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Traffic-induced air pollution at traffic intersections in Dhaka: seasonal patterns and associated health implications

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Air pollution poses serious environmental and health challenges in Bangladesh. It is necessary to understand the concentration and seasonal variation of particulate matter (PM) and gaseous pollutants at traffic intersections to assess their impact on public health. This study was conducted to measure the levels of PM ($PM_{1.0}$, $PM_{2.5}$ and PM_{10}) and trace gases (CO_2, NO_2) at five traffic intersections in Dhaka, Bangladesh, with the aim of evaluating seasonal variations and associated health risks. Sampling was conducted during the winter (December 2023–January 2024) and pre-monsoon (April–May 2024). Results revealed higher PM concentrations during winter: $PM_{1.0}$, $PM_{2.5}$ and PM_{10} averaged 108.3 ± 14.0, 336.1 ± 68.3 and 449.2 ± 98.7 μg m^{-3} respectively, compared to lower values in the pre-monsoon (41.7 ± 8.6, 93.1 ± 20.1 and 151.9 ± 33.3 μg m^{-3}). NO_2 concentrations were higher during winter (0.13 ± 0.01 ppm) with oscillating diurnal variation and declined in pre-monsoon (0.10 ± 0.02 ppm), which exhibits a clear rising trend. CO_2 levels remained steady around 790 ± 30 ppm throughout both seasons. Health risk assessment showed hazard quotient (HQ) values above 1 for NO_2 (between 1.06 and 1.58), $PM_{2.5}$ (between 0.89 and 4.78) and PM_{10} (between 0.82 and 5.31) posing severe risks to infants. The hazard ratio (HR) for CO_2 ranged between 0.7 and 0.85, indicating no direct health effects. This study emphasizes the immediate need for specific mitigation strategies at traffic intersections to protect public health.

Environmental significance

Traffic intersections in rapidly growing megacities represent critical pollution hotspots with intense human exposure. This study quantifies seasonal variations of particulate matter ($PM_{1.0}$, $PM_{2.5}$, PM_{10}) and gaseous pollutants (NO_2, CO_2) at major intersections in Dhaka, Bangladesh. Winter concentrations of PM were several times higher than pre-monsoon levels, and health risk assessment revealed hazard quotient (HQ) values >1 for $PM_{2.5}$, PM_{10}, and NO_2, particularly for infants. Strong correlations between pollutants and vehicle density highlight traffic emissions as a dominant source. These findings emphasize the urgent need for targeted traffic management and emission-control strategies to reduce human exposure at urban intersection hotspots.

1. Introduction

Air pollution is now regarded as a major global threat due to its negative effects on the environment, the economy and human health[1–4] and is also responsible worldwide for 9 to 12 million deaths annually.[5,6] It is commonly acknowledged that transportation is one of the major and growing global sources of air pollution[2,7–9] and traffic intersections are the centers of air pollution and create complicated traffic activities involving numerous pedestrians.[10–13] The emission of traffic-related air pollutants at traffic intersections can be two to three times greater than the ambient background resulting from vehicles' continuous acceleration, slowdown and idling.[14,15] The emissions of PM and gases (NO_x, SO_x, CO_2, VOCs, *etc.*) from engine exhaust, as well as secondary air pollutants, are some of the ways that road traffic contributes to air pollution.[14,16,17] Non-exhaust emissions include resuspended dust and wear on the tires, brakes and road surface.[18,19]

Low-Middle Income Countries (LMICs) like Bangladesh are seeing a sharp rise in air pollution from brick kilns, mining, automobiles, industry and agriculture.[20–25] Air pollutants, including PM and gaseous pollutants have accumulated as a result of these activities.[26] Dhaka is the commercial and industrial hub of Bangladesh with a population of more than 21 million and is expanding quickly despite all the issues that

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come with being a megacity.[16,27–29] Among the many issues brought on by the city's explosive growth is traffic congestion, which has grown to be a significant burden for commuters and locals alike. The rapid growth in motorized vehicles has resulted from Dhaka's fast urbanization and population development, greatly increasing urban air pollution.[25,26,30] The country's inadequate transportation system contributes to the high levels of PM pollution on the majority of its roadways, which has a detrimental health effect on the city people.[31–33] Recent studies have demonstrated increased illness and mortality among drivers, passengers and those residing close to major roadways as a result of traffic congestion.[16,34] Respiratory ailments are more common in Dhaka's urban dwellers due to traffic-related air pollution, and hospitalization for respiratory disorders is closely linked to air pollutant exposure.[21,35,36] The high level of air pollution has particularly impacted children and the elderly.[37] Road users experience high to extreme levels of stress due to traffic congestion.[38,39]

Monitoring air quality at traffic intersections is essential to determine its impact on human health and how seasonal variations influence daily activity, yet empirical data remain limited. Mullick[40] along with Hashem[41] has studied a cross-sectional survey regarding the knowledge, practices and respiratory health effects of air pollution among the traffic police exposed to vehicular emissions in Dhaka city, Bangladesh, and Rahman[42] has studied the self-reported health effects of air pollution on urban residents in Dhaka city, Bangladesh. Hoque[43] analyzed the spatiotemporal distribution and seasonal variations of air pollutants in fifteen different locations of Dhaka city, Bangladesh; no study has yet directly focused on air pollution at traffic intersections. Furthermore, the correlation between air pollutants and vehicles at the traffic intersections also needs to be monitored to assess the contribution of air pollution due to traffic.

This study shows the temporal and seasonal variations of air quality at traffic intersections with their health effects. The relationship between average traffic number and air pollutants, which directly affects all types of intersection users, as well as a deeper understanding of the origin of PM, CO_2 and NO_2 is studied. The study's findings focus on the insight into current implementation and policy gaps and offer suggestions for possible ways to lower emissions from pollution sources generated by humans.

2. Methodology

2.1. Meteorology of Bangladesh

Bangladesh's weather pattern is characterized by its tropical monsoon, which is marked by high temperatures, humidity and clear seasonal fluctuations.[32,44] From a climatic perspective, there are four distinct seasons: (1) the hot summer pre-monsoon season, which lasts from March to May; (2) the dry winter season, which lasts from December to February; (3) the wet monsoon season, which lasts from June to September and (4) the post monsoon fall season, which lasts from October to November.[27,31,44] The usual pre-monsoon temperature ranges from 27 to 29 °C, whereas the average winter temperature ranges from 18 to 21 °C.[45,46] The relative humidity ranges from 65 to 79% during pre-monsoon and has a mean of 74% during winter.[47]

2.2. Sampling sites

Five traffic intersections (Fig. 1) in Bangladesh's capital, Dhaka (latitude 23°76′N, longitude 90°38′E, 8 m above sea level),[48] were sampled to guarantee representativeness and diversity under traffic conditions. Mirpur-10 (23°48′24.9″N 90°22′06.6″E) crossroads, an important intersection in Mirpur, is often used by both public and private transportation. It is notoriously congested during the rush hour because of its advantageous location that links several roads. Traffic intersection Mirpur-1 (23°46′54.4″N 90°21′06.4″E) is an entrance to large urban districts; this crossroads is another important one in Mirpur, with high traffic density, especially from local transportation services and business vehicles. Bijoy Sarani (23°45′52.1″N 90°23′19.4″E) crossroads, ideally situated close to important business and administrative areas, experiences a mixture of vehicles including motorcycles, buses and cars that make up the intense commuting traffic. Gulistan (23°43′40.2″N 90°24′37.8″E) crossroads is a busy and central Dhaka traffic center, characterized by a high volume of traffic including private vehicles, rickshaws and buses. The intersection of Banani (23°47′49.1″N 90°24′06.0″E) situated in an affluent residential and business district, has heavy traffic because it's close to schools, shopping malls and business offices.

2.3. Sampling procedure

The study employed a comprehensive temporal sampling strategy to monitor air quality parameters across multiple sites during two distinct seasonal periods: the winter season, which was from December 2023 to January 2024 and the pre-monsoon period from April 2024 to May 2024. The sampling protocol for PM, NO_2 and CO_2 was systematically designed to capture diurnal variations by conducting measurements at three specific time intervals throughout the day: morning time (9:00 AM to 10:00 AM), afternoon time (1:00 PM to 2:00 PM) and evening (5:00 PM to 6:00 PM).[43,49,50] The number of vehicles was counted manually throughout the sample time in the traffic intersections. To ensure temporal consistency between traffic volume and pollutant concentration data, trained field personnel recorded all vehicles passing while also sampling air pollutants. To generate a representative estimate of traffic intensity, vehicle counts were averaged during the whole sample period at each site. This approach was used to establish a correlation between traffic volume and pollutant concentrations (PM, CO_2 and NO_2), as vehicles are the primary source of these pollutants in the research area.

Sampling of PM, NO_2 and CO_2 was done for three successive days in each location. The study spanned a total of 30 sampling days with 15 days in each season. Gaseous pollutants NO_2 and CO_2 were monitored by the AEROQUAL 500 SERIES (Aeroqual Ltd, Auckland, New Zealand) successively in one hour and with intervals of 15 minutes. PM concentrations were recorded using an AEROCET 531S (Met One Instrument, Washington, USA)

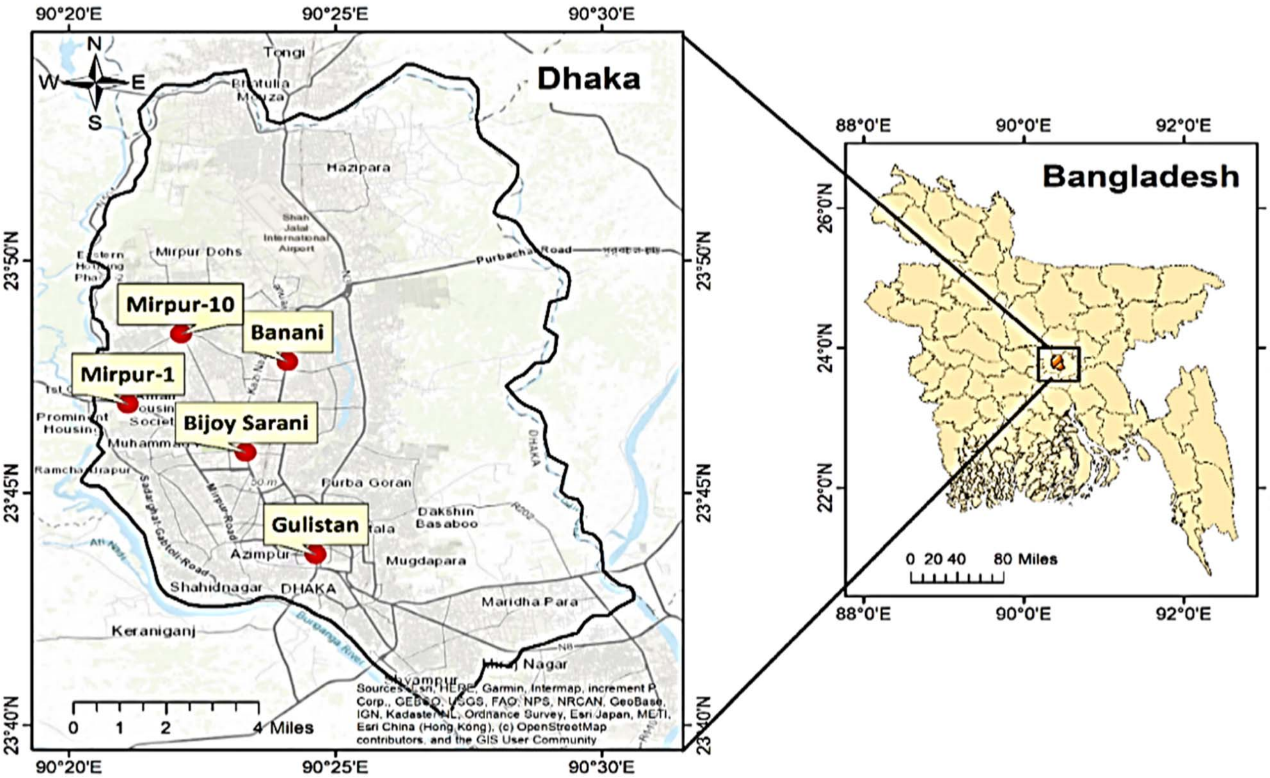

Fig. 1 Five sampling locations (Mirpur-10, Mirpur-1, Bijoy Sarani, Gulistan and Banani) chosen for particulate and gaseous pollutants sampling in Dhaka city, Bangladesh.

Table 1 Health risk assessment data for different ages[21,57,58]

Factors	Infant (0–1 year)	Children (6–12 years)	Adult (21–70 years)
Inhalation rate (m^3 h^{-1})	6.8	13.8	16
Body weight (kg)	11.3	45.3	80
Exposure frequency (days per year)	350	350	350
Exposure duration (years)	1	12	30
Average time for a lifetime (days)	365	4380	10 950

every 3 minutes, which allowed achieving high temporal resolution of particle size distribution.[31,37,43,49,51,52]

2.4. Health risk assessment due to PM and NO_2 exposure

NO_2 and PM ($PM_{2.5}$ and PM_{10}) are categorized as Group 1 carcinogens to humans as per the IARC.[53,54] NO_2 is classified as a component of air pollution and is associated with combustion processes, such as from power plants or vehicles. There is sufficient evidence of the human carcinogenic risk of exposure to NO_2 demonstrated by this categorization.[54,55] Only non-carcinogenic risk was identified for PM and NO_2 using the USEPA-recommended technique (USEPA, 2009). The lifetime average daily dosage (LADD) is determined using the following equation:[21,37,56]

$$\text{LADD} = \frac{\text{CA} \times \text{IR} \times \text{ED} \times \text{EF}}{\text{BW} \times \text{AT}} \tag{1}$$

where CA = contaminant concentration (μg m^{-3}), IR = inhalation rate (m^3 h^{-1}), ED = exposure duration (years), EF = exposure frequency (days per year), BW = body weight (kg) and AT = average time for a lifetime (days) (Table 1).

The HQ is determined by the ratio of LADD to REL:[57]

$$\text{HQ} = \frac{\text{LADD}}{\text{REL}} \tag{2}$$

where REL = reference exposure level. For $PM_{2.5}$ and PM_{10} the values for REL are 50 and 75 μg m^{-3} respectively[21,58,59] and according to USEPA (2008), REL value of NO_2 is 100 μg m^{-3}. REL is the threshold at which exposed groups may experience negative health impacts in comparison to unexposed groups.[60]

2.5. Health risk assessment of CO_2

Global average atmospheric CO_2 concentration has been increasing and it has exceeded 420 ppm now (USEPA). Although CO_2 is a normal constituent of the earth's atmosphere, high concentration can have several impacts on human health and thus should be evaluated. Using formula (3), the hazard ratio (HR) was computed by dividing the average CO_2 concentration by the reference concentration:[61]

$$\mathrm{HR} = \frac{C}{\mathrm{RfC}} \tag{3}$$

where C = average observed CO_2 concentration, R_fC = reference concentration (1000 ppm).

When the HR is less than 1, non-carcinogenic health consequences are not taken into account. On the other hand, if HR is more than 1, the exposure may be associated with non-cancer risks.

2.6. Quality control and quality assurance

AEROQUAL 500 SERIES (Aeroqual Ltd, Auckland, New Zealand) implements a nondispersive infrared (NDIR) approach with a precision of <±10 ppm + 5% for the measurement of CO_2 concentration. NO_2 concentrations are detected with a precision of <±0.02 ppm + 10% using gas-sensitive electrochemical (GSE) sensors. PM concentrations were recorded using an AEROCET 531S (Met One Instrument, Washington, USA) in μg m^{-3} with a ±10% accuracy.[31,37,43,49,51,52] Additionally, a standard filter-based device termed SIBATA (Model-090860-504, Saitama, Japan) was used to compare the devices[31] and the results were in good agreement within 10%. The AEROCET 531S works on the principle of scattered light, which is studied as aerosols pass through a laser beam. Volume and distribution of the scattered light are therefore followed in order to understand the size and concentration of particles within the sample. This makes it possible to monitor aerosol particles in real-time while the size range is from the nanometer scale to the micrometer scale.[62]

2.7. Statistical analysis

The correlation coefficient (R^2), Pearson's correlation and Analysis of Variance (ANOVA) test were determined using Origin 2025 and Microsoft Excel, respectively, to identify the pollutants' primary sources, study the correlation among the pollutants and evaluate the significance of contributing variables.

2.7.1 Principal component analysis (PCA). PCA is a multivariate statistical technique that simplifies the complexity of large datasets by representing most of the information with a smaller set of variables.[63,64] This method is based on the hypothesis that limited numbers of the primary components, obtained as linear combinations of the original variables, can adequately capture the fundamental patterns of the data.[65] The primary components are uncorrelated, therefore lowering redundancy in the obtained information.[66] In PCA, the following dimensionless standard equation is established based on the chemical dataset in order to normalize the variables:

$$Z_{ij} = \frac{C_{ij} - \overline{C_j}}{\sigma_j} \tag{4}$$

In this analysis, i denotes the individual samples, ranging from 1 to n; while j indicates the components under consideration, varying from 1 to m. (C_{ij}) is the presentation of component j's concentration in sample i. The arithmetic mean concentration of component j (C_j) and its standard deviation (σ_j) are used to standardize the data.

3. Results and discussion

3.1. Temporal and seasonal distribution of PM in Dhaka city

The average levels of PM in Mirpur-10, Gulistan, Bijoy Sarani, Mirpur-1 and Banani across three size categories: $PM_{1.0}$, $PM_{2.5}$ and PM_{10} are shown in Fig. 2. PM concentrations during winter: $PM_{1.0}$, $PM_{2.5}$ and PM_{10} averaged 108.3 ± 14.0, 336.1 ± 68.3 and 449.2 ± 98.7 μg m^{-3}, respectively, compared to lower values in the pre-monsoon season, roughly about one-third to half of winter levels (41.7 ± 8.6, 93.1 ± 20.1 and 151.9 ± 33.3 μg m^{-3}), indicating improved air quality than during the winter season. Traffic and construction influenced areas Mirpur-1 and Banani showed higher PM levels than relatively less impacted traffic intersections. PM_{10} was significantly influenced by vehicles, road dust and construction activities. The intermediate source of $PM_{2.5}$, which was mostly produced by combustion processes in factories and automobiles, had a value between 270 and 300 μg m^{-3} during winter and 70 to 110 μg m^{-3} during pre-monsoon across five traffic intersections. Observations in 2017 showed that $PM_{2.5}$ was 29.6 μg m^{-3} and PM_{10} was 56.6 μg m^{-3}.[29] Between 2016 and 2022, $PM_{2.5}$ values ranged from 4.94 to 351.2 μg m^{-3}, with an observed range of 346.3 μg m^{-3} (ref. 67) and the winter months (December–February) had significantly higher $PM_{2.5}$ concentrations, which exceeded 250 μg m^{-3}.[68,69] Throughout the dry season, the average mass concentration of $PM_{2.5}$ and PM_{10} were 27 ± 8 and 109 ± 38 μg m^{-3}, respectively, at an industrial site in Nigeria.[70] The lowest concentrations were seen in $PM_{1.0}$, the minimal particle size, which was between 90 and 120 μg m^{-3} during winter and 30 and 50 μg m^{-3} during the pre-monsoon season. $PM_{1.0}$ might penetrate deeper lung tissues and blood arteries, making it extremely harmful to human health.[71,72] During winter, PM concentrations peaked in the morning at all five traffic intersections due to rush-hour vehicular emissions and a shallow planetary boundary layer. A distinct diurnal trend with high PM levels in the morning hours has been observed for Dhaka, principally impacted by traffic emissions and time-of-day climatic influences.[73,74] During the afternoon, concentrations gradually decreased as solar heating extended the boundary layer, increasing vertical mixing and atmospheric dilution.[75,76] Pre-monsoon PM concentrations were significantly lower, with a weaker diurnal structure due to stronger winds, higher temperatures that promote air mixing and increased wet deposition. Strong winds during the pre-monsoon disperse PM concentrations, and meteorological conditions explain up to 76% of daily PM variability.[77]

3.2. Temporal and seasonal distribution of NO_2 in Dhaka city

NO_2 levels were consistently higher during the winter than pre-monsoon at all locations (Fig. 3). Depending on the region under study, average winter NO_2 concentrations ranged from

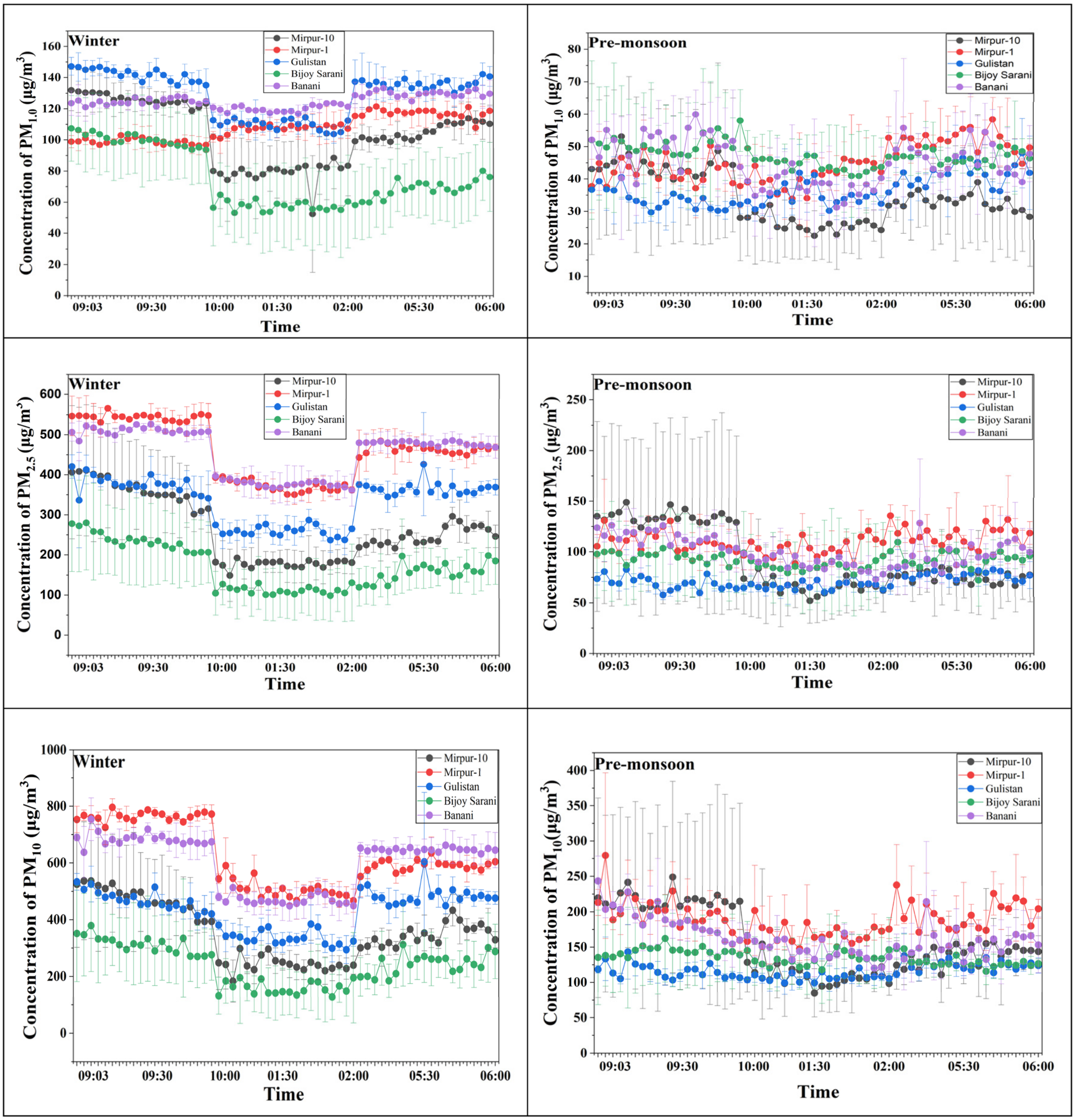

Fig. 2 Seasonal distribution of PM concentration during winter and pre-monsoon seasons at Mirpur-10, Mirpur-1, Bijoy Sarani, Gulistan and Banani in Dhaka city, Bangladesh.

0.12 to 0.16 ppm. Concentrations dropped to between 0.08 and 0.12 ppm during the pre-monsoon. The winter season is characterized by low ultra-violet radiation intensity, high relative humidity and a significant decrease in the height of the atmospheric boundary layer. As a result, the concentration of NO_2 released by vehicles is concentrated in a shallow surface layer, increasing the concentration at the ground level. Gulistan and Bijoy-Sarani had the greatest NO_2 concentrations in winter and pre-monsoon seasons, respectively, possibly as a result of industrialization and vehicle density. The comparatively lower results from two stations, Banani and Mirpur-10, suggested a smaller contribution from local emissions. Excessive coal burning in the brickfields close to Dhaka city during the winter may be linked to high NO_2 concentrations in the atmosphere.[78] A similar pattern of NO_2 concentrations was observed in Dhaka city in 2003 to 2019,[22,29,79] suggesting a consistent trend over the decade. The average NO_2 concentration was 5.8 ppm, with a range of 5.6 to 6.1 ppm during December 2021 and January 2022 in Dhaka.[43] Similar trends were noted in India and China as well, suggesting a more widespread regional uniformity in the levels of NO_2 pollution in metropolitan areas.[80,81] These results also imply that vehicle emissions continue to be the primary cause of NO_2 concentrations in densely populated urban areas.[80–84] Low temperatures and slow airflow brought on by cold-season weather patterns might be the origin of this seasonal trend, which confines pollutants to the atmosphere. In the pre-monsoon, high spatial and temporal variability was observed, whereas it is considerably larger around midday and afternoon during the winter, showing higher variability. Later in the day, converging concentrations are visible at all five traffic intersections during the winter season. NO_2 concentrations remain consistently higher and more fluctuating during the winter, whereas pre-monsoon seasons exhibit a clear rising trend, indicating stronger diurnal variation across all traffic intersections. NO_2 concentrations increase with progression of the day, indicating vehicular emissions as a significant source.[43,78] Greater air mixing and increased solar energy radiation, which cause pollutant fluctuation, are the causes of the pre-monsoon's more significant diurnal variation. Pollutants remain trapped close to the surface during the winter months due to temperature inversions and slow winds, which keep concentrations mostly constant throughout the day.[76,85,86]

3.3. Temporal and seasonal distribution of CO_2 in Dhaka city

CO_2 levels (Fig. 4) are generally greater in winter than in the pre-monsoon season. A similar seasonal variation in CO_2 concentration was also observed in Ahmedabad, India, during the period from 2014 to 2015, although the overall levels were lower. Specifically, concentration averaged 424.8 ± 17 ppm in winter and 398.8 ± 2.8 ppm in the pre-monsoon season.[87] CO_2 concentrations varied from 537 to 568 ppm (average: 554 ppm) during December 2021 and January 2022 in Dhaka.[43] Nearly identical levels of CO_2 concentration were suggested by each of the five traffic intersections. All of the location's CO_2 levels stayed between 700 and 900 ppm, indicating that CO_2 levels were often high in metropolitan areas. Concentrations typically peak in the early morning during both seasons, fall during the middle of the day and then slightly increase again in the evening which is also evident in China and Korea.[88–90] Heavy traffic emissions during the morning rush hour and an insignificant boundary layer that restricts the dispersion of pollutants near the surface are the main causes of the elevated CO_2 concentrations seen in the early morning. A similar diurnal pattern was seen during the pre-monsoon season, however there was less variability and a lower peak concentration than during the winter. Bijoy Sarani typically has the lowest CO_2 levels, whereas Mirpur-10 and Banani have the highest amounts as a result of increased traffic or local emissions. These patterns show how urban activity and weather patterns affect the distribution of CO_2 throughout the day. It was evident that diverse sources of emissions were responsible for the equal amounts of CO_2 concentrations.

3.4. Correlation among the pollutants

Pearson's correlation (r) and ANOVA test were carried out to analyze the relationship among the various pollutants (CO_2, NO_2, $PM_{1.0}$, $PM_{2.5}$ and PM_{10}). The correlation coefficient (R^2) was determined to relate to the air pollutants with the average vehicle number at different traffic intersections in Dhaka city. Pearson's correlation analysis results are presented in Table S2. The correlation analysis showed positive correlations among NO_2, CO_2, $PM_{1.0}$, $PM_{2.5}$ and PM_{10} concentrations. The Pearson correlation coefficients of pollutants during winter were 0.96 (NO_2 and CO_2), 0.53 ($PM_{1.0}$ and $PM_{2.5}$) and 0.78 ($PM_{2.5}$ and PM_{10}) and during pre-monsoon were 0.58 ($PM_{1.0}$ and $PM_{2.5}$), 0.95 ($PM_{2.5}$ and PM_{10}) and 0.64 (CO_2 and PM_{10}) ($p < 0.05$). Positive correlations indicate a strong linear correlation among the pollutants. According to the results of the ANOVA test, the connection between PM and gaseous pollutants is statistically significant ($p < 0.05$) (Table S2). Strongly positive correlation was also observed in Dhaka,[43] Chattogram,[91] Bangladesh, and

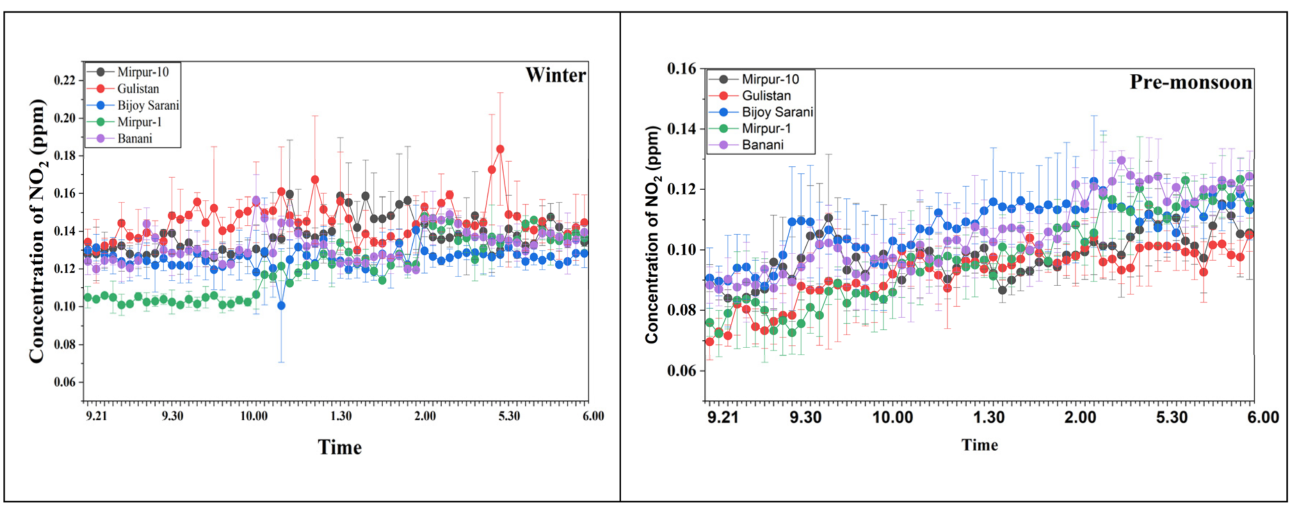

Fig. 3 Seasonal distribution of NO_2 concentration during winter and pre-monsoon at Mirpur-10, Mirpur-1, Bijoy Sarani, Gulistan and Banani in Dhaka city, Bangladesh.

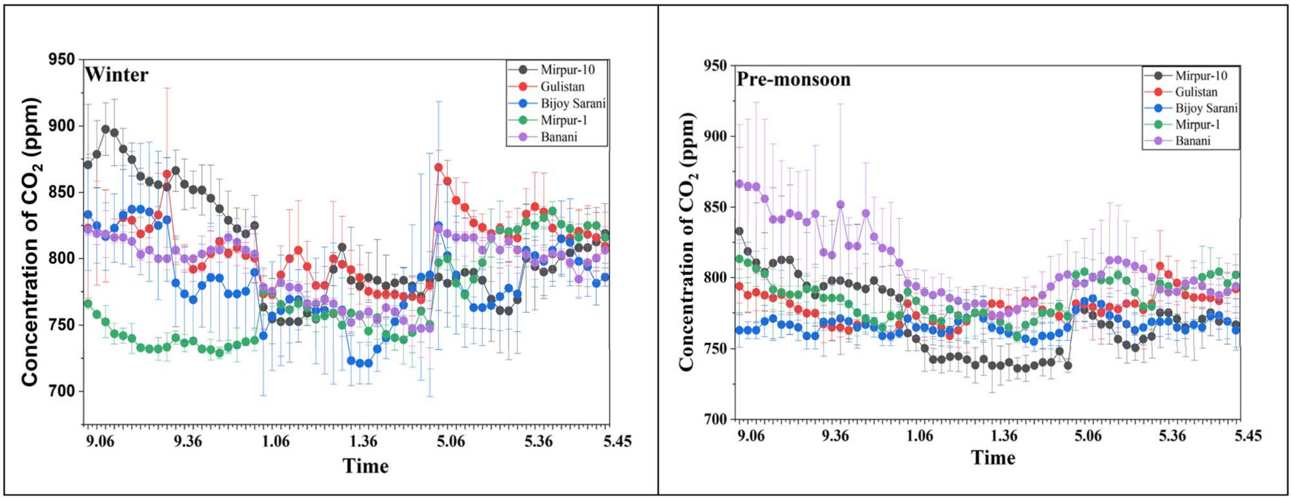

Fig. 4 Seasonal distribution of CO_2 concentration during pre-monsoon and winter at Mirpur-10, Mirpur-1, Bijoy Sarani, Gulistan and Banani in Dhaka city, Bangladesh.

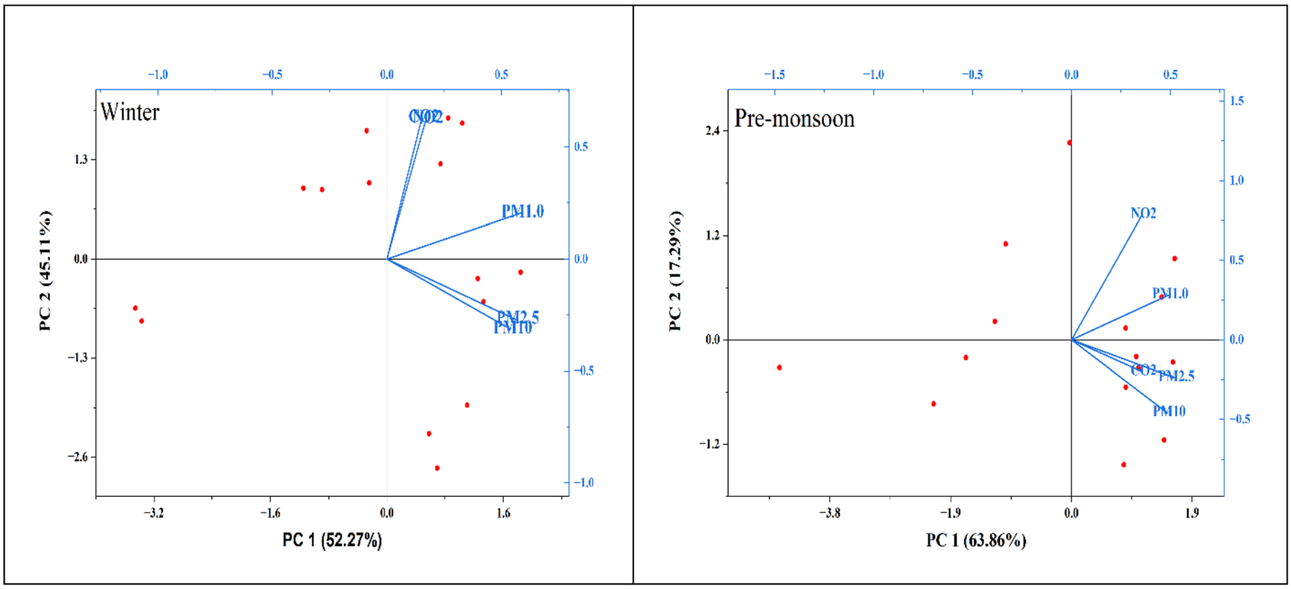

Fig. 5 The PCA biplot highlighting the relationships between particulate matter and gaseous pollutants during winter and pre-monsoon seasons at Mirpur-10, Mirpur-1, Bijoy Sarani, Gulistan and Banani in Dhaka city, Bangladesh.

Southern China and California.[78,92] In contrast, during the COVID-19 lockdown, a weakly positive correlation was observed between the pollutants in Wuhan, China.[93] Vehicular emissions are a primary source of NO_2 and CO_2 both of which contribute to the formation of PM.[82] The present study analysis showed a statistically significant ($p < 0.001$) moderately positive correlation ($R^2 = 0.40$) between $PM_{1.0}$ concentration and the average vehicle number during the pre-monsoon season. This correlation indicates that fossil fuel combustion from vehicles is a dominant contributor to $PM_{1.0}$ pollution in traffic intersections. $PM_{2.5}$ and PM_{10} show strong positive correlations, while positive associations were also found among NO_2, CO_2, $PM_{1.0}$, $PM_{2.5}$ and PM_{10}.[94–96] These findings suggested that pollutants were emitted from similar sources, primarily linked to vehicular activity, emphasizing the need for stringent vehicular emission controls and enhanced traffic management to alleviate air pollution in traffic intersections.

3.4.1 Principal component analysis (PCA). Principal Component Analysis (PCA) was employed to identify the major sources contributing to particulate matter and gaseous pollutants at the traffic intersections during winter and the pre-monsoon season in Dhaka city, Bangladesh. The analysis employed a Varimax rotation to improve the interpretability of factor loadings by maximizing the coefficient of variation. This allows for a clearer identification of groups influencing particulate matter and gaseous pollutants (Fig. 5).

During the winter season, the first two principal components (PC1 and PC2) exhibited eigenvalues of 2.61 and 2.26 respectively, accounting for 97.38% of the total variance, showing that they sufficiently reflect the dataset (Table S4). PC1 accounted for 52.27% of the total variance and exhibited a significant correlation with particulate matter fractions, specifically $PM_{1.0}$ (0.583), $PM_{2.5}$ (0.562) and PM_{10} (0.540) (Table S5). The substantial positive loadings of these variables indicate that PC1 is a particulate matter-dominated source, most likely due to resuspended road dust, construction activities and traffic-related emissions.[97] PC2 indicated a very distinct loading pattern, with strong positive loadings for CO_2 (0.629) and NO_2 (0.625) (Table S5). This bipolar arrangement is consistent with a gaseous combustion emission factor, which is mostly caused by industrial burning, vehicle exhaust and energy generation activities that release CO_2 and NO_2 at the same time. The first two principal components (PC1 and PC2) exhibited eigenvalues of 3.193 and 0.865, respectively, cumulatively explaining 81.16% during the pre-monsoon season (Table S6). PC1 is a general air pollution factor that reflects the overall intensity of anthropogenic emission activity, such as fuel combustion, and recorded high and approximately uniform positive loadings across all five pollutants: NO_2 (0.356), CO_2 (0.356), PM_{10} (0.485), $PM_{2.5}$ (0.521) and $PM_{1.0}$ (0.490) (Table S7). PC2 showed a unique loading pattern, with a substantial positive loading for NO_2 (0.784), indicating NO_2 from industrial and vehicle combustion. PC3 was dominated by an unusually high loading for CO_2 (0.908). This component captures industrial emissions that are uncorrelated with the major emission complex. These results are consistent with prior PCA based source apportionment studies conducted in urban environments, which consistently identify different gaseous and particle emission sources as the main causes of air pollution variance.[43,98–100]

3.5. Health risk assessment

Air pollution had a major chronic impact on all age groups, with infants and children suffering the most.[101–105] HQ was used to evaluate the non-cancer hazards related to air pollution.[106,107]

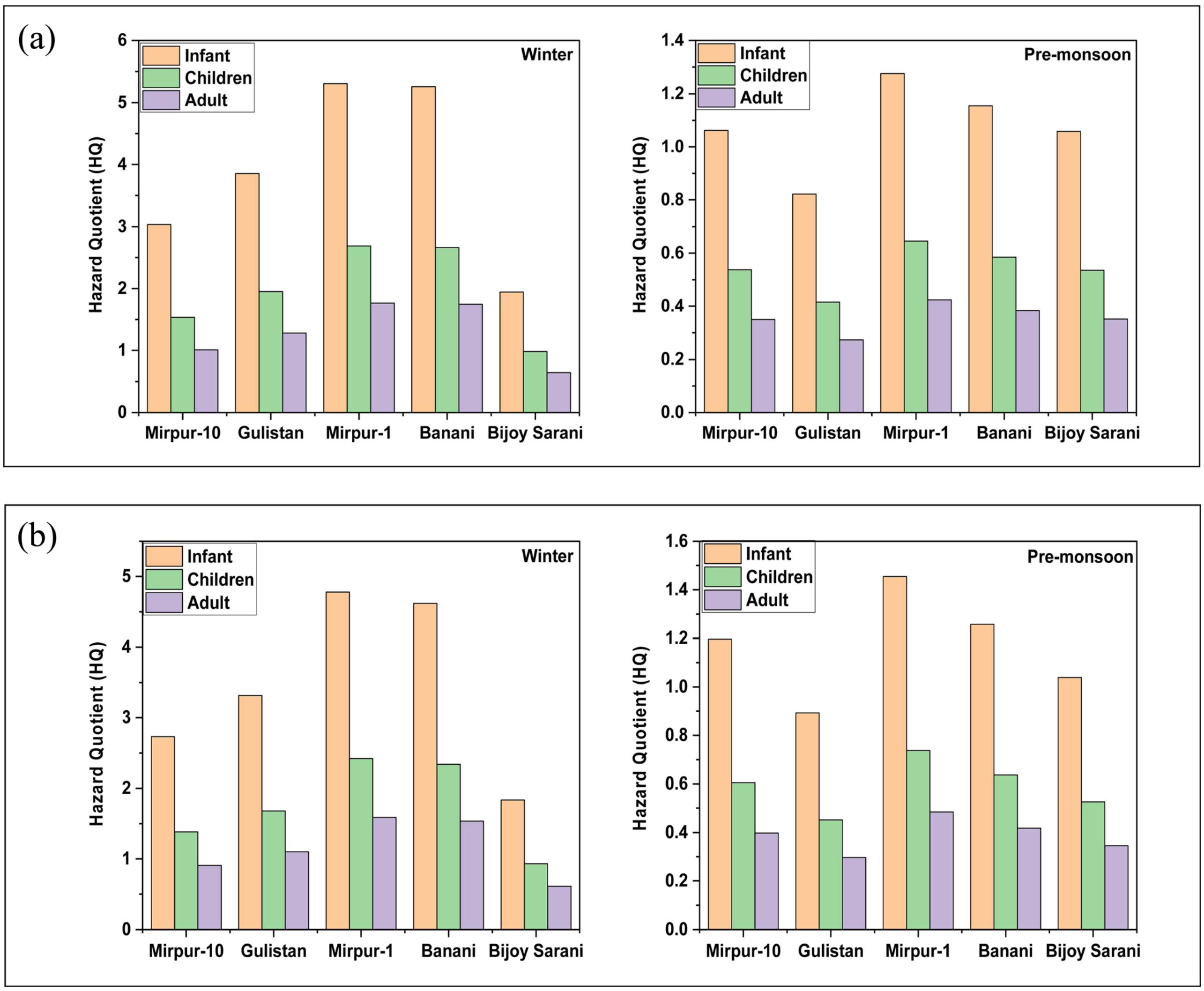

Fig. 6 (a) HQ variation of $PM_{2.5}$ during winter and pre-monsoon seasons for different ages at Mirpur-10, Mirpur-1, Bijoy Sarani, Gulistan and Banani in Dhaka city, Bangladesh. (b) HQ variation of PM_{10} during winter and pre-monsoon for different ages at Mirpur-10, Mirpur-1, Bijoy Sarani, Gulistan and Banani in Dhaka city, Bangladesh.

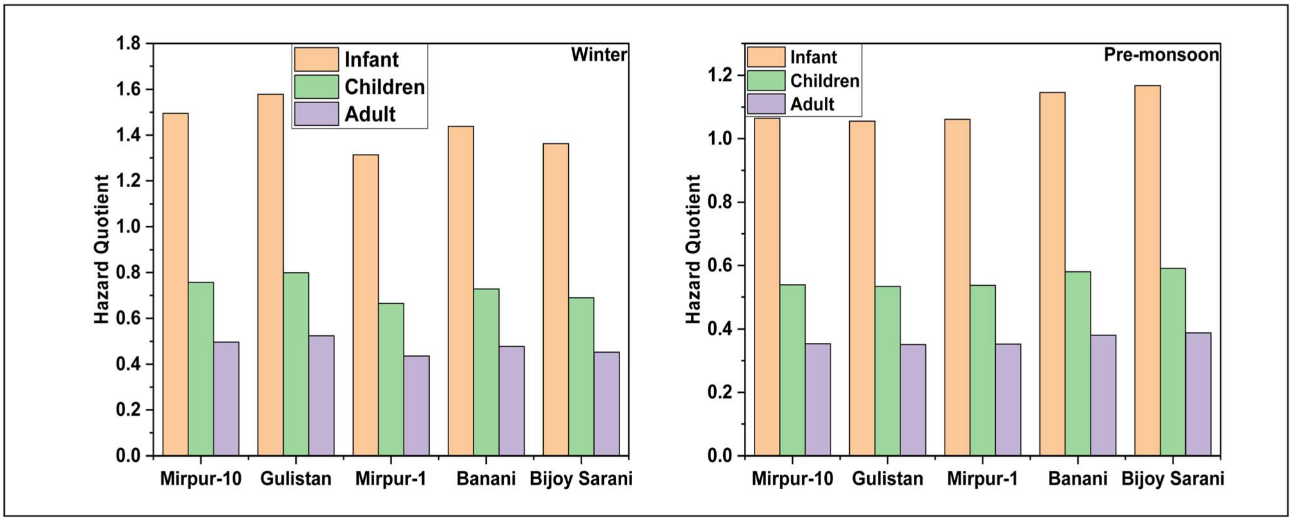

Fig. 7 HQ variation of NO_2 during winter and pre-monsoon for different ages at Mirpur-10, Mirpur-1, Bijoy Sarani, Gulistan and Banani in Dhaka city, Bangladesh.

While there was no risk of adverse health consequences (HQ < 1) for the pollutants in the case of adults, the HQ values posed a considerable health threat (HQ > 1) for infants and children. Low breathing heights with other air pollution sources may be the primary cause of this problem in youngsters, who are especially vulnerable to ground-level pollution.[108] Infants are exposed to concentrations of fine particles that are up to 44% greater than those of adults, according to research done at a school by Sharma and Kumar.[109]

3.5.1 Health risk assessment of PM. At every site, the HQ values of $PM_{2.5}$ and PM_{10} (Fig. 6(a) and (b)) for every age group were greater throughout the winter than they were during the pre-monsoon season. This could happen as a result of wintertime weather conditions which prevent reduction of PM.[110,111] Although HQ levels continue to decline during the pre-monsoon season, newborns are particularly at risk and in certain clusters, the HQ stays over the allowed limits. Because the young population is more susceptible to particulate matter exposure due to the physiological immaturity of the respiratory tract and higher inhalation rates of particulate matter per unit body weight, newborns had much higher HQ values than children and adults.[112–114] Mirpur-1 and Banani showed the highest HQ values for all age groups, with infants exceeding a hazard quotient of 4. According to Bijoy Sarani's appendix, it had lower HQ values than any other place for both adults and children, indicating less exposure to PM or cleaner air. Similar to the winter, the HQ values in Banani and Mirpur-1 were higher during pre-monsoon. In locations like Bijoy Sarani and Banani, pre-monsoon PM levels remained hazardous despite being lower, particularly for young children. $PM_{2.5}$ can enter the lungs,[115] whereas $PM_{1.0}$ can penetrate blood vessels through alveoli, capturing the entire body.[116,117] In addition, $PM_{1.0}$ has a greater surface to mass ratio and can contain a high concentration of potentially toxic anthropogenic components.[118] Short-term exposure to $PM_{1.0}$ has been regarded as the cause of death due to stroke, while long-term inhalation can raise the risk of neurological diseases.[119–121] It was also noted that babies who grow up in places with PM concentrations higher than the upper limit are more likely to experience harmful health consequences, including respiratory ailments and heart problems.[122–124] The population most vulnerable to environmental pollution, particularly children because of their developing organs and immune systems, was at risk for serious health impacts from PM.[125–127]

PM causes numerous adverse health consequences, including a higher incidence of myocardial infarction, diabetes, respiratory diseases, cardiovascular and cerebrovascular diseases and lung cancer,[5,122,128,129] in addition to negative health effects, including bronchial asthma, pneumonia and pulmonary disease.[130–133]

3.5.2 Health risk assessment of NO_2. The overall HQ values (Fig. 7) for all age groups and all locations were greater throughout the winter than they were during pre-monsoon. This might be due to wintertime weather conditions, which limit the concentration of pollutants to areas near the surface (*e.g.*, low mixing heights).[134,135] Infants exhibited the greatest HQ values, followed by children and adults. Infants were exposed to more air pollution than adults, making them far more vulnerable due to their developing organ systems. Mirpur-10, Gulistan and Bijoy Sarani have higher HQ levels than the Banani and

Table 2 Hazard ratio (HR) data for health risk assessment of CO_2

Sampling sites	Hazard ratio (HR) Pre-monsoon	Winter
Mirpur-10	0.7705	0.8069
Gulistan	0.7781	0.8086
Mirpur-1	0.7856	0.7694
Banani	0.8074	0.7928
Bijoy Sarani	0.7666	0.7832

Mirpur-1 areas. These discrepancies might have resulted from variations in the industrial activity and vehicle emissions that caused urban traffic congestion in various regions. Wintertime HQ values for infants at Mirpur-10, Gulistan and Bijoy Sarani were seen to increase to levels near or over the crucial level of 1. Therefore, NO_2 exposure was found to provide a non-carcinogenic health risk for newborns exposed to several places during the winter, as indicated by HQ values >1 (USEPA). Airway inflammation and obstruction of airflow are caused by NO_2 exposure.[136–140] Annually, ambient NO_2 is responsible for 3.52 million new cases of asthma in children and adolescents.[141]

3.5.3 Health risk assessment of CO_2. The HR of CO_2 for the pre-monsoon and winter seasons for the five traffic intersections is shown in Table 2. The HR values range from 0.7 to 0.85. With minor seasonal fluctuations noted at various places, the HR values were generally steady across both seasons. As CO_2 concentrations raised, the mean raw scores for seven of the nine decision-making performance scales consistently fell[142,143] and cognitive impacts[144] were observed in comparison to 600 to 1000 ppm ($0.6 < HR < 1.0$).

Short sampling duration, fewer traffic intersections and non-simultaneous pollution measurements are the limitations of this study. Future research should include simultaneous measurements, more traffic intersections and prolonged sampling period throughout several seasons (winter, pre-monsoon, monsoon and post-monsoon) to better capture the spatial and temporal variability in traffic-related air pollution.

4. Conclusion

This study investigated the seasonal and temporal variations of particulate matter ($PM_{1.0}$, $PM_{2.5}$, PM_{10}) and gaseous pollutants (NO_2, CO_2) at five major traffic intersections in Dhaka during winter (December 2023–January 2024) and pre-monsoon (April–May 2024). Results showed substantially higher pollutant levels in winter ($PM_{1.0} = 108.3 \pm 14.0\ \mu g\ m^{-3}$, $PM_{2.5} = 336.1 \pm 68.3\ \mu g\ m^{-3}$ and $PM_{10} = 449.2 \pm 98.7\ \mu g\ m^{-3}$, $NO_2 = 0.13 \pm 0.01$ ppm) with Gulistan, Mirpur-10, Banani and Mirpur-1 emerging as hotspots for different pollutants. Health risk assessment revealed HQ values greater than one for NO_2, $PM_{2.5}$ and PM_{10}, indicating serious risks, particularly for infants, while CO_2 levels (790 ± 30 ppm) mainly highlighted climatic rather than direct health impacts. The Pearson correlation analyses demonstrated strong associations among pollutants and a moderate link between $PM_{1.0}$ and vehicle numbers ($p < 0.001$, $R^2 = 0.40$) during the pre-monsoon season, underscoring the central role of traffic emissions. The PCA analysis indicated that traffic emissions are one of the major sources of PM, NO_2 and CO_2. The findings of this study indicate the urgent need for sustained assessment and effective intervention strategies to mitigate traffic-related air pollution in Dhaka. Future research should focus on expanding spatial and temporal coverage, including more intersections and continuous year-round monitoring, to capture long-term trends and the influence of meteorology.

Author contributions

Md. Khorshed Alam Howlader: conceptualization, sampling, methodology, data analysis, writing original draft, review & editing. Shahid Uz Zaman: review & editing, supervision. Md. Al-Amin Hossen: review & editing. Md. Adnan Kiber: review & editing. Abdus Salam: conceptualization, review & editing, supervision.

Conflicts 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.

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d6ea00036c.

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