May | 49.28 ± 28.18 | 67.44 ± 66.51 | 52.06 ± 25.07 | 64.63 ± 32.17 | 53.52 ± 32.43 | 53.41 ± 36.83 | 35.09 ± 16.8 | 46.18 ± 22.25 |
| Jun | 30.44 ± 17.93 | 31.21 ± 22.13 | 28.8 ± 14.64 | 33.96 ± 16.26 | 32.27 ± 19.92 | 33.16 ± 20.36 | 31.81 ± 12.79 | 36.61 ± 16.03 |
| Jul | 30.44 ± 17.93 | 31.21 ± 22.13 | 28.8 ± 14.64 | 33.96 ± 16.26 | 32.92 ± 21.46 | 32.42 ± 21 | 29.34 ± 13.76 | 32.62 ± 13.08 |
| Aug | 29.16 ± 16.58 | 22.26 ± 14.36 | 20.82 ± 10.82 | 31.15 ± 14.86 | 30.95 ± 23.26 | 25.61 ± 16.59 | 23.14 ± 11.49 | 30.67 ± 17.76 |
| Sep | 34.68 ± 22.15 | 37.06 ± 23.01 | 32.86 ± 15.96 | 37.57 ± 16.86 | 39.71 ± 26.05 | 31.75 ± 22.48 | 25.56 ± 12.24 | 40.41 ± 18.96 |
| Oct | 66.44 ± 32.93 | 61.25 ± 34.24 | 47.65 ± 24.34 | 67.44 ± 29 | 66.86 ± 37.5 | 55.19 ± 31.81 | 41.93 ± 20.16 | 65.49 ± 31.59 |
| Nov | 109.87 ± 47.02 | 94.01 ± 43.63 | 63.95 ± 28.68 | 99.91 ± 43.57 | 116.61 ± 60.21 | 96.65 ± 53.58 | 66.11 ± 38.02 | 112.55 ± 51.55 |
| Dec | 160.85 ± 52.92 | 147 ± 54.05 | 113.1 ± 50.22 | 163.21 ± 55.62 | 198.49 ± 49.95 | 181.74 ± 58.32 | 133.93 ± 40.82 | 198.72 ± 50.93 |
| 2021 | | | | | | | | |
| Jan | 242.3 ± 66.94 | 221.08 ± 76.24 | 164.08 ± 56.93 | 217.54 ± 58.39 | | | | |
| Feb | 217.14 ± 81.85 | 201.31 ± 86.82 | 117.85 ± 39.69 | 185.97 ± 63.62 | | | | |
| Mar | 186.37 ± 133.45 | 171.14 ± 103.65 | 102.87 ± 38.12 | 133.47 ± 51.41 | | | | |
| Apr | 94.83 ± 75.85 | 91.33 ± 74.93 | 68.55 ± 30.77 | 77.62 ± 35.29 | | | | |
| May | 56.85 ± 45.67 | 54.82 ± 48.32 | 41.55 ± 23.85 | 44.82 ± 25.45 | | | | |
| Jun | 50.49 ± 27.31 | 43.15 ± 24.52 | 40.81 ± 22.34 | 41.93 ± 18.87 | | | | |

found the inverse relationship between rainfall and PM concentrations for different study areas [17, 29].

### 3.4.2 Nexus between $PM_{2.5}$ concentrations and temperature in Dhaka

Another cross-dependence analysis between temperature and the investigated $PM_{2.5}$ concentration profiles was carried out to further investigate the pollutants' seasonal dependencies. Figure 4b shows the $PM_{2.5}$ distribution under different varied temperature conditions in the study area. The average daily temperature ranged between 13 and 33 °C during the study period. This study found the inverse relationship between $PM_{2.5}$ concentrations and temperature with a $R^2$ value of around 0.52751 and Pearson's r =− 0.7263. During winter temperature decreases, but the dust and air pollutants increase due to the dry environment. On the other hand, during the rainy season, the atmospheric temperature ranges between 23 and 28 °C in the study area, but the rainfall reduces the PM concentrations. However, a negative correlation has been found in several studies including [29, 30].

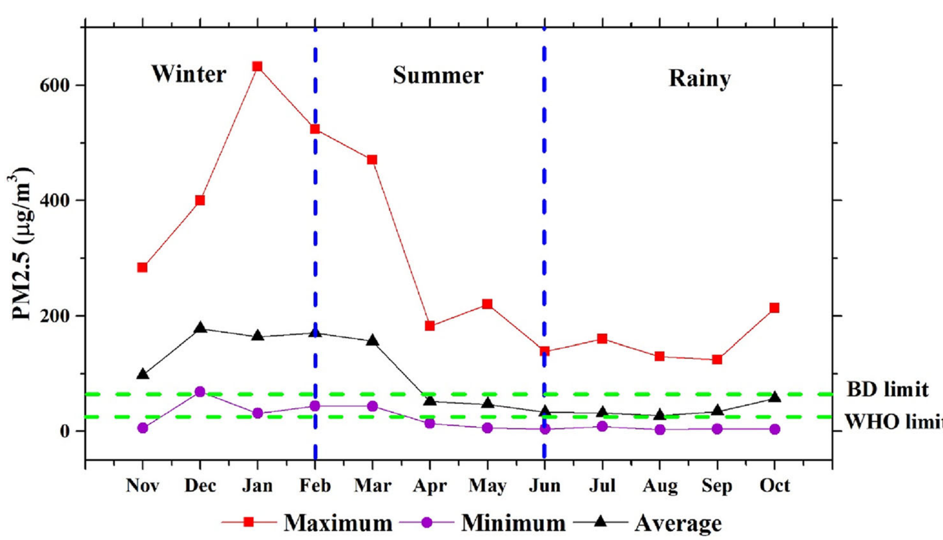
### 3.4.3 Nexus between $PM_{2.5}$ concentrations and humidity in Dhaka

Figure 4c shows the distribution of $PM_{2.5}$ concentrations under different humidity conditions and the correlation coefficient and Pearson's coefficients of $PM_{2.5}$ concentrations related to humidity in Dhaka City during the study period. The $R^2$ value (0.67011) and Pearson's coefficient (–0.8186) indicates the strong negative correlation between humidity and PM concentrations for Dhaka City which is consistent with the findings of [17, 29]. Higher relative humidity can cause suspended particles to clump together, causing them to fall to the ground and lower $PM_{2.5}$ concentrations. Moreover, during the winter season, $PM_{2.5}$ concentrations increase and decrease during the rainy season, on the other hand, humidity decreases during winter and increases during the rainy season.

### 3.4.4 Nexus between $PM_{2.5}$ concentrations and wind speed in Dhaka

The wind is an important meteorological factor in analyzing the air pollutants variations, which cannot be ignored. Figure 4d shows the $PM_{2.5}$ variations under different wind speed conditions in Dhaka City. This study found a positive association between wind speed and $PM_{2.5}$ concentrations. Figure 4d shows that higher wind speed led to higher concentrations of $PM_{2.5}$ in the atmosphere. Generally, $PM_{2.5}$ concentrations remained higher during the study period, when the windspeed of Dhaka City ranged between 2 and 5 m/s. Chen et al. [29], Wang and Ogawa [31] found a positive correlation between wind speed and $PM_{2.5}$ concentrations while Rosenfeld and Woodley [26] found the inverse correlation, possibly for the effects of mountainous terrain on the wind. Cities surrounded by Dhaka City such as Narayanganj, Tejgaon, Savar, Tongi, etc. are heavy industrial areas and emits huge amounts of air pollutants every day. As the wind speed increases, the air pollutants spread all over Dhaka City with

**Fig. 3** Average monthly variations of $PM_{2.5}$ concentrations



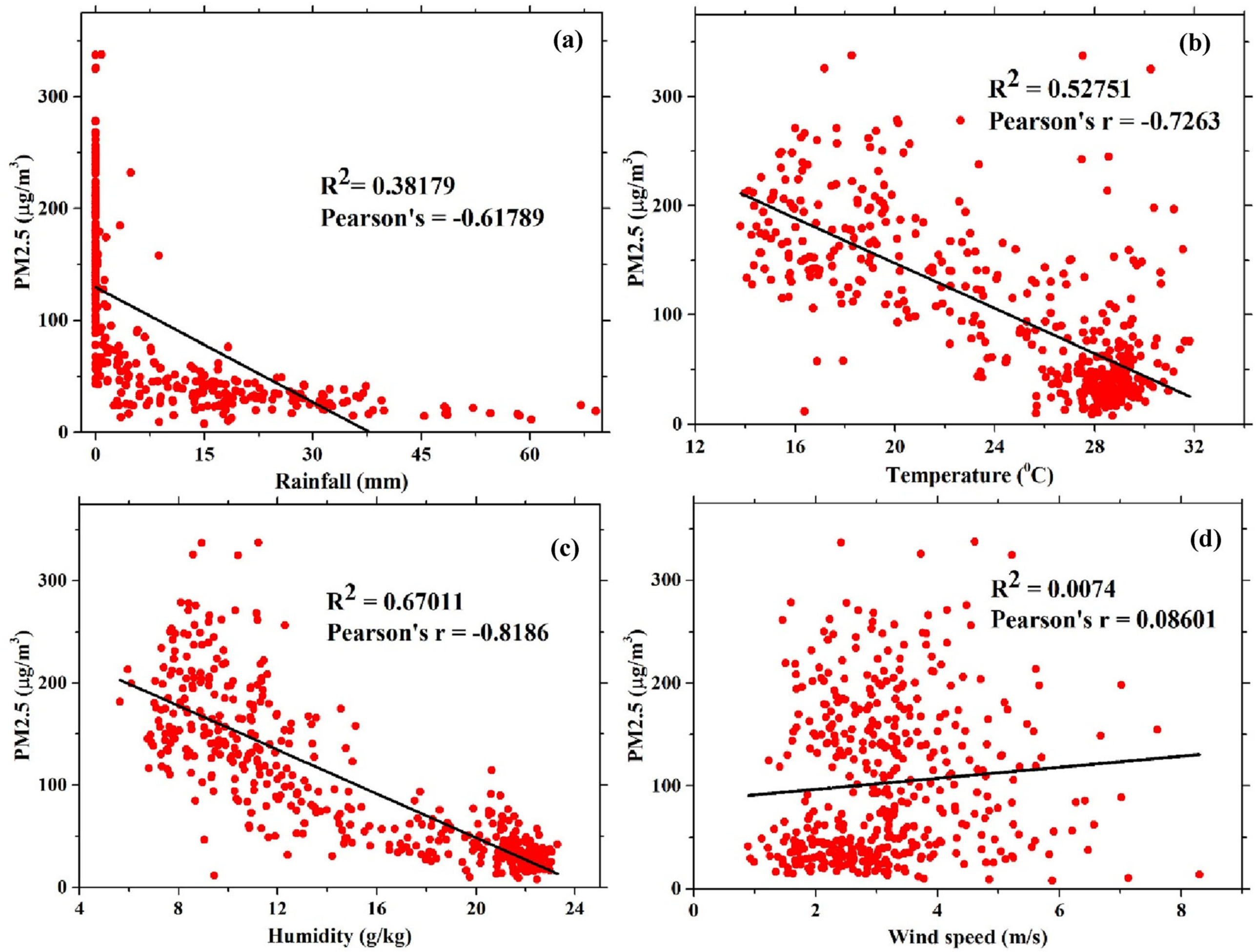



**Fig. 4** Correlation of $PM_{2.5}$ concentrations and **a** rainfall **b** temperature **c** humidity and **d** windspeed

the wind and increases $PM_{2.5}$ concentrations level. The primary hypothesis was stated based on the mentioned statement and authors tried to find the correlation values to justify it. However, the result indicates a low positive correlation and concluded a minor and positive influence of wind speed over $PM_{2.5}$.

### 3.5 Change in AQI of Dhaka

Rapid urbanization and modern construction have put human health at severe risk. The consequences of the tendency of ruling over nature have created those health hazards and issues. Air pollution is one of the prominent reasons that have been caused by industrialization and the reduction of vegetation covers. The adverse effects of this phenomenon have made mankind pay in the form of health damage.

Bangladesh is currently getting the flare of rapid urbanization and installment of industries in the urban outskirts. The results of this study showed an exceeding limit of $PM_{2.5}$ in both Bangladesh standards and WHO standards. Moreover, the rapid shifting of $PM_{2.5}$ values in peak hours creates a vulnerable situation for the urban health situation.

The AQI is a daily air quality index that is used to report on the quality of the air. It shows you how clean or dirty your air is, as well as what health impacts may be a worry. The AQI focuses on the health consequences that may occur within a few hours or days of breathing in polluted air. The AQI is computed for four primary air pollutants that are controlled by the Clean Air Act: ground-level ozone, particle pollution, carbon monoxide, and sulfur dioxide. To safeguard human health, the Environmental Protection Agency (EPA) has developed national air quality guidelines for each of these contaminants. The value of AQI ranges between 0 to 500, the lower value indicates the sound and healthy air quality, while the higher value indicates the hazardous condition. Table 2 indicates the extent of different AQI levels from 2019 to 2021. In Table 2, the quality of Dhaka's air remained extremely poor on most of the days of each of the years, as most of the unhealthy AQI levels covered the highest percentage, followed by very unhealthy and unhealthy for sensitive groups. Table 2 shows that the percentage of days in a year within the very unhealthy and hazardous AQI level increased every year, while the percentage of days with good and moderate AQI levels decreased. This implies that the air quality of Dhaka City is deteriorating rapidly and indicates an unhealthy and hazardous urban environment in the future. However, it can be said that the higher value of $PM_{2.5}$ in the study area may put the population in a tight spot which, however, if not taken steps in time, may turn into an unchangeable state.

### 3.6 Lockdown effects on $PM_{2.5}$ in Dhaka

The probability of the outbreak of the COVID-19 virus can be controlled by reducing air pollutants. Due to the easy absorption of these particulate matters via the respiration process, a high level of $PM_{2.5}$ and $PM_{10}$ may increase the odds of the COVID-19 virus entering the human body. Moreover, researchers found that coronavirus spreads mostly through community transmission, for which lockdown is the most effective way to reduce community transmission. Bangladesh experienced the strict lockdown from 26th March 2020 to 12th April 2020 and the partial lockdown from 13th April to 30th May 2020. The changes in the trend of $PM_{2.5}$ concentrations before lockdown, during the strict lockdown, and partial lockdown are presented in Fig. 5. Analysis shows that the average $PM_{2.5}$ concentration was 105.83 $\mu g/m^3$ before lockdown. During the strict lockdown, daily average concentrations were reduced to 67.99 $\mu g/m^3$ (reduced by 35.76%) in Dhaka City, due to the reduction of transport activities, and industrial activities. The $PM_{2.5}$ concentrations continued to decrease during the partial lockdown from April 13 to May 30, 2020 and reached 45.02 $\mu g/m^3$ (decreased by 57.46%). The lowest concentrations of the pollutants were observed in this period, and the average concentration level also remained below the Bangladesh standard. The lockdown, reduction of transport activities, closure of offices, schools, and all types of industrial activities contributed to a large extent to the declination in the $PM_{2.5}$ emissions in Dhaka City. The $R^2$ value of 0.5176 also indicates that the lockdown has moderate significance in the declination of the $PM_{2.5}$ concentrations in Dhaka City.

### 3.7 Mitigation strategies

A mitigation strategy for combating $PM_{2.5}$ is explicitly quite complex because of its characteristics of ambient air pollution. Ambient air pollution is quite different, as this is the mixture of both particles and gases. Based on the results, the authors decided on some mitigation strategies which are as follows:

Industrial areas are, however, to be blamed the most for $PM_{2.5}$ emissions. The industries situated on the urban outskirts are the prime users of energy gained from fossil fuels increases $PM_{2.5}$ emissions [32] resulting industries being the largest contenders for particles of ambient air pollution. In this context, cost minimization energy system, MARKAL [33] might be introduced in some selected industries. This model puts an emphasis on renewable energy sources. Another way to focus on renewable energy sources is biomass combustion, which has already been a worthy competitor to fossil fuels [34]. Moreover, most of the industries in Bangladesh are dependent on traditional machines and processes. In this case, modern technologies like CCT (Clean Coal Technology) must be included. The development of the CCT strategy plays a role similar to a big drop in the bucket in both the economic and environmental sustainability of a country.

Emissions (exhaust fumes) from transport and diesel engines accelerate the concentration of $PM_{2.5}$ in the air. Substitutions for diesel can mitigate the particle concentration potentially up to 80% in Dhaka city. In the traffic congestion of Dhaka city, 43% of the vehicles are private vehicles [35]. In order to cope with the current situation, more public commuters should be encouraged. Moreover, pedestrian walks and foot-overs should also be considered as a solution. Those media of communication will engage the urban population in physical activities that reduce the risk of coronary and cardiovascular diseases [36].

Households also play a prolific role in ambient air pollution as well as the emission of $PM_{2.5}$. Some residential and commercial cooking activities are still using solid fuels which creates health hazards similar to $PM_{2.5}$. Green Roof Technologies can reduce the risk of $PM_{2.5}$ in a significant way [37] and are highly suitable and sustainable with respect to the economic, socio-economic and housing properties of Dhaka city.

The mitigation strategy should be associated with urban and site planning. The concept of a sustainable and efficient "smart city" is now a time demanding term with respect to the situation in Dhaka. Long time mitigation plans should be implemented instead of short visioned ones. The mitigation of $PM_{2.5}$ does not only depend on the emission data, but also has to be analyzed with regard to the population exposure. Accordingly, the higher is the tree coverage, the higher is the scope for more $PM_{2.5}$ reduction [38]. Hence, green space is mandatory in the urban fringes and in specific areas where the population is exposed to a greater threat. The findings of this research can also be associated with population exposure data and thus the research will be helpful to meet the vision of mitigating the deadly $PM_{2.5}$ in the cities of Bangladesh as well as Dhaka.

**Table 2** Percentage of AQI level in from 2019 to 2021

| AQI levels of health concern | Numerical value | Indicators | Percentage (2019) | Percentage (2020) | Percentage (2021)—Till June |
|---|---|---|---|---|---|
| Good | 0–50 | Air quality is considered satisfactory, and air pollution poses little or no risk | 3.90 | 2.98 | 0.80 |
| Moderate | 51–100 | Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution | 24.72 | 29.87 | 16.21 |
| Unhealthy for Sensitive Groups | 101–150 | Members of sensitive groups may experience health effects. The general public is not likely to be affected | 17.69 | 15.86 | 14.79 |
| Unhealthy | 151–200 | Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects | 37.08 | 32.39 | 36.18 |
| Very Unhealthy | 201–300 | Health warnings of emergency conditions. The entire population is more likely to be affected | 12.22 | 15.51 | 22.76 |
| Hazardous | 301–500 | Health alert: everyone may experience more serious health effects | 4.39 | 3.40 | 9.26 |

## 4 Conclusion

The correlation of ambient airborne pollution with urban health issues is now a significant point of discussion among urban planners, policymakers, and changemakers. As a result of rapid urbanization, industrial smog and vehicle exhaust create a dense layer of $PM_{2.5}$ in urban areas. Threatening the health of city dwellers, $PM_{2.5}$ is also an agent that causes greenhouse effects, which increase the temperature of the land surface. Dhaka is one of the world's most densely populated and uncontrolled urbanized cities. Ambient air pollution in this city is also an acid headache for the urban planning personnel.

The authors factualized a statistical and analytic presentation on the current status of $PM_{2.5}$ in this study. The prime parameter was the density of $PM_{2.5}$ in the atmosphere. This parameter was evaluated on the basis of time period shifting, lockdown due to COVID 19, wind speed, temperature, and so on. However, all the evaluations showed similarities in the fact that $PM_{2.5}$ concentration in the atmosphere creates a menace in Dhaka's overall urban fabric. Bangladesh government and World Health Organization (WHO) have set standards for $PM_{2.5}$ average concentrations in the atmosphere. The findings of Dhaka city (average concentration = 112.49 $\mu g/m^3$) had crossed both the limits in a pre-eminent proportion. The shifting based findings indicated that the higher deviation of the concentration of $PM_{2.5}$ was found on winter mornings and nights. Rainy seasons had comparatively less deviation due to atmospheric reasons in this time period. The winter season has dry periods that increase dust, pollutants, particulates, and $PM_{2.5}$ concentration. Humidity also plays a key role in increasing and decreasing $PM_{2.5}$ concentration. The correlation between humidity and the density of concentration was found arithmetically disproportional. The COVID-19 issue is prolific in mitigating the ambient air pollution in Dhaka city. The lockdown situation reduced the concentration to a rate of 35.76% in the year 2021. Furthermore, the authors' also proposed mitigation strategies to combat the situation analyzed before. Indication

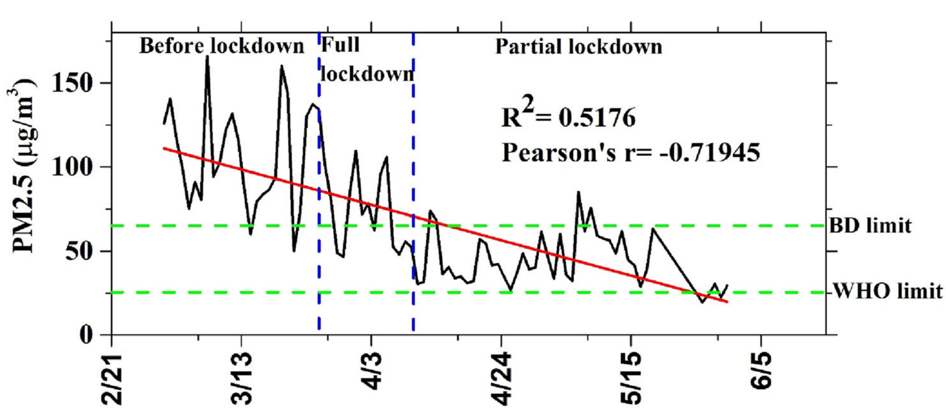



**Fig. 5** $PM_{2.5}$ concentrations in Dhaka City before lockdown, during the strict and partial lockdown

towards smart city planning and increase of green coverage was a prime recommendation. The overall findings and mitigation strategies in this study might help the officials concerned about city planning to an extent. Moreover, three key recommendations based on transportation, industrial, and household particulate emission will assist transport planners, urban planners, and policymakers in sustainable city planning.

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**Authors' contribution** Abdullah-Al- Faisal generated the main ideas, created contents, analyzed, wrote the paper, made proofreading, and drafted the whole manuscript. Abdulla – Al Kafy analyzed, wrote the paper, made proofreading, and drafted the whole manuscript. Md. Abdul Fattah analyzed the data and wrote the introduction and some results section of the manuscript. Dewan Md. Amir Jahir wrote the mitigation strategies and health risk analysis and some portion of the paper. Abdullah Al Rakib, Zullyadini A. Rahaman, Jannatul Ferdousi, Xiao Huang, created maps data analysis, revised the paper based on the reviewer's comments and wrote the manuscript.

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**Data availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Code availability** It will be available on reasonable request.

**Declarations**

**Conflict of interest** 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.

**Ethical approval** This article does not contain any studies with human participants or animals performed by any of the authors.

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