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Measurement of ambient particulate matter ($PM_{1.0}$, $PM_{2.5}$ and PM_{10}) in Khulna City of Bangladesh and their implications for human health

Jobaer Ahmed Saju[1*], Quazi Hamidul Bari[1], Kazi A. B. M. Mohiuddin[1] and Vladimir Strezov[2]

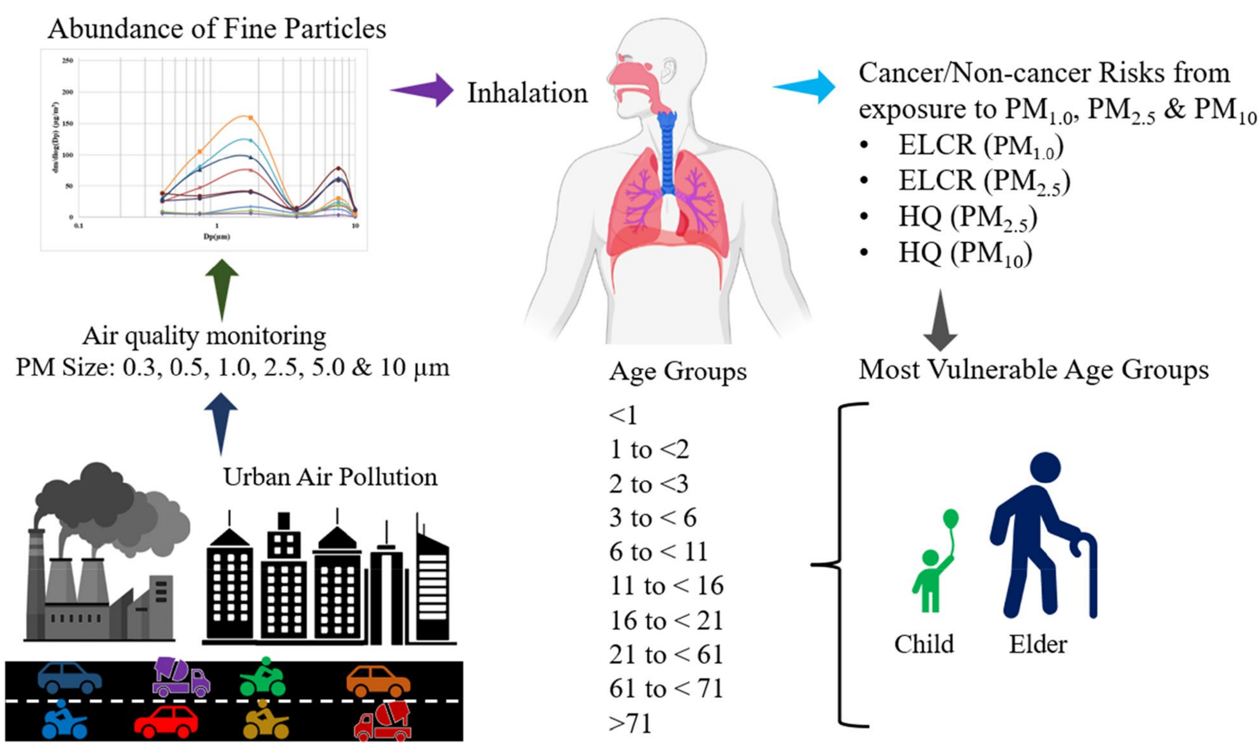
Abstract

Atmospheric particles have been significantly affecting urban air quality and urban-oriented living in an increasing share of the population in Bangladesh. This study assessed the concentration of $PM_{1.0}$, $PM_{2.5}$, and PM_{10} in Khulna, one of the largest cities in Bangladesh located near the Bay of Bengal. The maximum average concentrations were recorded 415 ± 184.01 µg/m^3 for $PM_{10,}$ 302 ± 109.89 µg/m^3 for $PM_{2.5,}$ and 143 ± 45.05 µg/m^3 for $PM_{1.0}$. These values are several times higher than the World Health Organization air quality standard and Bangladesh National Ambient Air Quality Standard. According to the size and fractional distribution of PM, most of the monitoring locations were dominated by fine particles. Carcinogenic and non-carcinogenic risks due to exposure to ambient $PM_{1.0,}$ $PM_{2.5}$ and PM_{10} were also quantified to illustrate the relevant potential human health risks. The excess lifetime cancer risk (ELCR) values of $PM_{1.0}$ ranged from 8.6E0–4 to 6.0E–07 and $PM_{2.5}$ varied between 8.6E–04 and 6.0E–07 exceeded the allowable limit at every location indicating the potential cancer-developing risk to the urban population. The health quotient (HQ) values also crossed the least permissible value at most of the locations depicting strong non-carcinogenic risks. Average HQ values of $PM_{2.5}$ varied from 1.07 to 20.13 while PM_{10} ranged from 0.44 to 8.3. This research revealed children and elderly people as the most vulnerable age groups with the highest carcinogenic risks through exposure to atmospheric PM in Khulna city. Therefore, air pollution reduction plans and risk mitigation strategies should be developed and implemented by the government authorities.

Keywords Air pollution, Size distribution, Fine particles, $PM_{1.0}$, Risk assessment

*Correspondence:
Jobaer Ahmed Saju
jobaerahmed.ce@gmail.com
Full list of author information is available at the end of the article

Graphical Abstract



Introduction

Air pollution has been a great global concern with significant impact on human health, the environment and quality of life (de los A. Gutiérrez et al. 2020; Goyal et al. 2019; Veld et al. 2023). The world has been experiencing 6.5 million yearly premature death events because of air pollution with the highest mortality rates experienced in developing countries (WHO 2021). There were estimated 173,500 deaths in 2019 in Bangladesh due to the polluted airshed of urban cities (Mehedi Hasan 2020). Air pollution in urban areas of Bangladesh is primarily due to emissions from transport and industrial activities (Begum and Hopke 2019; Hoque et al. 2022). Due to the population and economic activities in Dhaka City, air pollutant emissions are much higher than in the other three major cities, namely Chattogram, Khulna and Rajshahi (Bari and Shagor 2016; Mahmood et al. 2019). Major air pollutants affecting the urban air quality in Bangladesh are particulate matter (PM), sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen oxides (NO_x), ozone (O_3) and lead (Pb) (Rana. et al. 2018; Saju et al. 2022). Begum et al. (2014) claimed that in Bangladesh air pollution by PM is more severe than gaseous pollutants. PMs contain varying physicochemical properties (Kwon et al. 2018), which affect human health and the environment according to the variation of their size (Taiwo et al. 2014).

Aerodynamic size and chemical composition are the two most important PM properties that reflect the hazard potential (Harrison and Yin 2000; Deng et al. 2019). PM_{10} (PM with diameter of less than 10 µm) is capable of depositing firmly in the upper respiratory tract (USEPA 2013; Sánchez-Soberón et al. 2015), $PM_{2.5}$ (diameter less than 2.5 µm) can enter the lung function (Park and Wexler 2008; Anderson et al. 2012; Ciarelli et al. 2019), while $PM_{1.0}$ (diameter less than 1.0 µm) has the ability to extend the penetration up to the bloodstream through alveoli, capturing the whole body (Akther et al. 2019; Alam and Mohiuddin 2022). Short-time exposure to $PM_{1.0}$ has been considered to be the reason for death due to stroke, while long-time inhalation can increase the risks of neurological disorders (Mainka 2021; Liu et al. 2022). Smaller size particles, such as $PM_{1.0}$ carry greater human health risks (Sánchez-Soberón et al. 2015). Monitoring and characterization of atmospheric PM are thereby critical to determine the human health risks from exposure to PM. The Department of Environment (DoE) is the only authorized body of the Bangladesh government to monitor air quality and has 11 continuous monitoring stations in 8 cities with the capacity to monitor $PM_{2.5}$, $PM_{10,}$ and other criteria pollutants (Begum et al. 2010; Rana. et al. 2018). $PM_{1.0}$ is not monitored continually in Bangladesh causing a limited availability of datasets to categorize and assess the impacts associated with exposure to this PM size range.

Size distribution is an important parameter in understanding the presence of PM and the dominant mode of an individual fraction (Majoral et al. 2006; Mohiuddin et al. 2014; Zhao et al. 2020). The fractional distribution of PM is considerably influenced by the originating sources (Kwon et al. 2018). The compatibility of PM size distribution and human health risk assessment is high as PM exposure level is associated with mortality and morbidity (Zhang et al. 2013; Reyes-Zárate et al. 2016; Sarkodie et al. 2019; Doyi et al. 2020). The International Agency for Research on Cancer (IARC) recognized $PM_{2.5}$ and PM_{10} as Group-I carcinogens (Prasannavenkatesh et al. 2015), with human health risks potentially influenced by PM pollution (Yunesian et al. 2019). The World Health Organization (WHO) set standard concentrations for $PM_{2.5}$ (daily average 15 $\mu g/m^3$; annual average 5 $\mu g/m^3$) and PM_{10} (daily average 45 $\mu g/m^3$; annual average 15 $\mu g/m^3$) as the mean for reducing their respective exposure risks (WHO 2021). According to Bangladesh's national ambient air quality standard (BNAAQS), the daily and annual average standard concentrations of $PM_{2.5}$ are 65 $\mu g/m^3$ and 15 $\mu g/m^3$, while accordingly for PM_{10} the concentrations are 150 $\mu g/m^3$ and 50 $\mu g/m^3$ respectively (Rana et al. 2018). According to the Agency for Toxic Substances and Disease Registry (ATSDR), long-term inhalation of 33.7 $\mu g/m^3$ of $PM_{2.5}$ can cause endpoint lung cancer in Asia, while in the USA and Canada, exposure to 6.3–23.6 $\mu g/m^3$ of $PM_{2.5}$ can drive a similar scenario (ATSDR 2020). The enormously increasing PM emissions in Bangladesh due to unbound urbanization and industrialization necessitates assessing PM exposure risks. Several epidemiological researchers conducted numerous studies related to human health risk assessment in association with chronic and acute inhalation of $PM_{2.5}$ and PM_{10} due to the rapidly incremental concern. The United States Environmental Protection Agency (USEPA 2005, 2009, 2011) guidelines for health risk assessment have been utilized by most researchers (de Oliveira et al. 2012; di Vaio et al. 2018; Das et al. 2020; Wambebe and Duan 2020; Vo et al. 2022; Pabroa et al. 2022; Sakunkoo et al. 2022; Boré et al. 2022; Sidibe et al. 2022) and the required information is readily available. However, in terms of assessing the exposure risk of $PM_{1.0}$, even though it poses a higher risk than the larger PM sizes, there is no specific guideline for this size range.

In Bangladesh, there have been different air pollution-related studies (Biswas et al. 2003; Begum et al. 2005, 2006, 2010, 2013, 2014; Iqbal and Kim Oanh 2011; Begum and Hopke 2013, 2019; Rahman et al. 2019, 2021; Pal and Masum 2021) with limited focus on the PM size distribution and health risk assessment. Therefore, this study was conducted to assess the governing particle by distributing their size and the associated human health risk to the different PM sizes. Khulna city, close to the Bay of Bengal, was selected for this research as it is the third largest city in Bangladesh and has nearly 1 million people (Bangladesh Bureau of Statistics 2011). This city has been recently connected to the capital of the country 201 km away by the 6.15 km long Padma Bridge, which will likely impact higher air pollution related to industrialization and urbanization. The primary objective of this study was to ascertain the governing particle mode mostly responsible for polluting the airshed of Khulna city. Besides the fractional distribution of PM, this study also estimated carcinogenic and non-carcinogenic health risks associated with exposure to ambient $PM_{1.0,}$ $PM_{2.5}$ and PM_{10}. The outcome of this research may support the development of an improved PM regulatory program for the country since previously no study was found to assess human health risk by considering real-time monitoring data of PM.

Materials and methods

Monitoring locations of PM

Khulna city was considered for this study which is one of the four major cities in Bangladesh. The city is connected to the Bay of Bengal by three adjacent rivers named Bhairab, Rupsha, and Mayur (Bari & Sayeed 2022). The city has a total area of 45.65 km^2 and nearly 1 million population (Bangladesh Bureau of Statistics 2011). Additionally, the city area consists of 31 Wards (Local administrative zone) (Cookey et al. 2020). The meteorological seasons of this area are demarcated as Pre-monsoon: March to May; Monsoon: June to September; Post-monsoon: October to November; and Winter: December to February (Begum et al. 2014). Nine specific locations in the city were selected to monitor the concentration of PM after the reconnaissance survey, as depicted in Table 1 and illustrated in Fig. 1. The selected locations covered three commercial zones (Newmarket, Rupsha Ghat, and Fulbarigate), two residential zones (Nirala Residential Area and Banargati Residential Area), one university or official zone (Khulna University of Engineering & Technology campus), one bus terminal (Sonadanga Intercity Bus Terminal), one industrial area (Bagmara Industrial Area) and one rail station (Khulna Intercity Rail Station). The general sources of PM in the concerned city are mainly anthropogenic (Mazumder et al. 2020; Saju et al. 2021). However, the DoE of Bangladesh operates one continuous air monitoring station in Khulna (Rana. et al.

Table 1 Indications of PM monitoring locations including GPS coordinate and location category

Locations	Acronyms	Latitude and longitude	Location category	Daytime monitoring duration (hours), day^{-1}
Sonadanga	L1	22.81715455 N 89.54244818 E	Khulna intercity bus terminal	8
Nirala R/A	L2	22.80074502 N 89.55286837 E	Residential zone	8
Newmarket	L3	22.82534201 N 89.55090115 E	Commercial zone	8
KUET Campus (W)	L4W	22.8994349 N 89.5018945 E	University campus	8
KUET Campus (M)	L4M	22.8994349 N 89.5018945 E	University campus	8
Banargati R/A	L5	22.80495657 N 89.54618556 E	Residential zone	5–8
Khulna Rail Station	L6	22.8203227 N 89.5574843 E	Khulna intercity rail station	8
Bagmara I/A	L7	22.790854 N 89.586826 E	Industrial zone	6–8
Rupsha Ghat	L8	22.8018806 N 89.58044619 E	Commercial zone	3–8
Fulbarigate	L9	22.89644275 N 89.51009742 E	Commercial zone	8

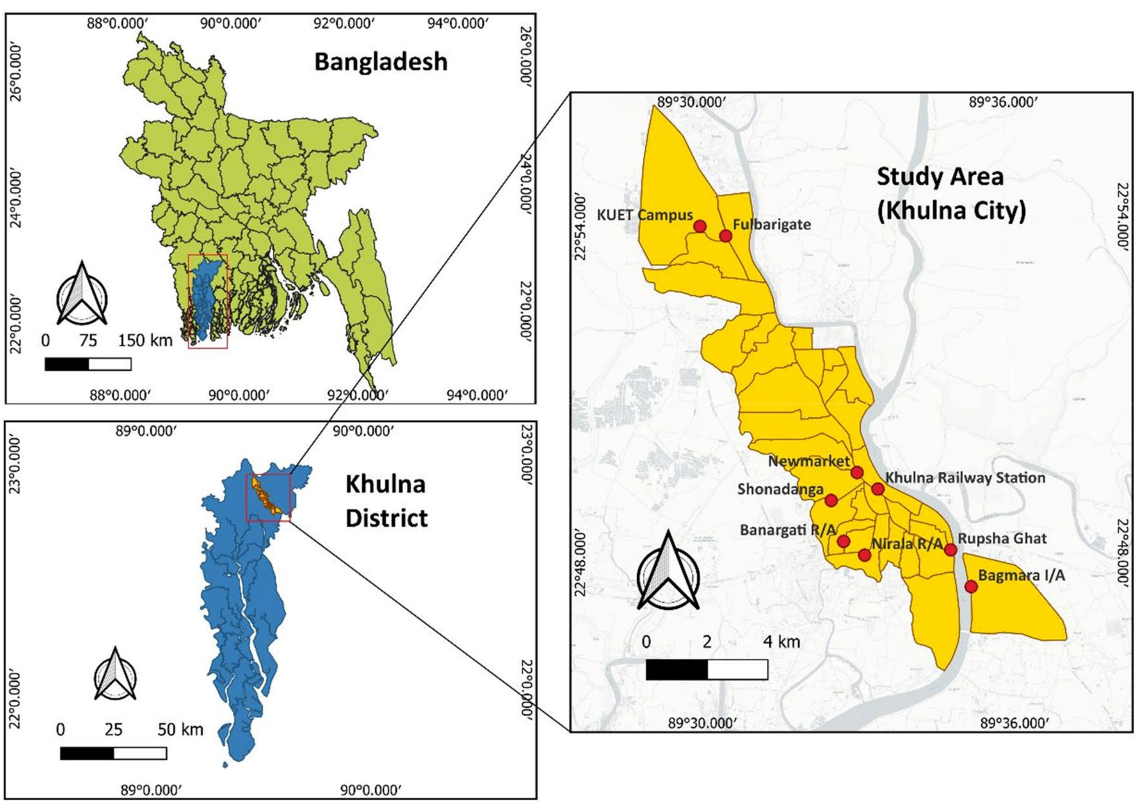


Fig. 1 Visualization map of selected monitoring locations in Khulna City in the context of Khulna district and Bangladesh

2018) which is not sufficient to represent the whole city airshed.

Accumulation of PMs concentration

"HANDHELD 3016; Laser Particle Counter" is a real-time air quality monitoring equipment with 0.3 μm sensibility used for the measurement of PM concentration in this study. The selected locations were monitored for three consecutive days, spanning eight hours each day and commencing at 9:00 AM. This monitoring campaign took place in several months during the years 2018 (October, November and December), 2019 (January, February, June, July, September, October, November and December), and 2020 (January, February). The laser particle counter was positioned above 1.52 m of the ground level to maintain the average nose height. The one-minute automated average concentration was considered for the accumulation of the PM dataset. The concentration of individual PM fractions was displayed as 0.3, 0.5, 1.0, 2.5, 5.0 & 10 μm. Afterward, the concentration of $PM_{1.0}$; $PM_{2.5}$; and PM_{10} was calculated according to their respective accumulation order. The Banargati Residential Area was monitored for seven consecutive days to exhibit a weekly variation in PM concentration. Additionally, the Khulna University of Engineering & Technology (KUET) campus was monitored twice, once in the winter and another time in the monsoon season. This study followed the data monitoring protocols of the Department of Environment (DoE) in Bangladesh. To ensure accuracy, the PM monitoring data was crosschecked with daily PM data monitored by the DoE in Khulna. Additionally, all selected locations were monitored for three consecutive days to ensure the precision of the collected PM data. Accumulated PM data from all monitoring locations are available and attached as Additional file 1.

Analysis of PM

The accumulated concentrations of ambient PM have been displayed through box and whisker plots to exert the statistical variation in large quantities. Box whisker, a descriptive statistical tool was utilized in this study to illustrate the mean, median, maximum, minimum and interquartile range for the accumulated concentrations of $PM_{1.0}$, $PM_{2.5,}$ and PM_{10} at specified monitoring locations. The concentration of particles was also analyzed to find the dominant PM fractions in the Khulna city airshed. Distribution of different-sized particles was performed by graphing the PM size as Dp against their respective concentration as dm/dlog (Dp) (μg/m^3). The size distribution and other statistical characteristics of particulate matter assist in expressing the potential impacts and the origins of particles (Mohiuddin et al. 2014). The mass median aerodynamic diameter (MMAD) and geometric standard deviation (GSD) values were calculated through regression lines from size versus cumulative mass to find out the dominating affluence of specific-sized particles. The MMAD values are defined as the particle size corresponding to the cumulative distribution of 50% denoted as %50 d_p (Mohiuddin et al. 2014). The GSD values were calculated by following equation (i) for PM in unimodal distribution, and equation (ii) for PM in bimodal distribution (Nag et al. 2005).

$$\mathrm{GSD}(\sigma_g) = \frac{\%84.13d_p}{\%50d_p} = \frac{\%50d_p}{\%15.87d_p} \tag{1}$$

$$\mathrm{GSD}(\sigma_g) = \sqrt{\frac{\%84.13d_p}{\%15.87d_p}} \tag{2}$$

In this study, the individual atmospheric PM fractions i.e., 0.3 μm; 0.5 μm; 1.0 μm; 2.5 μm; 5.0 μm and 10 μm were further distributed into ultrafine, submicron, intermodal and coarse categories. The course particles consist of diameters greater than 2.5 μm and less than 10 μm, the intermodal particles have diameters in the range between 1 μm and 2.5 μm, submicron particles are in the range between 0.5 μm and 1 μm and the ultrafine particles are classified as PM with diameter less than 0.5 μm (Mohiuddin et al. 2014; Yang et al. 2019).

Risk assessment of PM

The human health risk assessment of PM is a significant parameter to quantify the impact of exposure to a certain concentration for a particular time duration. This study quantified carcinogenic and non-carcinogenic health risks of ambient $PM_{1.0,}$ $PM_{2.5}$ and PM_{10} using the USEPA risk assessment method. The probability of developing cancer risk due to exposure to PM can be determined through the assessment of carcinogenic risk (Sidibe et al. 2022). The maximal allowable value of carcinogenic risk for PM inhalation is 10^{-5} while 10^{-6} has been considered safe. Excess lifetime cancer risk (ELCR) of ambient $PM_{1.0}$ and $PM_{2.5}$ were calculated by considering ten age groups starting from < 1 year to > 71 years as different age groups have different respiratory characteristics (Yunesian et al. 2019; Sakunkoo et al. 2022). The ELCR of $PM_{1.0}$ was estimated using equations (iii), (v) and (vi). Accordingly, the ELCR of $PM_{2.5}$ was estimated by using equations (iv), (v) and (vi).

$$ELCR(PM_{1.0}) = LADD * SF \tag{3}$$

$$ELCR(PM_{2.5}) = [ELCR(PM_{1.0}) + \{LADD(PM_{2.5} - PM_{1.0}) * SF(PM_{2.5} - PM_{1.0})\}] \tag{4}$$

$$ADD = \frac{C * IR * ED * EF}{BW * AT} \tag{5}$$

Table 2 Risk assessment parameters and associated reference values for calculating cancer and non-cancer health risk of $PM_{1.0}$, $PM_{2.5}$, and PM_{10} in Khulna city airshed

Parameters	Denotation	Unit	Age, year										Sources
			< 1	1 to < 2	2 to < 3	3 to < 6	6 to < 11	11 to < 16	16 to < 21	21 to < 61	61 to < 71	> 71	(USEPA 2011)
Inhalation rate	IR	m^3/day	8	8.9	10.1	12	15.2	16.3	15.7	16	14.2	12.9	(USEPA, 2005, 2011; Yunesian et al. 2019)
Body weight	BW	Kg	9.2	11.4	13.8	18.6	31.8	56.8	71.6	80	80	80	(USEPA, 2005, 2011)
Exposure frequency	EF	Day/year	365	365	365	365	365	365	365	365	365	365	(Sakunkoo et al. 2022; USEPA 2011)
Exposure duration	ED	Year	1	1	1	3	5	5	5	49	49	49	(USEPA 2011; Yunesian et al. 2019)
Reference concentration	RfC	μg/m^3	15 for $PM_{2.5}$ and 50 for PM_{10}										(Rana. et al. 2018)
Inhalation unit risk	IUR ($PM_{2.5}$)	μg/m^3	0.008 for $PM_{2.5}$										(Mbazima 2022; Yunesian et al. 2019)

$$SF = \frac{IUR}{BW * IR} \quad (6)$$

where, ELCR is Excess Lifetime Cancer Risk; LADD is Lifetime average daily dose (μg/kg day); SF is slope factor (kg day/μg); C is the concentration of PM (μg/m^3), IR is inhalation rate (m^3/day); ED is exposure duration (years); EF is exposure frequency (days/year); BW is body weight (kg); AT is averaging exposure time (days); IUR is the inhalation unit risk (μg/m^3).

The calculation of ELCR is directly influenced by excess lifetime average daily dose (LADD) and slope factor (SF). According to the guideline of (USEPA 2010) for Quantitative Health Risk Assessment and several epidemiological studies, the IUR value of $PM_{2.5}$ can be considered as 0.008 μg/m^3 (di Vaio et al. 2018; Yunesian et al. 2019; Mbazima 2022). However, there is no available information for the IUR value of $PM_{1.0}$. Therefore, in terms of assessing the health risk of $PM_{1.0}$, the assessment of carcinogenic metals associated with $PM_{1.0}$ has been assessed. Cr(VI), Cd, Ni and Pb are identified as carcinogenic metals embedded with PM (USEPA 2005; Das et al. 2020; Wang et al. 2020; Mainka 2021). The average inhalation unit risk of Cr(VI), Cd, Ni and Pb associated with $PM_{1.0}$ was assumed and considered as the IUR of $PM_{1.0}$ which is 0.0215 μg/m^3. The IUR values of Cr(VI), Cd, Ni and Pb have been collected through USEPA guidelines (USEPA 2011, 2014). This study accumulated the dataset of PM by monitoring the locations with the help of a laser particle counter and did not conduct the elemental analysis of PM. Therefore, the assumption was considered to address the health risk of $PM_{1.0}$. Due to the depicted assumption, the calculation of the ELCR of $PM_{2.5}$ has been modified as expressed in equation (iv). The average exposure time (AT) was considered as 70*365 days for carcinogenic risks and ED*365 days for non-carcinogenic risks (USEPA 2009). The information and dataset used to quantify the health risk from inhalation of PM according to USEPA (2011) and other studies are presented in Table 2.

The non-carcinogenic risk generally expresses the health risks other than developing cancer. This research evaluated and quantified the non-carcinogenic risk of $PM_{2.5}$ and PM_{10} for all the monitoring locations. The HQ values were calculated using equation (vii), and the reference dose (RfD) was calculated by following equation (viii). HQ value greater than 1 is considered a potential non-carcinogenic risk where HQ value less or equal to 1 presents an allowable condition (Sidibe et al. 2022). Reference concentration (RfC) was considered in the Bangladesh context as 15 μg/m^3 for $PM_{2.5}$ and 50 μg/m^3 for PM_{10} (USEPA 2012; Rana. et al. 2018). Risk-assessing parameters are illustrated in Table 2. ELCR values of $PM_{1.0}$ & $PM_{2.5}$ and HQ values of $PM_{2.5}$ & PM_{10} have been calculated for the nine monitoring locations in Khulna city of Bangladesh as the very first approach. Due to the unavailability of the reference concentration of $PM_{1.0}$, this study did not estimate the HQ of $PM_{1.0.}$ Similarly, in the absence of the inhalation unit risk of PM_{10}, the ELCR of PM_{10} was not calculated. However, the detailed calculation of health risks due to the inhalation of size variant PM is attached as Additional file 2.

$$\mathrm{HQ} = \frac{\mathrm{LADD}}{\mathrm{RfD}} \quad (7)$$

$$RfD = \frac{RfC * IR}{BW} \quad (8)$$

where, HQ = Hazard quotient; LADD = Lifetime average daily dose (μg/kg day); RfD = Reference dose (μg/kg day); RfC = Reference concentration of pollutants (μg/m^3).

Results and discussion

Concentration of ambient PM in Khulna city airshed

The concentrations of $PM_{1.0}$, $PM_{2.5}$ and PM_{10} measured at the nine monitoring locations in Khulna are illustrated in Fig. 2a–c. $PM_{2.5}$ exceeded the WHO 24 h standard at all sites, with KUET campus (M), Banargati R/A, and Khulna Rail Station exceeding BNAAQS. PM_{10} followed a similar trend, except at the KUET campus (M), also exceeding WHO standards and BNAAQS. The concentration of PM_{10} also exceeded the BNAAQS. The monitoring campaign of the three locations i.e., KUET campus (M), Banargati R/A and Khulna Rail Station was conducted during the monsoon season. The other locations were monitored during the post-monsoon and winter seasons. The locations monitored in the months of winter and post-monsoon depicted comparatively higher concentrations for all PM fractions. In contrast, the locations monitored in the months of monsoon exhibited lower values. This can be evident due to the changes in meteorological variables, such as rain events, wind speed and humidity during the monitoring period (Begum et al. 2014).

The highest concentration of PM_{10} (415 ± 184.01 μg/m^3) was recorded at the Rupsha Ghat location and the highest concentration of $PM_{2.5}$ (302 ± 109.89 μg/m^3) and $PM_{1.0}$ (143 ± 45.05 μg/m^3) at Newmarket location. Rupsha Ghat location is surrounded by several industries and excessive vehicular movement was observed during the monitoring program. The Newmarket location is a well-recognized marketplace in Khulna city. A large number of people visit Newmarket for shopping using various motorized vehicles. Significant emissions from a large number of vehicular movements and industrial activities can cause the highest concentration at these two locations. The

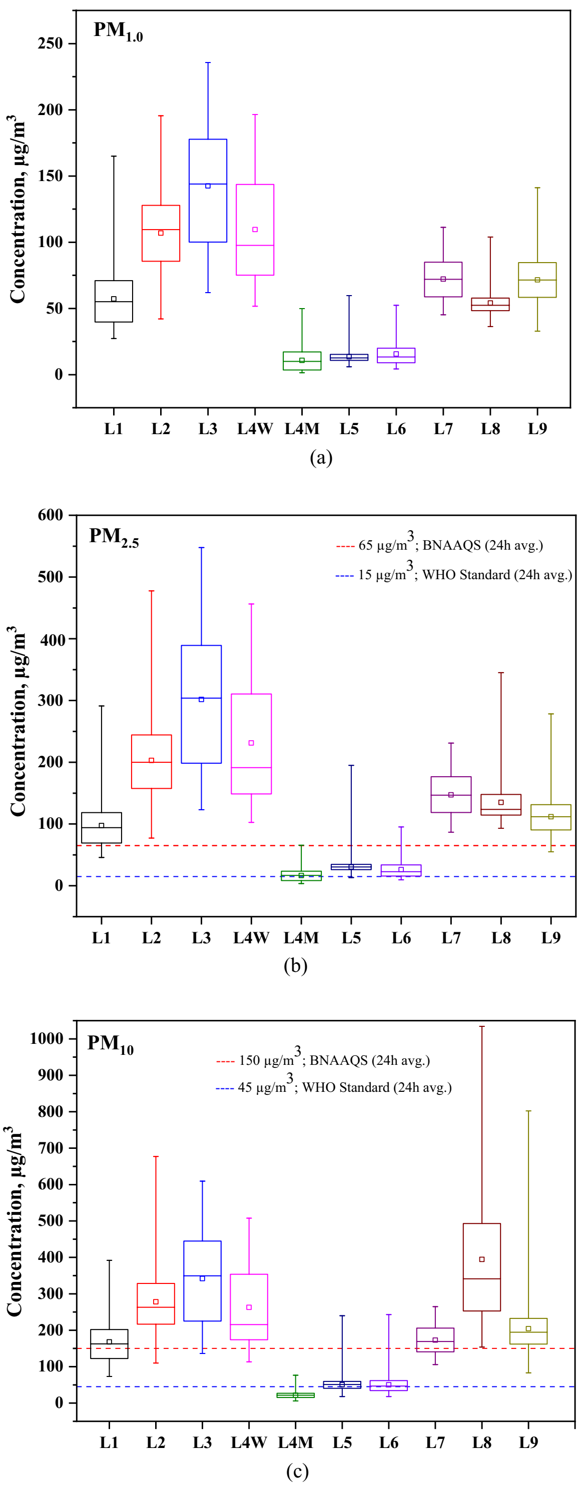


Fig. 2 Concentration of ambient PM at selected monitoring locations in Khulna city of Bangladesh; **a** variation of $PM_{1.0}$ concentration, **b** changes in $PM_{2.5}$ levels concerning WHO standard and BNAAQS and **c** fluctuation of PM_{10} concentration in comparison to WHO standard and BNAAQS

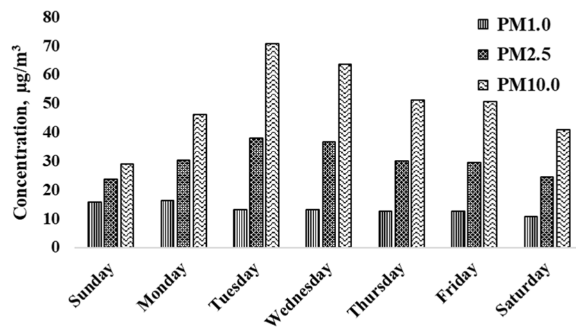


Fig. 3 Weekly variation in the concentration of $PM_{1.0}$, $PM_{2.5}$ and PM_{10} in the Banargati residential area of Khulna city

lowest concentrations of PM_{10} (22 ± 7.83 μg/m^3), $PM_{2.5}$ (16 ± 9.18 μg/m^3) and $PM_{1.0}$ (11 ± 7.61 μg/m^3) were reported at the KUET campus (M). The monitoring campaign was conducted twice at this location, once in winter and another time during the monsoon season. The minimum values of PM fractions were observed from the monsoon monitoring campaign. Variations in the total concentration of all PM fractions can also be observed in Fig. 2. Newmarket, Nirala R/A and KUET campus (winter) provided significantly higher interquartile ranges in $PM_{1.0}$, $PM_{2.5}$ and PM_{10} concentrations. However, the evident larger vehicular movement, construction works and solid waste open burning scenario at Newmarket and Nirala R/A could be the reasons for a higher interquartile range in all atmospheric PM concentrations. The minimum interquartile range was observed in the KUET campus (M) location including the lowest mean concentration of all PM fractions. Emran et al. (2020) reported higher $PM_{2.5}$ (136 ± 14.0 μg/m^3) concentrations in winter than in summer (60 ± 7.0 μg/m^3) and also claimed the contribution of vehicular emission in Khulna.

Weekly and seasonal trends of PM

Figure 3 displayed the weekly changing pattern of $PM_{1.0}$, $PM_{2.5}$ and PM_{10} concentrations at Banargati R/A. A consecutive 7 monitoring campaign was conducted at this location to explore the weekly variation of PM. It can be observed from the figure that the variation of PM presents a parabolic shape from Sunday to Saturday. Higher values of $PM_{1.0}$, $PM_{2.5}$ and PM_{10} were found within the working days from Monday to Thursday. On the other hand, off days, such as Friday and Saturday, showed lower concentrations. However, the rain event that occurred on Sunday during the monitoring campaign led to a comparatively lower concentration of PM than on the other considered days.

The seasonal variation in the average concentration of PM fraction is illustrated in Fig. 4. Seasonal variation was calculated from the average concentration of different monitoring locations. Higher concentration of PM

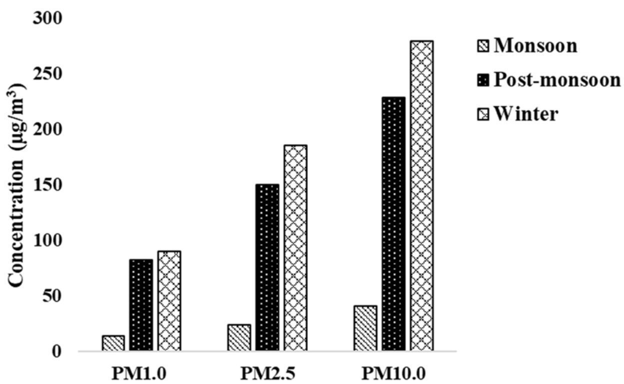


Fig. 4 Seasonal disparity of ambient PM ($PM_{1.0}$, $PM_{2.5}$ and PM_{10}) in the urban area of Khulna

was reported in winter and post-monsoon and minimal values were during the monsoon period. The maximum concentration of PM recorded in winter was 90 μg/m^3 for $PM_{1.0}$, 186 μg/m^3 for $PM_{2.5}$, and 280 μg/m^3 for PM_{10}. In contrast, the lowest values of PM fractions observed during monsoon were 14 μg/m^3 for $PM_{1.0}$, 24 μg/m^3 for $PM_{2.5}$, and 41 μg/m^3 for PM_{10}. The concentration of particles recorded in winter was six to seven times higher than during monsoon. This seasonal variation of atmospheric PM was found similar to the corresponding result of Begum et al. (2010) who reported four times higher concentrations of particles in winter than in monsoon. Bari and Shagor (2016), Begum et al. (2014), Sarasamma and Narayanan (2014) and Tantadprasert et al. (2011) also found larger values of PM in the winter season and smaller values in the monsoon season in Bangladesh and India. The concentration of atmospheric PM is found to be significantly higher in winter than in other seasons. The wind direction of the winter season in Bangladesh follows a "north to south" direction (Begum et al. 2013), and additionally, the study area, Khulna city is in the southern part of the country. Moreover, Hu et al. (2006) addressed the short mixture altitude of PM and minimum wind speed for the lower values of PM concentration in the months of the winter season. The geographical location, natural wind-blowing pattern and seasonal fluctuation of PM emission could lead the city to face more polluting airsheds in winter.

Size distribution of atmospheric PM

This study conducted an average size distribution of the accumulated dataset of PM fraction to explore the governing particle size polluting the city airshed. Figure 5 illustrates the average size distribution of PM for all selected locations in Khulna city. The vertical lines in the figure represent the maximum and minimum concentrations of PM. Rupsha Ghat, Sonadanga, and Fulbarigate were the locations with the highest affluence in the range of particle diameter from Dp 3.75 μm to Dp 7.5 μm. On the other hand, Nirala R/A, Bagmara I/A, Newmarket and KUET campus (winter) exhibited the maximum affluence in the range of particle diameters Dp 0.4 μm to Dp 1.75 μm. However, these locations also displayed another peak of PM mode lower than the previous in the range of Dp 3.75 μm to Dp 7.5 μm. The other locations, namely Banargati R/A, KUET campus (Monsoon) and Khulna Rail Station, also showed a peak mode within the range of particle diameter from Dp 0.4 μm to Dp 1.75 μm, and Dp 3.75 μm to Dp 7.5 μm. These locations were found to carry lower PM values than other depicted locations. The MMAD and GSD values for the measured concentration at all monitoring locations are illustrated in Table 3. Rupsha Ghat and Khulna Rail Station exhibited higher average MMAD values of 8.6 and 6.5 μm, respectively. Meanwhile, the location KUET campus (winter) and Newmarket exhibited the lowest MMAD values of 1.1 μm. The highest and lowest values of MMAD indicate the dominant mode of coarse particles at Rupsha Ghat and Sonadanga, and fine particles at Newmarket and KUET campus (winter). In addition, the KUET campus (winter) and KUET campus (monsoon) displayed almost similar values of MMAD. MMAD value at the KUET campus (winter) was observed as 1.1 μm while the KUET campus (monsoon) exhibited a value of 1.8 μm which informs the presence of fine particles at the KUET campus both in the monsoon and winter seasons. Water droplets of rain events may assist in cleaning up the airshed only by reducing coarse particles (Hu et al. 2006) and this should be the reason for the similar appearance of fine PM at the KUET campus location in both winter and monsoon seasons. The bimodal distribution of particles was considered for the estimation of GSD values. All the monitoring locations showed higher GSD values than MMAD except Rupsha Ghat and Khulna Rail Station. This may occur due to the additional mode occurring with the significant height in the submicron particle size range relative to the coarse particle mode. The presence of fine particles with the dominant aspect at almost all the monitoring locations in Khulna carries the relevancy of developing health risks due to exposure to ambient PM. Fine particles are more detrimental to human health than coarse particles (Sidibe et al. 2022). Thereby, the monitoring and assessment programs should be designed and implemented to regulate PM pollution in Bangladesh by emphasizing Khulna city. However, the difference in the frequency of PM in coarse and fine particles for all monitoring locations further suggests the need for individual particle size monitoring in the city.

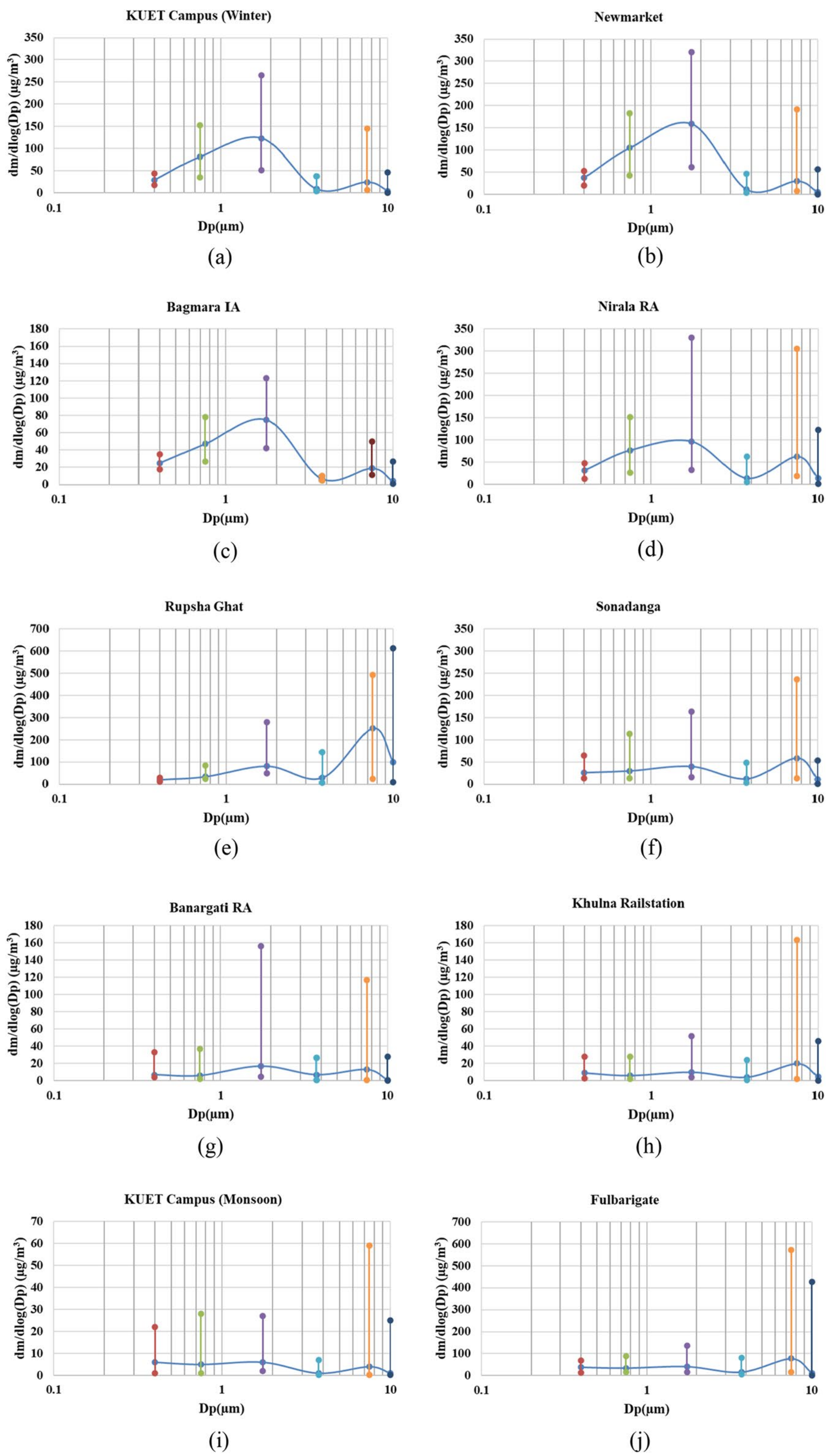


Fig. 5 Average size distributions of atmospheric PM in Khulna city at nine monitoring locations; **a** KUET Campus (winter), **b** Newmarket **c** Bagmara I/A, **d** Nirala R/A, **e** Rupsha Ghat, **f** Sonadanga, **g** Banargati R/A, **h** Khulna Rail Station, **i** KUET campus (monsoon), **j** Fulbarigate

Table 3 MMAD and GSD values at PM monitoring locations in Khulna city

Location	MMAD (μm)	GSD (dimensionless)
L1	3.2	3.4
L2	2.4	3.3
L3	1.1	2.0
L4W	1.1	2.0
L4M	1.8	4.0
L5	3.0	3.1
L6	6.5	3.9
L7	2.2	2.2
L8	8.6	2.0
L9	3.4	3.6

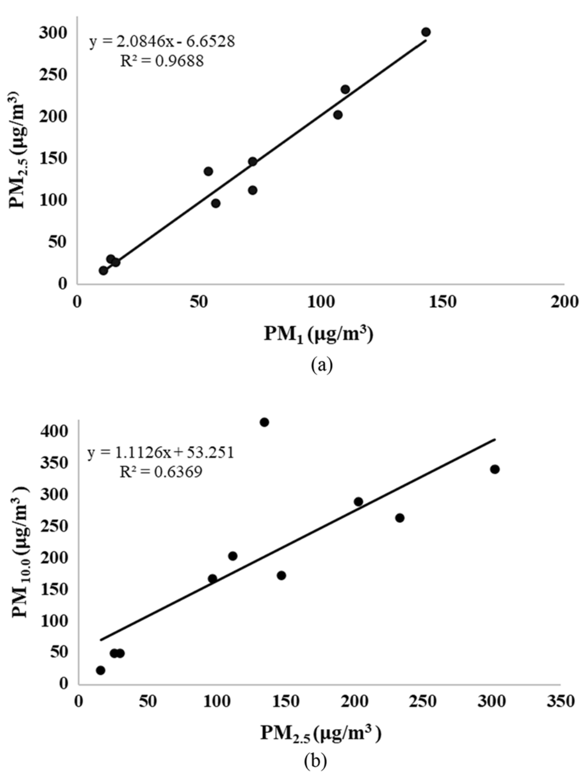


Fig. 6 Correlation coefficient of PM fractions **a** between $PM_{1.0}$ and $PM_{2.5}$; **b** between $PM_{2.5}$ and PM_{10}

Figure 6 exhibits the correlation between $PM_{1.0}$, $PM_{2.5}$ and $PM_{10.}$ The correlation coefficient of $PM_{1.0}$ and $PM_{2.5}$ was 0.969 denoting a strongly significant correlation. Similarly, the correlation coefficient between $PM_{2.5}$ and PM_{10} was found as 0.637 which indicates a moderate correlation. The correlation coefficient values express the relevancy of the dominant presence of fine PM to the total concentration of $PM_{10.}$ To quantify the individual fractions of PM contributing to the concentration of $PM_{10,}$ the individual fraction of ambient PM was further calculated. The categorized fractions were coarse, intermodal, submicron and ultrafine ambient PM. Figure 7 illustrates the fractional distribution of categorized particles for nine monitoring locations of the study area. It was observed that 9 to 27% of ultrafine particles have been attributed to the total ambient PM concentration. KUET campus (Monsoon) displayed the maximum contribution of ultrafine particles as 27%. Conversely, the Fulbarigate location showed a minimum contribution of ultrafine particles at 9%. 31% of the maximum submicron particles appeared at the KUET campus (winter) and Newmarket. In contrast, the Fulbarigate location exhibited the least submicron particle concentration at 4%. The intermodal particle concentrations varied from 19 to 46% and the fraction of the coarse particles fluctuated from 12 to 68%. The ultrafine and submicron PM fractions are the main components of $PM_{1.0}$. The laser particle counter used in this study assisted in the quantification of the individual PM fractions attributed to the total concentration of ambient PM. Islam et al. (2020) reported that 68.1% of the maximum $PM_{2.5}$ concentrations contributed to the total values of PM_{10}. However, exposure to ultrafine and submicron PM fractions consists of great detrimental effects on the human body (Caggiano et al. 2019; Wang et al. 2020). According to ATSDR (2020), long-time inhalation of fine particles at the range of 6 to 28 μg/m^3 can cause lung function growth at a decremental rate. Prakash et al. (2018) also reported that the fine fraction of atmospheric PM plays an important role in climate change.

Health risk assessment of ambient PM

Risk assessment of the exposed population to atmospheric PM in the Khulna city airshed was conducted in this research. The ELCR values of $PM_{1.0}$ investigated for ten variant age groups at nine monitoring locations are given in Table 4. It can be observed from the table that the ELCR ($PM_{1.0}$) values were greater than the standard allowable value of 1.0E-6 (USEPA 2010) at every monitoring location. The maximum and minimum ELCR values of $PM_{1.0}$ ranged from 8.6E–04 to 6.0E–07. Higher ELCR ($PM_{1.0}$) values were obtained for the age groups < 1; 1 to < 2; 2 to < 3; 3 to < 6; 6 to < 11; 21 to < 61; 61 to < 71; > 71. Meanwhile, the age groups 11 to < 16 and 16 to < 21 were found to illustrate comparatively lower values of ELCR ($PM_{1.0}$), albeit still exceeding the standard. The most vulnerable groups found in the study are children i.e., < 1; 1 to < 2; 2 to < 3; 3 to < 6; 6 to < 11, adults 21 to < 61, and elderly i.e., 61 to < 71; > 71 as they exhibited higher values of ELCR ($PM_{1.0}$). Therefore, compatible mitigation measures should be considered to reduce

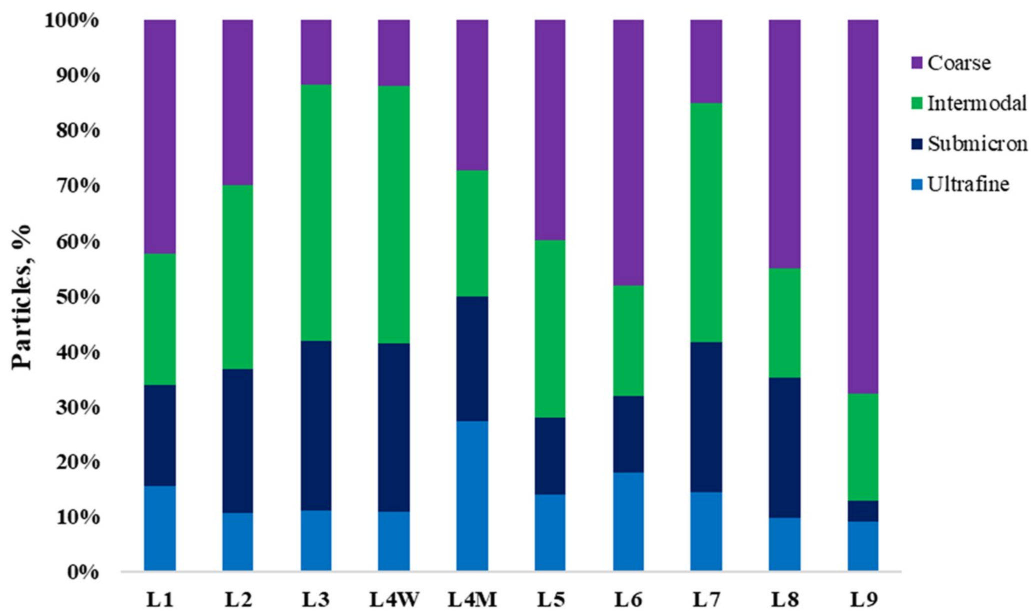


Fig. 7 Fractional distribution of ambient PM for all the monitoring locations in Khulna city

incremental cancer-developing risks among children and elderly people of Khulna city. It can also be seen in Table 4, Newmarket, Nirala R/A, Sondanga, and Bagmara I/A locations displayed higher ELCR values of $PM_{1.0}$ for all age groups. Heavy traffic loading at Newmarket and Sonadang, industrial emission at Bagmara I/A, solid waste open burning and continual construction projects at Nirala R/A were the events during the monitoring campaigns at these locations. However, Banargati R/A, Khulna Rail Station and the KUET campus (Monsoon) exhibited comparatively lower but exceeding the standard value of ELCR ($PM_{1.0}$). Banargati R/A is an established and older residential area of Khulna city with less vehicular movement, and Khulna Rail Station is a newly designed and functioning rail station of Bangladesh railway with a lower contribution to PM emissions. The KUET campus was also found to be calm and quiet during the monsoon monitoring period due to the disturbance of rain events to regular activities. Moreover, these locations were monitored during monsoon season as discussed earlier (Additional files 1, 2).

In order to quantify the cancer-developing risk of $PM_{2.5}$ exposures, ELCR values were also calculated for the nine monitoring locations. Table 5 illustrates the ELCR ($PM_{2.5}$) for the average, maximum and minimum accumulated concentrations of $PM_{2.5}$ at all the monitoring locations. The ELCR values of $PM_{2.5}$ were observed in between the range of 8.6E–04 to 6.0E–07. ELCR ($PM_{2.5}$) for the average concentration of $PM_{2.5}$ at every location in this study exceeded the standard guideline value of 1.0E–6. It can also be seen in Table 5 that the higher ELCR ($PM_{2.5}$) is present in the age groups: < 1; 1 to < 2; 2 to < 3; 3 to < 6; 6 to < 11; 21 to < 61; 61 to < 71; > 71. Comparatively lower values of ELCR ($PM_{2.5}$) were found within the age groups 11 to < 16 and 16 to < 21. Yunesian et al. (2019) conducted a similar type of study in Iran to quantify the cancer risk of $PM_{2.5}$ by considering ten age groups of people. However, their results are found to be analogous except for the cancer-developing risk of elderly people. Sakunkoo et al. (2022) assessed the health risk of heavy metals associated with $PM_{2.5}$. They found the child-age population to exhibit a higher risk than adults. In another study conducted by Sidibe et al. (2022) higher cancer risk for children than adults were also reported due to inhalation of PM emitted from household activities.

The non-carcinogenic health risk upon inhalation of atmospheric $PM_{2.5}$ and PM_{10} in Khulna city was estimated in this study. The calculated HQ presented in Table 6 conveys the non-carcinogenic risk values at every selected monitoring location. The average HQ values of $PM_{2.5}$ exceeded the allowable value (< 1) at every monitoring location indicating the probability of developing non-carcinogenic diseases. The locations Newmarket and KUET campus (W) displayed higher HQ ($PM_{2.5}$) values of 15.53 and 20.13 respectively, indicating the impermissible risk to the local population. However, the KUET campus (M), Banargati R/A, and Khulna Rail Station exhibited lower but exceeding standard HQ ($PM_{2.5}$) values as 1.07, 2 and 1.73. The mentioned HQ ($PM_{2.5}$) values also carry a detrimental effect on the human body. The range of average HQ values of PM_{10} varied from 0.44 to 8.3. The highest HQ (PM_{10}) value was illustrated by the

Table 4 Estimated cancer risk (ELCR) of variant people due to the inhalation of ambient $PM_{1.0}$

Location		< 1	1 to < 2	2 to < 3	3 to < 6	6 to < 11	11 to < 16	16 to < 21	21 to < 61	61 to < 71	> 71
L1	Average	2.07E−04	1.35E−04	9.20E−05	1.52E−04	8.66E−05	2.71E−05	1.71E−05	1.34E−04	1.34E−04	1.34E−04
	Max	5.70E−04	3.71E−04	2.53E−04	4.18E−04	2.39E−04	7.48E−05	4.71E−05	3.69E−04	3.69E−04	3.69E−04
	Min	9.80E−05	6.38E−05	4.36E−05	7.20E−05	4.10E−05	1.29E−05	8.09E−06	6.35E−05	6.35E−05	6.35E−05
L2	Average	3.89E−04	2.53E−04	1.73E−04	2.85E−04	1.63E−04	5.10E−05	3.21E−05	2.52E−04	2.52E−04	2.52E−04
	Max	7.12E−04	4.63E−04	3.16E−04	5.22E−04	2.98E−04	9.34E−05	5.87E−05	4.61E−04	4.61E−04	4.61E−04
	Min	1.53E−04	9.93E−05	6.78E−05	1.12E−04	6.38E−05	2.00E−05	1.26E−05	9.88E−05	9.88E−05	9.88E−05
L3	Average	5.19E−04	3.38E−04	2.31E−04	3.81E−04	2.17E−04	6.81E−05	4.29E−05	3.36E−04	3.36E−04	3.36E−04
	Max	8.57E−04	5.58E−04	3.81E−04	6.29E−04	3.59E−04	1.12E−04	7.07E−05	5.55E−04	5.55E−04	5.55E−04
	Min	2.25E−04	1.47E−04	1.00E−04	1.65E−04	9.42E−05	2.95E−05	1.86E−05	1.46E−04	1.46E−04	1.46E−04
L4W	Average	3.99E−04	2.60E−04	1.78E−04	2.93E−04	1.67E−04	5.24E−05	3.30E−05	2.59E−04	2.59E−04	2.59E−04
	Max	7.12E−04	4.63E−04	3.16E−04	5.22E−04	2.98E−04	9.34E−05	5.87E−05	4.61E−04	4.61E−04	4.61E−04
	Min	1.85E−04	1.21E−04	8.23E−05	1.36E−04	7.75E−05	2.43E−05	1.53E−05	1.20E−04	1.20E−04	1.20E−04
L4M	Average	3.99E−05	2.60E−05	1.78E−05	2.93E−05	1.67E−05	5.24E−06	3.30E−06	2.59E−05	2.59E−05	2.59E−05
	Max	1.82E−04	1.18E−04	8.07E−05	1.33E−04	7.60E−05	2.38E−05	1.50E−05	1.18E−04	1.18E−04	1.18E−04
	Min	7.26E−06	4.73E−06	3.23E−06	5.33E−06	3.04E−06	9.53E−07	5.99E−07	4.71E−06	4.71E−06	4.71E−06
L5	Average	5.08E−05	3.31E−05	2.26E−05	3.73E−05	2.13E−05	6.67E−06	4.20E−06	3.29E−05	3.29E−05	3.29E−05
	Max	2.18E−04	1.42E−04	9.68E−05	1.60E−04	9.12E−05	2.86E−05	1.80E−05	1.41E−04	1.41E−04	1.41E−04
	Min	2.18E−05	1.42E−05	9.68E−06	1.60E−05	9.12E−06	2.86E−06	1.80E−06	1.41E−05	1.41E−05	1.41E−05
L6	Average	5.81E−05	3.78E−05	2.58E−05	4.26E−05	2.43E−05	7.62E−06	4.80E−06	3.76E−05	3.76E−05	3.76E−05
	Max	1.89E−04	1.23E−04	8.39E−05	1.39E−04	7.90E−05	2.48E−05	1.56E−05	1.22E−04	1.22E−04	1.22E−04
	Min	1.45E−05	9.46E−06	6.46E−06	1.07E−05	6.08E−06	1.91E−06	1.20E−06	9.41E−06	9.41E−06	9.41E−06
L7	Average	2.61E−04	1.70E−04	1.16E−04	1.92E−04	1.09E−04	3.43E−05	2.16E−05	1.69E−04	1.69E−04	1.69E−04
	Max	1.63E−04	1.06E−04	7.26E−05	1.20E−04	6.84E−05	2.14E−05	1.35E−05	1.06E−04	1.06E−04	1.06E−04
	Min	3.99E−05	2.60E−05	1.78E−05	2.93E−05	1.67E−05	5.24E−06	3.30E−06	2.59E−05	2.59E−05	2.59E−05
L8	Average	1.96E−04	1.28E−04	8.71E−05	1.44E−04	8.21E−05	2.57E−05	1.62E−05	1.27E−04	1.27E−04	1.27E−04
	Max	3.74E−04	2.44E−04	1.66E−04	2.74E−04	1.57E−04	4.91E−05	3.09E−05	2.42E−04	2.42E−04	2.42E−04
	Min	1.31E−04	8.51E−05	5.81E−05	9.59E−05	5.47E−05	1.71E−05	1.08E−05	8.47E−05	8.47E−05	8.47E−05
L9	Average	2.61E−04	1.70E−04	1.16E−04	1.92E−04	1.09E−04	3.43E−05	2.16E−05	1.69E−04	1.69E−04	1.69E−04
	Max	5.12E−04	3.33E−04	2.28E−04	3.76E−04	2.14E−04	6.72E−05	4.23E−05	3.32E−04	3.32E−04	3.32E−04
	Min	1.20E−04	7.80E−05	5.33E−05	8.79E−05	5.01E−05	1.57E−05	9.89E−06	7.76E−05	7.76E−05	7.76E−05
Khulna City (Average)	Average	2.40E−04	1.56E−04	1.07E−04	1.76E−04	1.00E−04	3.14E−05	1.98E−05	1.55E−04	1.55E−04	1.55E−04
	Max	8.57E−04	5.58E−04	3.81E−04	6.29E−04	3.59E−04	1.12E−04	7.07E−05	5.55E−04	5.55E−04	5.55E−04
	Min	7.26E−06	4.73E−06	3.23E−06	5.33E−06	3.04E−06	9.53E−07	5.99E−07	4.71E−06	4.71E−06	4.71E−06

Rupsha Ghat location while the lowest was at the KUET campus (M). An analogous result was reported by Yunesian et al. (2019) who quantified the average HQ ($PM_{2.5}$) as 6.25. Pavel et al. (2020) assessed the health risks of $PM_{2.5}$ and PM_{10} in Dhaka city and addressed significant exposure risks to human health. di Vaio et al. (2018) assessed the health risk of heavy metals associated with PM_{10} in Italy and reported the average HQ for children as 3.11 ± 0.33.

The limitation of this research is the unavailability of reference information for assessing the health risk of PM by considering real-time monitoring data, especially $PM_{1.0}$. Lack of synergies in numerous epidemiological researchers while considering source values, such as inhalation rate, reference concentration of pollutants and inhalation unit risk, create obstacles in determining the associated health risk due to exposure to ambient $PM_{1.0}$. Another point of discussion is the unavailable data on risk-assessing parameters in the context of Bangladesh which led this research to gather information from the perspective of other countries. This study implies the first approach to assess the health risk of ambient $PM_{1.0}$, $PM_{2.5}$ and PM_{10} in Khulna city, one of the major cities of Bangladesh and could be the representable contextual method to consider in a broader aspect. Yet, expanding the monitoring locations and obtaining more frequent PM data could play a significant role in addressing the health risks associated with PM exposure in Bangladesh.

Table 5 Calculated cancer risk (ELCR) of variant people due to the inhalation of ambient $PM_{2.5}$

Location		< 1	1 to < 2	2 to < 3	3 to < 6	6 to < 11	11 to < 16	16 to < 21	21 to < 61	61 to < 71	> 71
L1	Average	2.61E−04	1.70E−04	1.16E−04	1.92E−04	1.09E−04	3.42E−05	2.15E−05	1.69E−04	1.69E−04	1.69E−04
	Max	7.51E−04	4.89E−04	3.34E−04	5.51E−04	3.14E−04	9.85E−05	6.20E−05	4.87E−04	4.87E−04	4.87E−04
	Min	1.24E−04	8.06E−05	5.50E−05	9.08E−05	5.18E−05	1.62E−05	1.02E−05	8.02E−05	8.02E−05	8.02E−05
L2	Average	5.18E−04	3.37E−04	2.30E−04	3.80E−04	2.17E−04	6.80E−05	4.28E−05	3.36E−04	3.36E−04	3.36E−04
	Max	1.09E−03	7.11E−04	4.86E−04	8.02E−04	4.57E−04	1.43E−04	9.02E−05	7.08E−04	7.08E−04	7.08E−04
	Min	2.00E−04	1.30E−04	8.88E−05	1.47E−04	8.36E−05	2.62E−05	1.65E−05	1.29E−04	1.29E−04	1.29E−04
L3	Average	7.34E−04	4.78E−04	3.26E−04	5.39E−04	3.07E−04	9.63E−05	6.06E−05	4.76E−04	4.76E−04	4.76E−04
	Max	1.28E−03	8.32E−04	5.68E−04	9.38E−04	5.35E−04	1.68E−04	1.06E−04	8.28E−04	8.28E−04	8.28E−04
	Min	3.07E−04	2.00E−04	1.37E−04	2.26E−04	1.29E−04	4.03E−05	2.54E−05	1.99E−04	1.99E−04	1.99E−04
L4W	Average	5.65E−04	3.68E−04	2.51E−04	4.15E−04	2.37E−04	7.42E−05	4.67E−05	3.66E−04	3.66E−04	3.66E−04
	Max	1.06E−03	6.92E−04	4.72E−04	7.80E−04	4.45E−04	1.39E−04	8.77E−05	6.89E−04	6.89E−04	6.89E−04
	Min	2.55E−04	1.66E−04	1.14E−04	1.87E−04	1.07E−04	3.35E−05	2.11E−05	1.66E−04	1.66E−04	1.66E−04
L4M	Average	4.67E−05	3.04E−05	2.08E−05	3.43E−05	1.95E−05	6.12E−06	3.85E−06	3.03E−05	3.03E−05	3.03E−05
	Max	2.03E−04	1.32E−04	9.03E−05	1.49E−04	8.50E−05	2.66E−05	1.68E−05	1.32E−04	1.32E−04	1.32E−04
	Min	9.96E−06	6.49E−06	4.43E−06	7.31E−06	4.17E−06	1.31E−06	8.22E−07	6.46E−06	6.46E−06	6.46E−06
L5	Average	7.24E−05	4.72E−05	3.22E−05	5.32E−05	3.03E−05	9.50E−06	5.98E−06	4.69E−05	4.69E−05	4.69E−05
	Max	4.00E−04	2.61E−04	1.78E−04	2.94E−04	1.67E−04	5.25E−05	3.30E−05	2.59E−04	2.59E−04	2.59E−04
	Min	3.12E−05	2.03E−05	1.39E−05	2.29E−05	1.31E−05	4.10E−06	2.58E−06	2.02E−05	2.02E−05	2.02E−05
L6	Average	7.16E−05	4.66E−05	3.18E−05	5.26E−05	3.00E−05	9.39E−06	5.91E−06	4.64E−05	4.64E−05	4.64E−05
	Max	2.47E−04	1.61E−04	1.10E−04	1.81E−04	1.03E−04	3.24E−05	2.04E−05	1.60E−04	1.60E−04	1.60E−04
	Min	2.26E−05	1.47E−05	1.01E−05	1.66E−05	9.47E−06	2.97E−06	1.87E−06	1.47E−05	1.47E−05	1.47E−05
L7	Average	3.63E−04	2.36E−04	1.61E−04	2.66E−04	1.52E−04	4.76E−05	2.99E−05	2.35E−04	2.35E−04	2.35E−04
	Max	4.15E−04	2.70E−04	1.84E−04	3.04E−04	1.73E−04	5.44E−05	3.42E−05	2.69E−04	2.69E−04	2.69E−04
	Min	1.43E−04	9.28E−05	6.34E−05	1.05E−04	5.97E−05	1.87E−05	1.18E−05	9.24E−05	9.24E−05	9.24E−05
L8	Average	3.05E−04	1.99E−04	1.36E−04	2.24E−04	1.28E−04	4.01E−05	2.52E−05	1.98E−04	1.98E−04	1.98E−04
	Max	7.01E−04	4.56E−04	3.11E−04	5.14E−04	2.93E−04	9.19E−05	5.78E−05	4.54E−04	4.54E−04	4.54E−04
	Min	2.08E−04	1.35E−04	9.23E−05	1.52E−04	8.69E−05	2.72E−05	1.71E−05	1.35E−04	1.35E−04	1.35E−04
L9	Average	3.15E−04	2.05E−04	1.40E−04	2.32E−04	1.32E−04	4.14E−05	2.60E−05	2.04E−04	2.04E−04	2.04E−04
	Max	6.97E−04	4.54E−04	3.10E−04	5.12E−04	2.92E−04	9.14E−05	5.75E−05	4.52E−04	4.52E−04	4.52E−04
	Min	1.50E−04	9.74E−05	6.65E−05	1.10E−04	6.26E−05	1.96E−05	1.23E−05	9.69E−05	9.69E−05	9.69E−05
Khulna City (Average)	Average	3.26E−04	2.12E−04	1.45E−04	2.39E−04	1.36E−04	4.28E−05	2.69E−05	2.11E−04	2.11E−04	2.11E−04
	Max	1.28E−03	8.32E−04	5.68E−04	9.38E−04	5.35E−04	1.68E−04	1.06E−04	8.28E−04	8.28E−04	8.28E−04
	Min	9.96E−06	6.49E−06	4.43E−06	7.31E−06	4.17E−06	1.31E−06	8.22E−07	6.46E−06	6.46E−06	6.46E−06

Table 6 Estimated HQ values of $PM_{2.5}$ and PM_{10} at different monitoring locations of Khulna city

Hazard		L1	L2	L3	L4W	L4M	L5	L6	L7	L8	L9	Khulna City
$PM_{2.5}$	Average	6.47	13.53	20.13	15.53	1.07	2	1.73	9.8	9	7.47	8.67
	Max	19.4	31.87	36.53	30.4	4.4	13	6.33	15.4	23	18.53	36.53
	Min	3.07	5.13	8.2	6.87	0.27	0.87	0.67	5.8	6.2	3.67	0.27
PM_{10}	Average	3.34	5.8	6.86	5.3	0.44	1	1	3.46	8.3	4.1	3.96
	Max	7.84	13.54	12.2	10.16	1.52	4.78	4.84	5.28	8.96	16.04	16.04
	Min	1.46	2.2	2.72	2.26	0.12	0.42	0.36	2.12	3.08	1.66	0.12

Conclusions

This study examined atmospheric PM concentrations and assessed health risks associated with $PM_{1.0}$, $PM_{2.5}$, and PM_{10} at specific locations in Khulna city. The findings revealed that the average concentrations of $PM_{2.5}$ and PM_{10} exceeded both WHO and BNAAQS standards in the majority of monitoring locations. This heightened pollution during the winter season, attributed to geographic and meteorological factors, resulted in particle concentrations six to seven times higher than during the monsoon period. The particle size distribution highlighted the significance of fine mode particles ranging from 0.4 µm to 1.75 µm in governing the overall composition. Fractional distribution of individual PM fractions indicated a substantial contribution from ultrafine (9–27%), submicron (4–31%), and intermodal (19–46%) fractions to the total ambient PM levels. The prevalence of fine particles emphasizes the necessity for a health risk assessment to measure the potential inhalation exposure risks associated with ambient PM. The results from the health risk assessment indicated that the standards (1.0E−6) were consistently exceeded by age-dependent incremental ELCR values for $PM_{1.0}$ and $PM_{2.5}$ at all monitoring locations in Khulna, suggesting a potential cancer risk from inhalation. In assessing non-carcinogenic risk, HQ values generally surpassed WHO and USEPA standards, except at three specific locations. To address these identified human health risks in Khulna, it is recommended that relevant authorities in the Bangladesh government consider implementing measures to reduce PM pollution and mitigate associated risks. Additionally, the urban population should adopt protective measures, such as minimizing exposure to atmospheric particles and using face masks, to reduce health risks.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40068-023-00327-2.

Additional file 1. Calculation of Carcinogenic and Non-carcinogenic Health Risks due to the Inhalation of $PM_{1.0}$, $PM_{2.5}$ and PM10.

Additional file 2. Accumulated PM Data from Ten Monitoring Locations in Khulna City.

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Author contributions

JAS: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Roles/Writing —original draft; Writing —review and editing. QHB: Conceptualization; Investigation; Methodology; Resources; Supervision; Writing—review and editing. KAM: Conceptualization; Data curation; Formal analysis; Validation; Visualization; Writing—review and editing. VS: Methodology; Supervision; Validation; Visualization; Writing—review and editing..

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Availability of data and materials

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

Declarations

Ethical approval and consent to participate

Not applicable.

Competing interests

The authors declare no potential competing with respect to the research work.

Author details

[1]Khulna University of Engineering & Technology, Khulna, Bangladesh. [2]School of Natural Sciences, Faculty of Science and Engineering, Macquarie University, Sydney, NSW, Australia.

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