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Research article

Wintertime black carbon assessment in dhaka, Bangladesh: Integrated health risk analysis

A.K.M. Nayem [a,1], Shahid Uz Zaman [b,*,1], Farida Begum [a], Abdus Salam [a]

[a] Department of Chemistry, Faculty of Science, University of Dhaka, Dhaka, 1000, Bangladesh
[b] Department of Chemistry, Faculty of Science, Bangladesh University of Engineering and Technology, Dhaka, 1000, Bangladesh

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ABSTRACT

This study investigated the ramifications of black carbon (BC) emissions on human health during the winter season of December 2019 to February 2020 in Dhaka, Bangladesh. BC, arising from incomplete combustion of fossil and biofuels, underwent meticulous measurement of densities, concentrations, and emissions at two pivotal sites. Employing low-volume air samplers with Quartz filters and subsequent analysis with an Aethalometer (Soot scanner, OT21, USA), the study unveiled monthly average BC densities of 1.64 μg cm^{-2}, concentrations of 4.99 μg m^{-3}, and emissions of 0.038 μg J^{-1}. Health risk assessments revealed higher cancer risks (CRs) at Site-1 (children: 2.82×10^{-4} and adult: 4.72×10^{-4}) compared to Site-2 (children: 2.56×10^{-4} and adult: 4.30×10^{-4}). Hazard quotients (HQs) averaged 0.29 for children and 0.19 for adults in Dhaka. BC exposure escalated relative risks (RR) for all-cause mortality (RR = 1.136), cardiovascular mortality (RR = 1.169), and respiratory mortality (RR = 1.277). These findings underscore the substantial implications of BC's influence, particularly in a nation like Bangladesh, and furnish invaluable insights into aerosol characteristics and emission sources in South Asia, facilitating the formulation of emission inventories.

1. Introduction

Black carbon (BC) stands as a unique aerosol species with the distinctive property of absorbing visible and near-infrared light, enabling its direct mass measurement. BC reflects not only incoming solar radiation, diminishing surface solar energy but also absorbs solar radiation and scatters sunlight, particularly when present above clouds alongside other absorbing aerosols [1]. Although BC comprises a relatively small fraction of urban air particles by mass, its nanoscale dimensions facilitate easy penetration into human lung tissue, leading to significant health concerns, including oxidative stress and respiratory irritation, as documented in various studies [2]. BC exhibits stronger associations with adverse health effects in contrast to fine particulate matter ($PM_{2.5}$) and coarse particulate matter (PM_{10}), as demonstrated by multiple studies [3]. In 2012, the International Agency for Research on Cancer (IARC) categorized soot, which is frequently used interchangeably with BC, as a Group 1 carcinogen for humans [4]. Additionally, BC plays a substantial role in varying the Earth's climate as a climate-forcing agent generated through the incomplete combustion of fossil fuels, biofuels, and biomass, with emissions stemming from both human activities and natural sources [5]. In the Earth's troposphere, BC serves as a significant factor in trapping heat by absorbing incoming shortwave solar radiation and concurrently capturing outgoing

* Corresponding author.
E-mail addresses: shahiduzzamanadil@gmail.com, suzaman@chem.buet.ac.bd (S.U. Zaman).
[1] A. K. M. Nayem and Shahid Uz Zaman have contributed equally to share the first authorship.

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terrestrial longwave radiation. This phenomenon positions BC as the second most substantial human-made contributor to global warming, accounting for roughly 55 % of the radiative forcing caused by CO_2 and nearly twice that of methane [6]. Nonetheless, BC's impact on climate is complex due to its composition, which incorporates elements that possess cooling properties, such as organic carbon and sulfates [7].

While various theories and models have been developed to assess BC's climate impacts [7–9], and research documenting the health effects of BC has been published [10], there remains a compelling need for a comprehensive and systematic evaluation of the health and climate benefits derived from controlling BC particles.

In the context of Bangladesh, BC emissions pose a significant challenge driven by factors such as uncontrolled biomass and fossil fuel burning, inadequate vehicle maintenance, unplanned industrialization, and transboundary air pollution [11–17]. Dhaka, the capital and economic nucleus of Bangladesh, grapples with heightened BC emissions stemming from extensive fuel combustion for transportation, industry, and energy demands. The escalating daily mean BC concentration in Dhaka surpasses recommended guidelines, resulting in substantial public health risks and exacerbating regional climate change.

The aims of this study encompass a multifaceted approach, including the determination of BC density, concentration, and emissions; conducting correlation analyses to explore the relationships between BC concentrations and levels of CO_2, $PM_{2.5}$, humidity, and temperature; performing backward air mass trajectory analyses to elucidate potential sources of BC; conducting health risk assessments that encompass both carcinogenic and chronic non-carcinogenic effects; and estimating relative risks (RR) associated with cause-specific mortality attributed to BC exposure. Our research endeavors to provide quantitative insights into the public health implications of BC exposure, underscoring the essential need for integrated methodologies that take into account BC's health effects to address pertinent policy inquiries concerning BC exposure.

2. Methodology

2.1. Meteorology of sampling locations (dhaka, Bangladesh)

Bangladesh experiences a climate marked by elevated temperatures and high humidity, featuring well-defined seasonal fluctuations in rainfall. Climatically, it can be categorized into four distinct seasons: winter (December–February), pre-monsoon

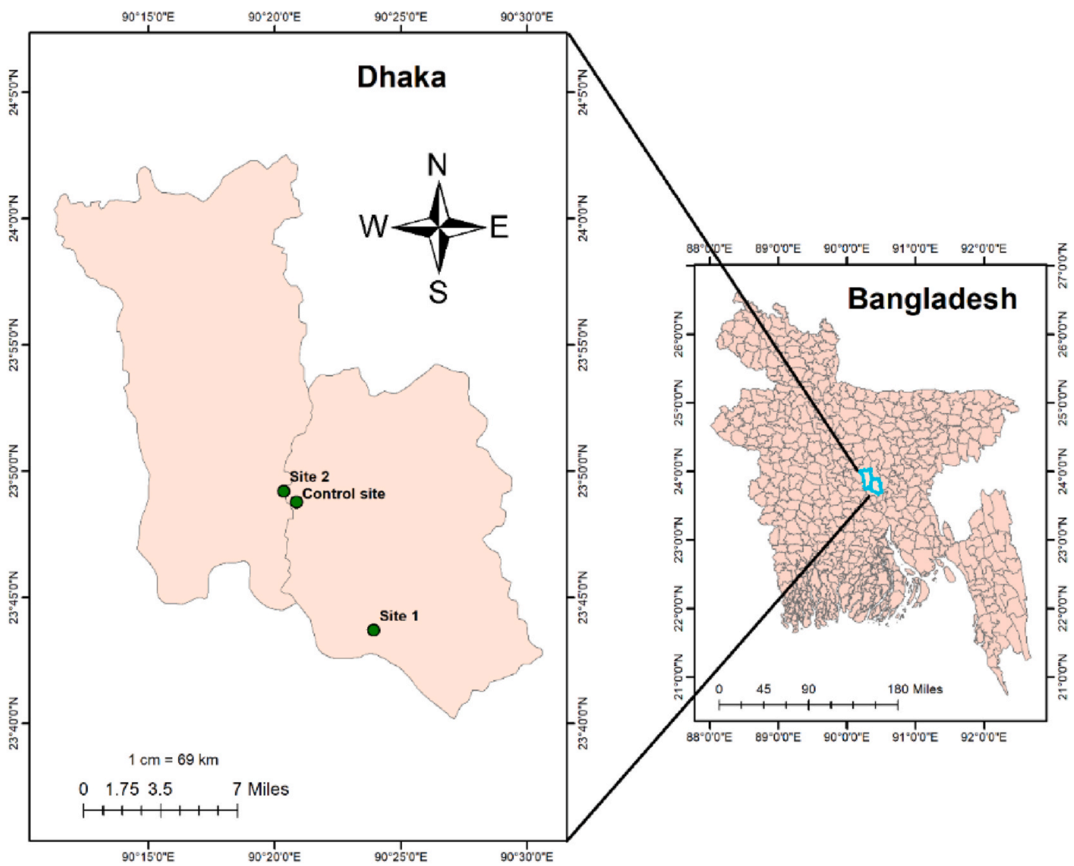


Fig. 1. Sampling sites for the evaluation of black carbon during the winter season in Dhaka. Site-1: Mukarram Bhaban, University of Dhaka, Site-2: Tamanna Park, Mirpur −1, Control Site: Botanical Garden, Mirpur-1.

(March–May), monsoon (June–August), and post-monsoon (September-November) [18]. In Dhaka city, the prevailing wind direction primarily originates from the West and South-West during the pre-monsoon season, shifting to the North and North-West during the winter [14]. The designated sampling locations include: (i) Site-1: Mukarram Bhaban, University of Dhaka (Latitude 23.7281° North, Longitude 90.3985° East), situated within the Dhaka South City Corporation, (ii) Site-2: Tamanna Park, Mirpur −1 (Latitude 23.8199° North, Longitude 90.3393° East) is situated in Dhaka North City Corporation and (iii) Control Site: Botanical Garden, Mirpur-1 (Latitude 23.8127° North, Longitude 90.3476° East) is also situated in Dhaka North City Corporation. Site-1 and Site-2 were selected as primary study locations due to their representation of significant anthropogenic and traffic-related activities within Dhaka South City Corporation and Dhaka North City Corporation, respectively, making them ideal for assessing urban BC pollution levels. The Control Site was chosen for its comparatively lower pollution levels, serving as a baseline for comparative analysis (Fig. 1).

2.2. Sampling procedure

A total of fourteen samples were collected in this study. Monthly, two samples were gathered from both Site-1 and Site-2 during the winter season spanning from December 2019 to February 2020. Additionally, two samples were collected from the Control Site in January 2020. A low-volume air sampler (BK G2, 5 krom//Schroder, ELSTER gastechnic) was used to collect $PM_{2.5}$ particles on Quartz filters (Gelman, Membrane Filters, 47 mm diameter). The PM sampler was programmed to collect $PM_{2.5}$ samples, each spanning a 2-h sampling period. All blank filter papers underwent heating at approximately 800 °C for approximately 3 h to minimize background levels of organic species on the filters and were subsequently placed in a desiccator for an additional 3 h for conditioning. The filter papers were carefully preserved in clean polyethylene Petri dishes until they were ready for field measurements. $PM_{2.5}$ concentrations were determined by measuring the difference between the loaded and blank filter papers using a digital balance. The loaded Quartz filter papers were stored and frozen in a refrigerator at 4 °C until analysis to reduce the potential loss of volatile components.

2.3. Attenuation measurement

To assess the attenuation, the measurement of light transmission through the filter containing the sample was employed. The attenuation coefficient, derived from the rate of attenuation change over time, was subsequently converted into the absorption coefficient, enabling the computation of the mass-equivalent BC concentration, as described by Pavel et al. [12]. The Aethalometer provided two readings at different wavelengths: one for the sample quartz filter and the other for the blank quartz filter. Specifically, the Aethalometer provided infrared (IR) readings at 880 nm and ultraviolet (UV) readings at 370 nm for both the blank filter and the sample filter. The attenuation coefficient (ATN) was calculated using the following formula [eq. (1)]:

$$\mathrm{ATN} = 100 \times \ln(\mathrm{Blanktransmission}\ /\ \mathrm{Sample\ transmission}) \ldots\ldots\ldots \tag{1}$$

Here, ATN represents the Attenuation Factor.

This equation was employed to determine the attenuation factor for BC measurement after sampling. The ATN_1, attenuation factor before heat treatment, was measured using this approach. Subsequently, the sample filter was heated at 340° for 3 h. After cooling, the sample filter was reintroduced into the Aethalometer, and IR readings at 880 nm were obtained for both the blank filter and the sample filter [19]. Using these values, ATN_2, the attenuation factor after heat treatment, was calculated following the previously mentioned equation.

2.4. Determination of the densities, concentrations, and emissions of black carbon (BC)

The determination of Black Carbon (BC) parameters, including density, concentration, and emission, was carried out using Aethalometer readings at 880 nm, and the following equations, which are based on the recommendations from ARCADIS, USA.

2.4.1. Density

BC densities (δ) were calculated using the ATN value at 880 nm with the following equation [eq. (2)] [20,21]:

$$\boldsymbol{\delta} = \frac{\mathbf{ATN_1 - ATN_2}}{\boldsymbol{\sigma}_{\mathbf{ATN}}} \ldots\ldots\ldots \tag{2}$$

Here, δ represents BC density in μg cm^{-2}, σATN stands for the specific attenuation coefficient in cm^2 μg^{-1} (with a value of 16.6 cm^2 μg^{-1} [ARCADIS]), ATN_1 refers to the attenuation of the sample before heat treatment, and ATN_2 refers to the attenuation of the sample after heat treatment.

2.4.2. Concentration

BC concentrations (C_d) were calculated from the densities of BC using the following equation [eq. (3)] [20,21]:

$$\mathbf{C_d} = \frac{\boldsymbol{\delta} \times \mathbf{A}}{\mathbf{V_{ms}}} \ldots\ldots\ldots \tag{3}$$

Here, C_d represents the measured BC concentration in μg m^{-3}, A represents the collection area of the filter in cm^2 (with a value of 14.5 cm^2, where the diameter of the quartz filter is 4.3 cm), and V_{ms} represents the volume of air during sampling from the dry gas meter in

m^3.

2.4.3. Emission

BC emission (E) were calculated from the BC concentration using the following equation [eq. (4)] [20,21]:

$$E = \frac{\mathbf{F_c} \times \mathbf{C_d} \times \mathbf{100\%}}{\mathbf{\%\ CO_2}} \quad \cdots\cdots\cdots \tag{4}$$

Here, E represents carbon emission in μg J^{-1}, Fc represents the carbon-based F factor (with a value of 4.84×10^{-6} m^3 J^{-1}), C_d represents the measured BC concentration in μg m^{-3}, and % CO_2 represents the percentage concentration of carbon dioxide at the sampling site (0.0678 % at Site-1, 0.0651 % at Site-2, and 0.0553 % at the Control Site). Concentrations of CO_2 were measured using the "AEROQUAL 500 SERIES" in ppm units and then converted to percentage concentration.

2.5. Correlation of BC with CO_2, $PM_{2.5}$, humidity and temperature in dhaka, Bangladesh

Pearson's correlations were performed to study the correlation of BC with CO_2, $PM_{2.5}$, Humidity, and Temperature, which predicts the linear relationship of BC with CO_2, $PM_{2.5}$, Humidity, and Temperature. For the correlation study, concentrations of CO_2 were measured by AEROQUAL 500 SERIES, and concentrations of $PM_{2.5}$, Humidity, and Temperature were measured by IGERESS Air Quality Monitor (Model No: WP6930S, China).

2.6. Backward air mass trajectories analysis in dhaka, Bangladesh

Backward air-mass trajectories that extended over Dhaka, Bangladesh, at altitudes of 500, 1000, and 2000 m above ground level were computed for a duration of 120 h throughout the winter season, spanning from December 2019 to February 2020. These calculations were performed utilizing the National Oceanic and Atmospheric Administration (NOAA) Hybrid Single-Particle Lagrangian Trajectory (HYSPLIT) model [14].

2.7. Health risk assessment of BC

The potential dose for the exposed population based on external atmospheric air pollutant exposure levels was calculated. To assess both cancer and non-cancer risks, we utilized the following equation [eq. (5)] for the chronic daily intake (CDI) (mg kg^{-1} day^{-1}) CDI calculations [22]:

$$CDI = \frac{\mathbf{C \times IR \times EF \times ED}}{\mathbf{BW \times AT}} \quad \cdots\cdots\cdots \tag{5}$$

Where: C represents the mean BC concentration (mg m^{-3}), IR indicates the inhalation rate (m^3 day^{-1}), EF indicates exposure frequency (days $year^{-1}$), ED stands for exposure duration (years), BW represents body weight (kg), and AT signifies averaging time (days) (Table 1).

Risk characterization involved quantitatively estimating the cancer probability risk of BC exposure by utilizing the cancer slope factor (CSF) derived from the OEHHA dataset. The reference concentration (RfC) and CSF values derived from OEHHA reports in 1998 and 2016, were determined to be 5×10^{-3} mg m^{-3} and 1.1 (mg kg^{-1} day^{-1}), respectively [23]. The cancer risk (CR) estimation was carried out using the following equation [eq. (6)]:

$$\mathbf{CR = CDI \times CSF} \quad \cdots\cdots\cdots \tag{6}$$

To evaluate non-cancer risks, we computed the Hazard Quotient (HQ) of BC exposure using RfC. HQ is defined as the ratio of the estimated exposure level to the reference dose for toxicity of the specific contaminant. An HQ value below one implies that the exposed population is unlikely to experience adverse non-cancer effects. The formula is expressed as follows [eq. (7)]:

$$\mathbf{HQ} = \frac{\mathbf{CDI}}{\mathbf{RfC}} \quad \cdots\cdots\cdots \tag{7}$$

In our investigation, we adopted a reference dose for inhalation toxicity of diesel exhaust particulate, which served as a proxy for BC, set at 5×10^{-3} mg m^{-3} [25].

Table-1
Input data for health risk assessment for different age [24].

Factors	Children (6–12 year)	Adult (21–70 year)
IR (m^3/day)	13.5	16
EF (days)	350	350
ED (years)	12	30
BW (kg)	45.3	80

2.8. Estimating the relative risk (RR) of cause-specific mortality of BC

To estimate the relative risk (RR) of BC-related cause-specific mortality, we applied a previously established prediction model, as outlined in previous studies [26,27]. The RR calculation is represented by the formula [eq. (8)]:

$$\mathbf{RR} = \mathbf{exp}\ (\boldsymbol{\beta}\ (\mathbf{C_n} - \mathbf{C_o}))\ \ldots\ldots\ldots \quad (8)$$

In this equation, C_n represents the mean BC concentrations during the exposure time, C_o stands for the mean BC concentrations in a designated baseline period, and β represents the risk coefficient associated with BC exposure and mortality.

Previous research, as documented in a systematic review [3], estimated the following values for these parameters: 0.014 (95 % CI: 0.013, 0.016) for all-cause mortality, 0.018 (95 % CI: 0.011, 0.031) for cardiovascular mortality, and 0.027 (95 % CI: 0.001, 0.054) for respiratory mortality. For our analysis, we considered the average BC concentration during the winter period (January 2020) at the Botanical Garden (Control Site) as the baseline due to its relatively low level, which measured at 1.33 μg m^{-3}. To assess the cause-specific mortality risk attributed to BC, we examined the winter season (December 2019–February 2020) as the exposure period for both Site-1 and Site-2.

3. Results and discussion

3.1. Determination of densities of black carbon (BC)

Fig. 2 illustrates the variation in BC densities in two sampling sites. In Site-1, the highest density of BC (3.71 μg cm^{-2}) was found in January 29, 2020 and the lowest density of BC (0.74 μg cm^{-2}) was found in February 12, 2020. Conversely, in Site-2 the highest density of BC (3.06 μg cm^{-2}) was found in January 27, 2020 and the lowest density of BC (0.57 μg cm^{-2}) was found in February 15, 2020. In Site-1, monthly average densities of BC in December 2019, January 2020 and February 2020 were found 1.01 μg cm^{-2}, 2.98 μg cm^{-2} and 1.24 μg cm^{-2} respectively. Monthly average densities of BC in Site-1, follow the sequence as – January 2020 > February 2020 > December 2019. In Site-2, monthly average densities of BC in December-2019, January-2020 and February- 2020 were found 0.88 μg cm^{-2}, 2.82 μg cm^{-2} and 0.93 μg cm^{-2} respectively. Monthly average densities of BC in Site-2, follow the sequence as – January 2020 > February 2020 > December 2019. Between Site-1 and Site-2, the highest monthly average density of BC (2.98 μg cm^{-2}) was found in January 2020 at Site-1 and the lowest monthly average density of BC (0.88 μg cm^{-2}) was found in December 2019 at Site-2 (0.88 μg cm^{-2}).

3.2. Determination of concentrations of black carbon (BC)

The monthly average concentrations of BC in Dhaka were found highest in January 2020 and lowest in December 2019. Between Site-1 and Site-2, the highest monthly average concentration of BC (8.94 μg m^{-3}) was found in January 2020 at Site-1, and the lowest monthly average density of BC (2.54 μg m^{-3}) was found in December 2019 at Site-2.

In Site-1, the highest recorded BC concentration was 11.18 μg m^{-3}, observed on January 29, 2020, while the lowest BC concentration of 2.16 μg m^{-3} was documented on December 4, 2019. Conversely, at Site-2, the highest BC concentration of 9.76 μg m^{-3} was noted on January 27, 2020, with the lowest concentration of 1.68 μg m^{-3} recorded on December 15, 2019. Fig. 3 illustrates the monthly average BC concentrations for both Site-1 and Site-2. For Site-1, the monthly average BC concentrations in December 2019, January 2020, and February 2020 were 2.96 μg m^{-3}, 8.94 μg m^{-3}, and 3.77 μg m^{-3}, respectively, following the sequence of January 2020 > February 2020 > December 2019. Meanwhile, at Site-2, the monthly average BC concentrations in December 2019, January 2020, and February 2020 were 2.54 μg m^{-3}, 8.81 μg m^{-3}, and 2.92 μg m^{-3}, respectively. Monthly average concentrations of BC in Site-

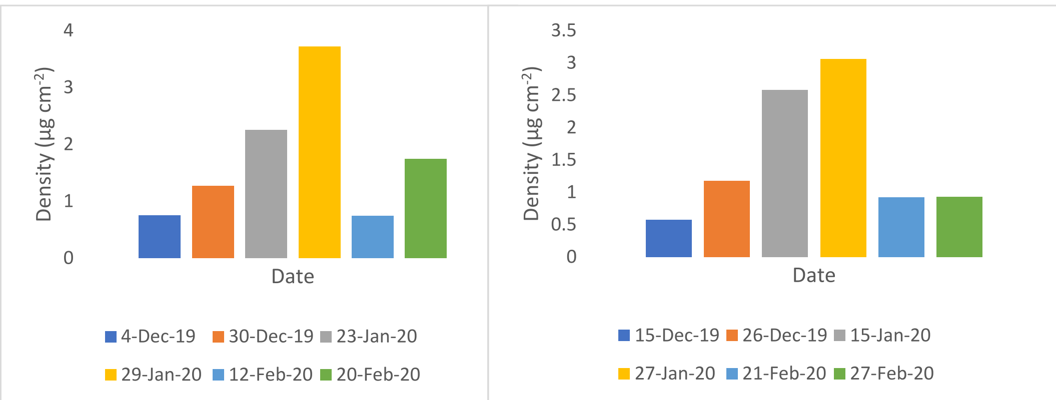


Fig. 2. Densities of BC in two sampling sites (Left panel: Site-1; Right panel: Site-2). Site-1: Mukarram Bhaban, University of Dhaka; Site-2: Tamanna Park, Mirpur −1.

2, follow the sequence as – January 2020 > February 2020 > December 2019 (Fig. 3).

The observed BC levels in this study are influenced by emissions from key sources, including biomass burning, traffic emissions, and coal combustion. Previous studies using dual carbon isotope analysis ($\delta^{13}C$ and $\Delta^{14}C$) have identified these sources as the dominant contributors to BC in Dhaka during the high-loading winter period [28]. These emission sources, combined with local meteorological conditions, significantly influence the temporal variations in BC concentrations observed in this study. Among these meteorological factors, the atmospheric boundary layer (ABL) height plays a critical role in governing pollutant dispersion and accumulation. A shallow ABL during nighttime and early morning restricts vertical mixing, exacerbating the accumulation of emissions from biomass burning, traffic, and coal combustion near the surface [29]. This effect is more pronounced during winter, when atmospheric stability is heightened, leading to the peak BC levels observed in January 2020 in this study.

BC concentration was compared with previous studies and found that our results were comparable to those in China [30], but higher than those in the United Kingdom [31] and Mexico [32]. However, wintertime BC concentration in India [33] was found to be significantly higher than in our study (Table 2).

3.3. Determination of emissions of black carbon (BC)

The highest emission of BC (0.08 μg J^{-1}) was found on January 29, 2020 and the lowest emission of BC (0.02 μg J^{-1}) was found on December 04, 2019 and February 12, 2020 for Site-1. In Site-2 the highest emission of BC (0.07 μg J^{-1}) was found on January 27, 2020 and the lowest emission of BC (0.01 μg J^{-1}) was found on December 15, 2019. Monthly average emissions of BC in both Site-1 and site-2 is given in Table 3. In Site-1, monthly average emissions of BC in December 2019, January 2020 and February- 2020 were found 0.025 μg J^{-1}, 0.065 μg J^{-1} and 0.030 μg J^{-1} respectively. Monthly average emissions of BC in Site-1, follow the sequence as – January 2020 > February 2020 > December 2019. In Site-2, monthly average emissions of BC in December 2019, January 2020 and February 2020 were found 0.020 μg J^{-1}, 0.065 μg J^{-1} and 0.020 μg J^{-1} respectively. Monthly average concentrations of BC in Site-2, follow the sequence as – January 2020 > February 2020 = December 2019. Between Site-1 and Site-2, the highest monthly average emissions of BC (0.065 μg J^{-1}) were found in January 2020 at both Sites (Site-1 and Site-2) and the lowest monthly average emissions of BC (0.020 μg J^{-1}) were found in both December 2019 and February 2020 at Site-2.

3.4. Correlation of black carbon (BC) with CO_2, $PM_{2.5}$, humidity and temperature in dhaka

3.4.1. Correlation of black carbon (BC) with CO_2 and $PM_{2.5}$

In this correlation analysis, interrelationships between BC, CO_2, $PM_{2.5}$ concentrations were investigated. Pearson correlation coefficients (r) were employed to quantify these associations, revealing both their strength and direction. Site-1 exhibited a robust and highly significant positive correlation ($r = 0.97$) between BC and CO_2 concentrations, indicating that increases in CO_2 levels correspond to concurrent increases in BC concentrations and vice versa (Fig. 4). A similar pattern was observed at Site-2, with a strong and statistically significant positive correlation ($r = 0.94$). When analyzing BC in relation to $PM_{2.5}$ concentrations, both Site-1 ($r = 0.95$) and Site-2 ($r = 0.90$) demonstrated strong and highly significant positive correlations, signifying those elevations in $PM_{2.5}$ concentrations are closely mirrored by corresponding increases in BC concentrations. These correlation analyses elucidate the intricate relationships among BC, CO_2, and $PM_{2.5}$, underscoring the strong positive associations between BC concentrations and both CO_2 and $PM_{2.5}$ concentrations at the study sites, offering insights into the complex dynamics of these atmospheric components.

3.4.2. Correlation of black carbon (BC) with humidity and temperature

In our investigation of the relationship between BC and Humidity, we observed robust and statistically significant positive correlations at both Site-1 ($r = 0.59$) and Site-2 ($r = 0.63$) (Fig. 5). This implies that as humidity levels rise, BC concentrations tend to increase concurrently. This phenomenon can be attributed to the role of humidity in influencing aerosol dynamics. Higher humidity levels promote the hygroscopic growth of BC particles, causing them to absorb moisture and become larger, increasing BC

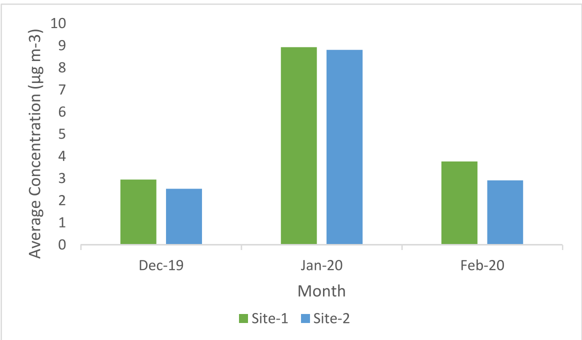


Fig. 3. Variations of monthly average concentrations of BC in Site-1 and Site-2. Site-1: Mukarram Bhaban, University of Dhaka; Site-2: Tamanna Park, Mirpur −1.

Table 2
Comparison of wintertime BC concentration with previous studies.

Study	Study area	Time period	BC concentration (μg m^{-3})
Liu et al. [30]	Beijing, China	2015–2016	5.31
Singh et al. [31]	United Kingdom	2009–2011	1.2–4.0
Peralta et al. [32]	Mexico	2015–2016	3.21
Sankar et al. [33]	Jamshedpur, India	2017	10.38
This study	Dhaka, Bangladesh	2019–2020	4.99

Table-3
Variations of monthly average emissions of BC in Site-1 and Site-2. Site-1: Mukarram Bhaban, University of Dhaka; Site-2: Tamanna Park, Mirpur −1.

Month	Monthly Average Emission (μg J^{-1})	
	Site-1	Site-2
December 2019	0.025	0.020
January 2020	0.065	0.065
February 2020	0.030	0.020
Overall Dhaka	0.038	

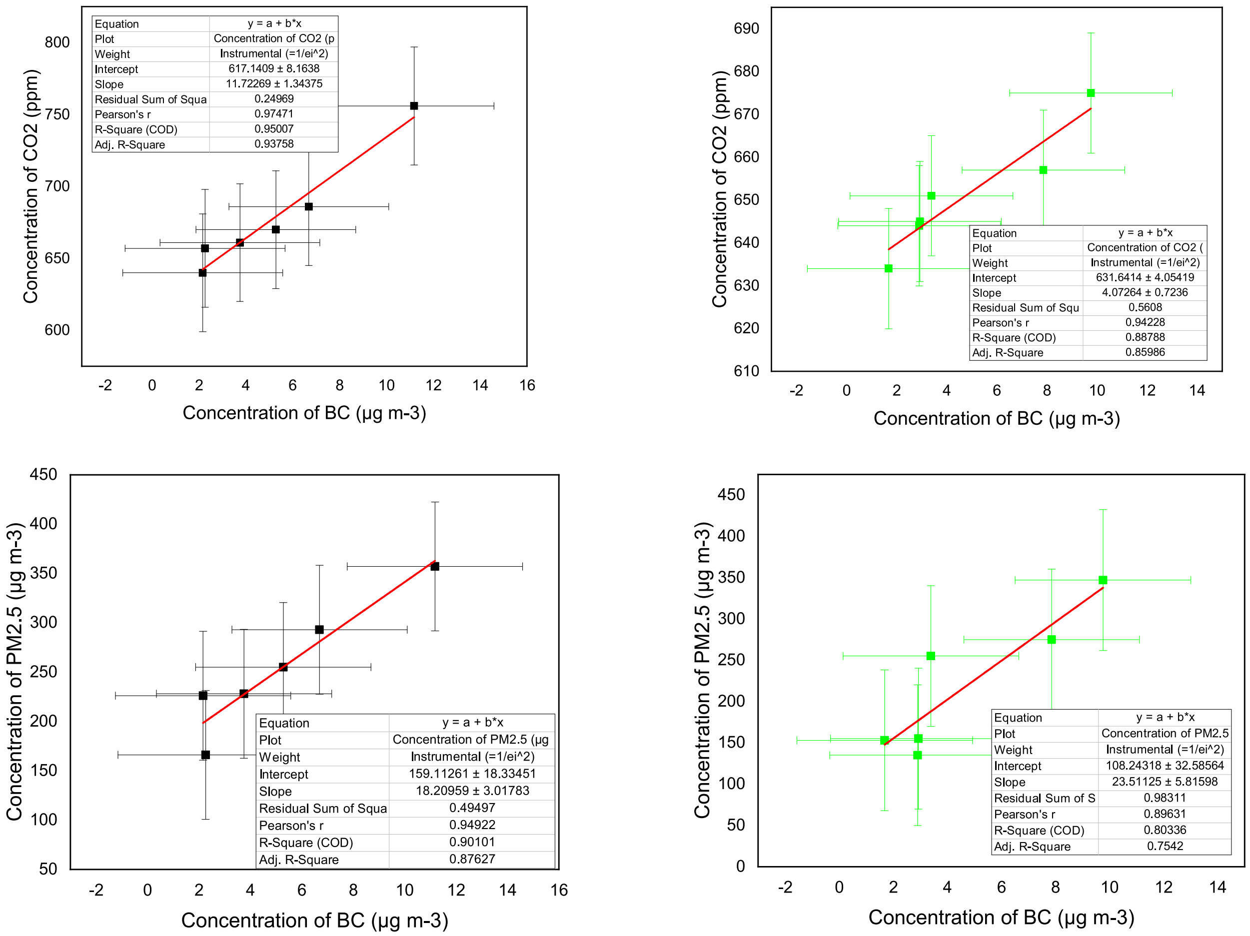


Fig. 4. Correlation of BC concentration (μg m^{-3}) with concentration of CO_2 (ppm) and $PM_{2.5}$ (μg m^{-3}) at Dhaka. Left panel: Site-1; Right panel: Site-2. Site-1: Mukarram Bhaban, University of Dhaka; Site-2: Tamanna Park, Mirpur −1.

concentrations in the atmosphere. Understanding this relationship has implications for the impact of BC on both air quality and climate.

For the BC and Temperature correlation analysis, Site-1 exhibited a robust and highly significant negative correlation (r = −0.80), while Site-2 displayed a similar pattern with a strong and statistically significant negative correlation (r = −0.78) (Fig. 5). These negative correlations indicate that as temperature decreases, BC concentrations tend to increase, and vice versa. This phenomenon can be attributed to variations in atmospheric stability. Lower temperatures often accompany stable atmospheric conditions, which can trap BC particles near the Earth's surface, resulting in elevated BC concentrations. Conversely, higher temperatures are associated with more turbulent atmospheric conditions, which can disperse BC particles, leading to lower concentrations. This understanding of the temperature-BC relationship is crucial for assessing BC's role in air quality, visibility, and climate change, particularly in regions with seasonal temperature variations.

3.5. Backward air mass trajectories analysis in dhaka, Bangladesh

During winter 2019–2020, backward trajectory analysis demonstrates how air masses transporting BC reached Dhaka at altitudes of 500 m, 1000 m, and 2000 m, revealing the significant role of transboundary pollution (Fig. 6). In December 2019, air masses arrived from India (500 m), the Bay of Bengal (1000 m), and the Middle East (2000 m), which generally bring moderate BC concentrations, resulting in relatively lower BC levels in Dhaka during this period. By January 2020, however, air masses were primarily originating from the highly polluted Indo-Gangetic Plain (IGP) region, particularly from the North-West at all altitude levels, transporting substantial BC loadings and significantly raising concentrations in Dhaka. This peak aligns with the typical high-pollution events of the winter season. It demonstrates how emissions from densely populated regions with intense industrial and agricultural activities in the IGP influence Dhaka's air quality. In February 2020, air masses arriving at 500 m and 1000 m continued to come from the IGP, while those at 2000 m came from Africa, resulting in moderate BC levels.

This analysis reveals strong seasonal and spatial correlations between elevated BC concentrations and air mass origins, especially from the IGP, underscoring how BC pollution peaks in winter are linked to regional air flows. Additionally, the winter meteorological

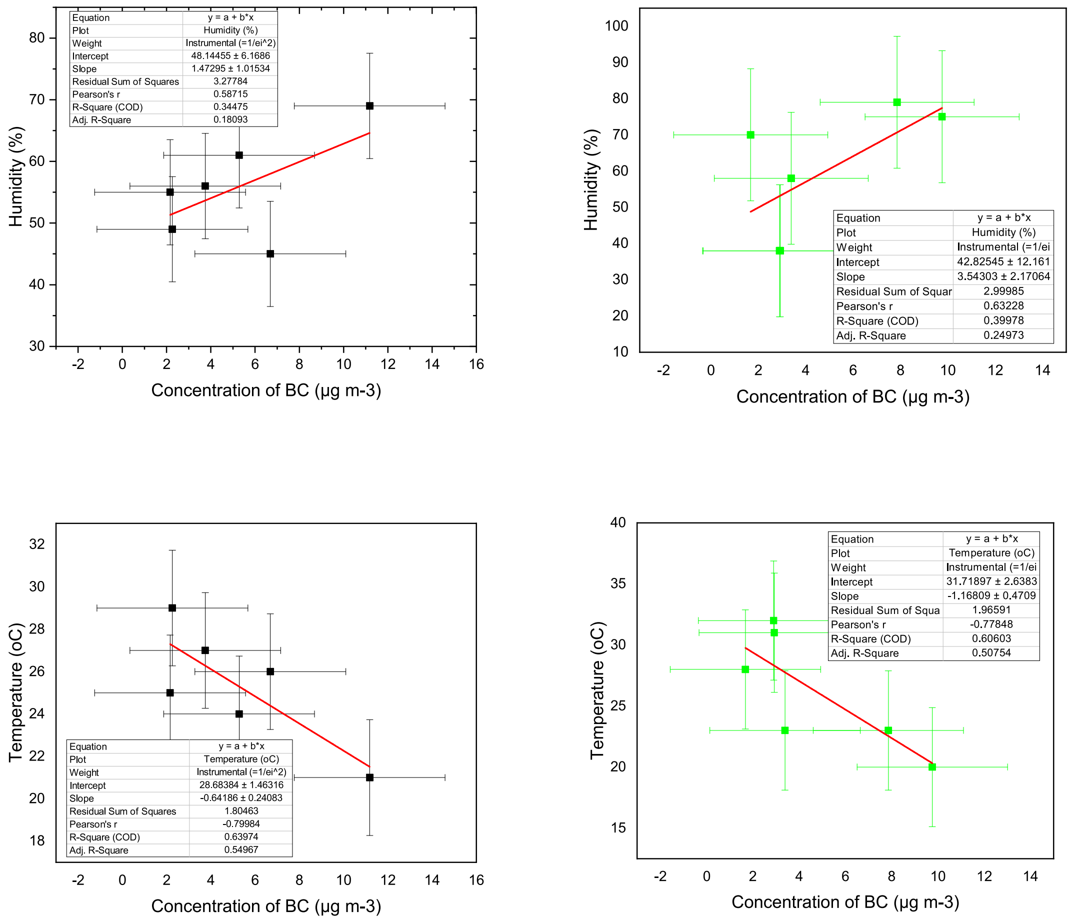
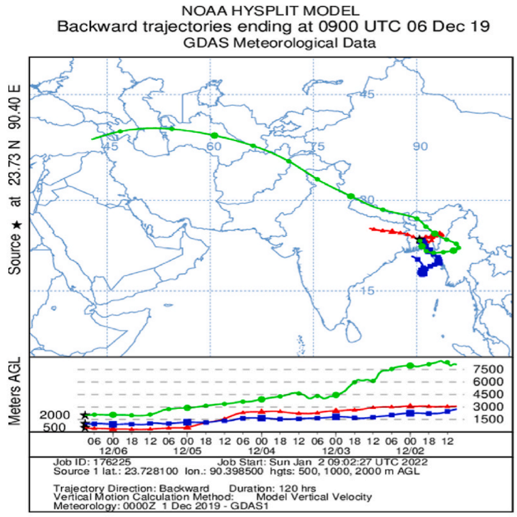
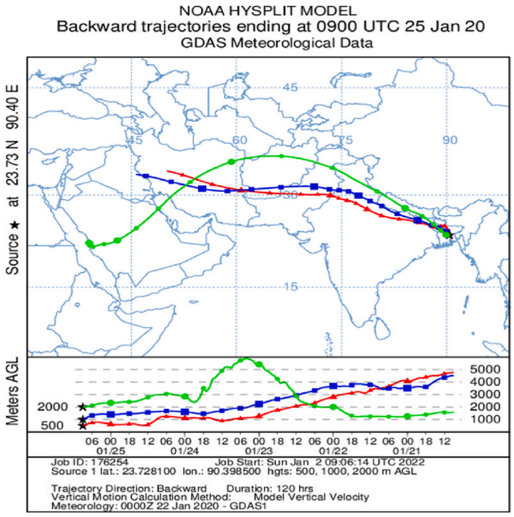


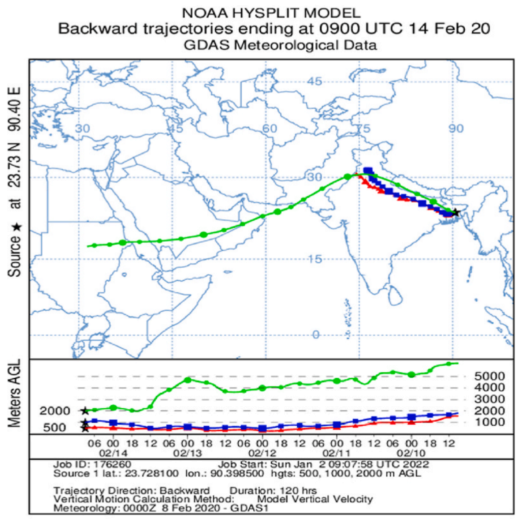
Fig. 5. Correlation of BC concentration (µg m^{-3}) with Humidity (%) and Tem**perature (°C) at Dhaka. Left panel: Site-1; Right panel: Site-2. Site-1: Mukarram Bhaban, University of Dhaka; Site-2: Tamanna Park, Mirpur -1**.



December 2019



January 2020



February 2020

Fig. 6. Backward Air Mass Trajectories Analysis During Winter Season in Dhaka, Bangladesh. (Left panel: December 2019; Right panel: January 2020; Bottom panel: February 2020).

Table-4
The carcinogenic risk assessment for black carbon (BC).

Sites	Month	CDI[a] (mg kg^{-1} day^{-1})		CR	
		Children	Adults	Children	Adults
Site-1	Dec 2019	1.45×10^{-4}	2.43×10^{-4}	1.60×10^{-4}	2.67×10^{-4}
	Jan 2020	4.37×10^{-4}	7.34×10^{-4}	4.81×10^{-4}	8.07×10^{-4}
	Feb 2020	1.85×10^{-4}	3.10×10^{-4}	2.04×10^{-4}	3.41×10^{-4}
Site-2	Dec 2019	1.24×10^{-4}	2.08×10^{-4}	1.36×10^{-4}	2.29×10^{-4}
	Jan 2020	4.32×10^{-4}	7.24×10^{-4}	4.75×10^{-4}	7.96×10^{-4}
	Feb 2020	1.43×10^{-4}	2.40×10^{-4}	1.57×10^{-4}	2.64×10^{-4}
Average	Site-1	2.55×10^{-4}	4.29×10^{-4}	2.82×10^{-4}	4.72×10^{-4}
	Site-2	2.33×10^{-4}	3.91×10^{-4}	2.56×10^{-4}	4.30×10^{-4}
	Dhaka	2.44×10^{-4}	4.10×10^{-4}	2.69×10^{-4}	4.51×10^{-4}

CDI[a] = The chronic daily intake for cancer risk, CR = Cancer risk. Site-1: Mukarram Bhaban, University of Dhaka; Site-2: Tamanna Park, Mirpur −1.

conditions in Dhaka, such as low wind speeds and temperature inversions, contribute to pollutant accumulation near the surface, amplifying these transboundary effects [14].

3.6. Health risk assessment

3.6.1. Carcinogenic risk assessment

A comprehensive assessment of the health implications associated with BC exposure was undertaken. It is pertinent to mention that the acceptable risk thresholds for carcinogenic substances, as recommended by the United States Environmental Protection Agency (EPA), typically range from 1×10^{-6} to 1×10^{-4} [34]. Table 4 provides a comprehensive compilation of the CR associated with exposure to BC for both children and adults. Significant disparities in CR were observed among the various sites, with Site-1 registering the highest CR values (2.82×10^{-4} for children and 4.72×10^{-4} for adults), while Site-2 displayed the lowest CR values (2.56×10^{-4} for children and 4.30×10^{-4} for adults). Higher CR levels were generally noted in adults as compared to children. The average CRs in Dhaka were computed as 2.69×10^{-4} for children and 4.51×10^{-4} for adults, respectively. Our calculations indicate that being exposed to the present levels of BC in Dhaka would lead to an additional 2.69 cancer instances per 10,000 children (2.69×10^{-4}) and 4.51 cancer occurrences per 10,000 adults (4.51×10^{-4}). It is noteworthy that our estimations for BC-associated cancer risks generally surpass those reported in other studies [35,36]. Typically, the EPA deems cancer risks below one case per million individuals (1×10^{-6}) as insignificant while risks exceeding one in 10,000 persons (1×10^{-4}) are deemed significant and warranting remedial action. Our analysis underscores the potential carcinogenicity linked to BC exposure in both children and adults. Regarding geographical locations, the highest risks were identified in Site-1 (Mukarram Bhaban, University of Dhaka), situated downwind from major pollution sources within Dhaka. Generally, areas influenced by the generation and subsequent dispersion of precursor emissions that contribute to the formation of BC tend to display heightened cancer risk levels.

Certain occupational groups, such as street vendors and rickshaw pullers, are among the most vulnerable to air pollution due to their prolonged exposure to traffic and industrial emissions. Recent studies indicate that street vendors in Dhaka are exposed to PM concentrations significantly exceeding safe thresholds, which increases the risks of reduced lung function, respiratory diseases, and cardiovascular conditions [37]. Such occupational exposure highlights a critical need for targeted interventions, including protective equipment, occupational safety regulations, and improved urban air quality management. These findings align with Sustainable Development Goal (SDG) 3, which emphasizes ensuring healthy lives and promoting well-being for all, and SDG 11, which aims to make cities inclusive, safe, resilient, and sustainable. Implementing targeted measures for these vulnerable populations not only mitigates health risks but also advances the broader goals of equity and sustainable urban development.

3.6.2. Non-carcinogenic risk assessment

Table 5 provides a comprehensive summary of the non-cancer risk, as quantified by the HQ, stemming from exposure to BC for both children and adults. Significant variations in HQ were observed among the different sites, with the highest HQ values (0.30 for children and 0.20 for adults) recorded at Site-1, while the lowest HQ values (0.27 for children and 0.18 for adults) were observed at Site-2. Higher HQ values were generally observed in children compared to adults. The average HQs in Dhaka were calculated as 0.29 for children and 0.19 for adults, respectively. Importantly, since the HQ values remained below 1, non-carcinogenic risks were not deemed to be occurring at our study sites. Nevertheless, our findings emphasize that existing levels of BC exposure continue to pose a significant risk to human health.

3.7. Assessment of BC-attributable relative risks

To gauge the relative risks of mortality associated with monthly fluctuations in black carbon (BC) concentrations within Dhaka, Bangladesh, alterations in concentration levels during specific time intervals are presented in Table 6. The RR pertaining to BC-attributed all-cause mortality reached its peak in January 2020 (RR = 1.289) at Site-1 and exhibited its lowest value in December 2019 (RR = 1.041) at Site-2. Analogously, the trends in relative risks linked to BC exposure for cardiovascular and respiratory

Table-5
The non-carcinogenic risk assessment for black carbon (BC).

Sites	Month	CDI[b] (mg kg^{-1} day^{-1})		HQ	
		Children	Adults	Children	Adults
Site-1	Dec 2019	8.44×10^{-4}	5.67×10^{-4}	0.17	0.11
	Jan 2020	2.55×10^{-3}	1.71×10^{-3}	0.51	0.34
	Feb 2020	1.08×10^{-3}	7.23×10^{-4}	0.22	0.14
Site-2	Dec 2019	7.24×10^{-4}	4.86×10^{-4}	0.15	0.10
	Jan 2020	2.52×10^{-3}	1.69×10^{-3}	0.50	0.34
	Feb 2020	8.33×10^{-4}	5.59×10^{-4}	0.17	0.11
Average	Site-1	1.49×10^{-3}	1.00×10^{-3}	0.30	0.20
	Site-2	1.36×10^{-3}	9.12×10^{-4}	0.27	0.18
	Dhaka	1.43×10^{-3}	9.56×10^{-4}	0.29	0.19

CDI[b] = The chronic daily intake for non-cancer risk; HQ = Hazard quotient. Site-1: Mukarram Bhaban, University of Dhaka; Site-2: Tamanna Park, Mirpur −1.

mortality remained consistent. Particularly, the effect estimates for BC were notably higher in January 2020 as compared to December 2019 and February 2020 for all-cause mortality, cardiovascular mortality, and respiratory mortality. In terms of geographic locations, the most elevated risks were observed at Site-1, in contrast to Site-2. In Dhaka, the average RR for BC-related mortality was calculated as 1.136 for all-cause mortality, 1.169 for cardiovascular mortality, and 1.277 for respiratory mortality.

Several studies in Bangladesh have identified strong associations between $PM_{2.5}$ and increased morbidity and mortality, specifically related to cardiovascular and respiratory conditions. Rahman et al. [38] highlight that $PM_{2.5}$ from fossil-fuel combustion has approximately four times the impact on cardiovascular disease (CVD) mortality compared to $PM_{2.5}$ from biomass combustion, and nearly double the effect on hospital admissions for CVD. This underscores the significant health burden from fossil-fuel-derived $PM_{2.5}$ pollution in urban settings like Dhaka. In addition, spatiotemporal analyses of $PM_{2.5}$ impacts indicate substantial increases in mortality rates for diseases such as lower respiratory infections (LRI), cardiovascular disease (CEV), ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), and lung cancer (LC) [39]. From 2001 to 2019, $PM_{2.5}$ exposure was linked to an estimated increase in excess mortality per 100,000 people of 101.64 deaths for LRI, 53.62 for CEV, 46.77 for IHD, 28.86 for COPD, and 10.78 for LC [39]. These findings illustrate the substantial health impacts of fine particulate matter pollution in Bangladesh, especially in urban areas with high exposure levels.

Furthermore, recent studies in Indonesia reinforce the health risks associated with $PM_{2.5}$ exposure. Siregar et al. [40] found a 29 % increase in CVD prevalence per 10 μgm^{-3} increase in $PM_{2.5}$ levels, utilizing satellite-based measurements and health survey data. Although this study focuses on BC, the findings on $PM_{2.5}$ are relevant, as BC is a major $PM_{2.5}$ component with similar cardiovascular and respiratory health impacts. These regional findings support the observed health risks in Bangladesh and underscore the need for targeted mitigation efforts.

To mitigate the documented health impacts of BC and other particulate matter, several policy actions are recommended. Strengthening emissions standards for industrial and vehicular sources, particularly in urban centers, could significantly reduce pollutant levels. Additionally, promoting cleaner transportation options, such as electric and hybrid vehicles, and enhancing public transport infrastructure would help reduce urban black carbon emissions. Urban planning that includes green spaces and tree planting can also serve as a natural buffer, improving air quality. Encouraging household energy shifts to cleaner technologies and subsidizing low-emission cooking methods would reduce residential emissions, particularly in areas reliant on biomass and coal. Establishing comprehensive air quality monitoring networks with early warning systems could protect vulnerable populations by alerting them during high pollution periods, especially in winter when pollution peaks. Finally, public awareness campaigns should be intensified to inform residents about the health risks of pollution and encourage protective actions. These recommendations provide a comprehensive approach to addressing the health burden associated with air pollution in urban environments.

Our research emphasizes the significant role played by meteorological factors as determinants of environmental health, especially when assessing the risks associated with BC exposure. The impact of BC exposure on mortality was particularly evident during January 2020 in Dhaka, Bangladesh. Our comprehensive assessment covered both the chronic, long-term effects, and the immediate, short-term consequences of BC exposure on human health. We evaluated BC's impact on cancer and non-cancer effects based on laboratory-based research findings, while also examining cause-specific mortality risks through population-based studies. This toxicology-based risk assessment process aided in identifying potential hazards and provided a valuable framework for determining the level of health threats faced by the exposed population.

4. Conclusion

The densities, concentrations, and emissions of black carbon were investigated at two distinct sites, Site-1 (Mukarram Bhaban, University of Dhaka) and Site-2 (Tamanna Park, Mirpur), during the winter season spanning December 2019 to February 2020 in Dhaka, Bangladesh. Both sites exhibited a monthly trend where BC values were consistently highest in January 2020, followed by February 2020, and lowest in December 2019. The recorded monthly average BC values in Dhaka were as follows: density 1.64 $\mu g\ cm^{-2}$, concentration 4.99 $\mu g\ m^{-3}$, and emissions 0.038 $\mu g\ J^{-1}$. The correlation analysis between BC and CO_2, $PM_{2.5}$, humidity, and temperature at both Site-1 and Site-2 in Dhaka demonstrated robust positive correlations with CO_2, $PM_{2.5}$, and humidity, while revealing a negative correlation with temperature. Furthermore, the investigation employing backward air mass trajectory analysis unveiled that during the winter season of January 2020, air masses carrying BC predominantly originated from the northwest region of the highly polluted IGP before reaching Dhaka. Consequently, this led to greater mass concentrations of BC in Dhaka during January 2020. Regarding Cancer Risk (CR) associated with BC exposure, it was observed that Site-1 exhibited higher CR values (2.82×10^{-4} for children and 4.72×10^{-4} for adults) compared to Site-2 (2.56×10^{-4} for children and 4.30×10^{-4} for adults). Additionally, adults exhibited higher CR levels than children. The average CRs in Dhaka were estimated at 2.69×10^{-4} for children and 4.51×10^{-4} for adults which suggests that current levels of BC exposure in Dhaka could lead to an additional 2.69 cases of cancer per 10,000 children and 4.51 cases of cancer per 10,000 adults. The HQ related to BC exposure displayed variations among the sites, with Site-1 having higher HQ values (0.30 for children and 0.20 for adults) compared to Site-2 (0.27 for children and 0.18 for adults). Children also exhibited higher HQ values compared to adults. The average HQs in Dhaka were calculated as 0.29 for children and 0.19 for adults. The Average Relative Risk (RR) for mortality attributed to BC exposure in Dhaka was found to be elevated for all-cause mortality (RR = 1.136), cardiovascular mortality (RR = 1.169), and respiratory mortality (RR = 1.277). These effects were notably more pronounced during January 2020 in Dhaka.

Dhaka is experiencing substantial health impacts due to BC pollution, necessitating urgent governmental measures to control BC emissions from both local and regional sources. Regional actions are also imperative to mitigate the transboundary effects of BC pollution. This study contributes valuable insights into the BC pollution issue and its implications for Dhaka's population.

Table-6
The Relative Risk (RR) for All-cause, Cardiovascular and Respiratory mortality due to Short-term Exposure to BC in Different Months at Site-1 and Site-2. Site-1: Mukarram Bhaban, University of Dhaka; Site-2: Tamanna Park, Mirpur −1.

Sites	Month	Average Concentration (μg m^{-3})	The RR for mortality		
			All-cause	Cardiovascular	Respiratory
Site-1	Dec 2019	2.96	1.056	1.068	1.107
	Jan 2020	8.94	1.289	1.363	1.610
	Feb 2020	3.77	1.085	1.105	1.165
Site-2	Dec 2019	2.54	1.041	1.050	1.078
	Jan 2020	8.81	1.284	1.356	1.596
	Feb 2020	2.92	1.054	1.067	1.104
Average	Site-1	5.22	1.143	1.179	1.294
	Site-2	4.75	1.126	1.158	1.259
	Dhaka City	4.99	1.136	1.169	1.277

CRediT authorship contribution statement

A.K.M. Nayem: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shahid Uz Zaman:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Farida Begum:** Writing – review & editing. **Abdus Salam:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

Data availability statement

Data will be made available on request. For requesting data, please write to the corresponding author.

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The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Abdus Salam reports equipment, drugs, or supplies was provided by US State Department. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] R.M. Harrison, D.C.S. Beddows, A.M. Jones, A. Calvo, C. Alves, C. Pio, An evaluation of some issues regarding the use of aethalometers to measure woodsmoke concentrations, Atmos. Environ. 80 (2013) 540–548, https://doi.org/10.1016/j.atmosenv.2013.08.026.
[2] W. Lin, T. Zhu, T. Xue, W. Peng, B. Brunekreef, U. Gehring, W. Huang, M. Hu, Y. Zhang, X. Tang, Association between changes in exposure to air pollution and biomarkers of oxidative stress in children before and during the Beijing olympics, Am. J. Epidemiol. 181 (2015) 575–583, https://doi.org/10.1093/aje/kwu327.
[3] N.A.H. Janssen, G. Hoek, M. Simic-Lawson, P. Fischer, L. van Bree, H. Ten Brink, M. Keuken, R.W. Atkinson, H. Ross Anderson, B. Brunekreef, F.R. Cassee, Black carbon as an additional indicator of the adverse health effects of airborne particles compared with pm10 and pm2.5, Environ. Health Perspect. 119 (2011) 1691–1699, https://doi.org/10.1289/ehp.1003369.
[4] T.C. Bond, R.W. Bergstrom, Light absorption by carbonaceous particles: an investigative review, Aerosol Sci. Technol. 40 (2006) 27–67, https://doi.org/10.1080/02786820500421521.
[5] I.H. Rehman, T. Ahmed, P.S. Praveen, A. Kar, V. Ramanathan, Black carbon emissions from biomass and fossil fuels in rural India, Atmos. Chem. Phys. 11 (2011) 7289–7299, https://doi.org/10.5194/acp-11-7289-2011.
[6] T. Subba, M.M. Gogoi, B. Pathak, P. Ajay, P.K. Bhuyan, F. Solmon, Assessment of 1D and 3D model simulated radiation flux based on surface measurements and estimation of aerosol forcing and their climatological aspects, Atmos. Res. 204 (2018) 110–127, https://doi.org/10.1016/j.atmosres.2018.01.012.
[7] S. Tiwari, U.C. Dumka, P.K. Hopke, P. Tunved, A.K. Srivastava, D.S. Bisht, R.K. Chakrabarty, Atmospheric heating due to black carbon aerosol during the summer monsoon period over Ballia: a rural environment over Indo-Gangetic Plain, Atmos. Res. 178–179 (2016) 393–400, https://doi.org/10.1016/j.atmosres.2016.04.008.
[8] Z. Salah, A. Shalaby, A.L. Steiner, A.S. Zakey, R. Gautam, M.M. Abdel Wahab, Study of aerosol direct and indirect effects and auto-conversion processes over the west african monsoon region using a regional climate model, Adv. Atmos. Sci. 35 (2018) 182–194, https://doi.org/10.1007/s00376-017-7077-3.
[9] S. Tiwari, R. Kumar, P. Tunved, S. Singh, A.S. Panicker, Significant cooling effect on the surface due to soot particles over Brahmaputra River Valley region, India: an impact on regional climate, Sci. Total Environ. 562 (2016) 504–516, https://doi.org/10.1016/j.scitotenv.2016.03.157.
[10] R. Beelen, M. Stafoggia, O. Raaschou-Nielsen, Z.J. Andersen, W.W. Xun, K. Katsouyanni, K. Dimakopoulou, B. Brunekreef, G. Weinmayr, B. Hoffmann, K. Wolf, E. Samoli, D. Houthuijs, M. Nieuwenhuijsen, A. Oudin, B. Forsberg, D. Olsson, V. Salomaa, T. Lanki, T. Yli-Tuomi, B. Oftedal, G. Aamodt, P. Nafstad, U. De Faire, N.L. Pedersen, C.G. Östenson, L. Fratiglioni, J. Penell, M. Korek, A. Pyko, K.T. Eriksen, A. Tjønneland, T. Becker, M. Eeftens, M. Bots, K. Meliefste, M. Wang,

B. Bueno-De-Mesquita, D. Sugiri, U. Krämer, J. Heinrich, K. De Hoogh, T. Key, A. Peters, J. Cyrys, H. Concin, G. Nagel, A. Ineichen, E. Schaffner, N. Probst-Hensch, J. Dratva, R. Ducret-Stich, A. Vilier, F. Clavel-Chapelon, M. Stempfelet, S. Grioni, V. Krogh, M.Y. Tsai, A. Marcon, F. Ricceri, C. Sacerdote, C. Galassi, E. Migliore, A. Ranzi, G. Cesaroni, C. Badaloni, F. Forastiere, I. Tamayo, P. Amiano, M. Dorronsoro, M. Katsoulis, A. Trichopoulou, P. Vineis, G. Hoek, Long-term exposure to air pollution and cardiovascular mortality: an analysis of 22 European cohorts, Epidemiology 25 (2014) 368–378, https://doi.org/10.1097/EDE.0000000000000076.

[11] M.R.S. Pavel, S.U. Zaman, F. Jeba, M.S. Islam, A. Salam, Long-term (2003–2019) air quality, climate variables, and human health consequences in Dhaka, Bangladesh, Front. Sustain. Cities 3 (2021) 52, https://doi.org/10.3389/frsc.2021.681759.

[12] M.R.S. Pavel, S.U. Zaman, S. Paul, P. Zaman, A. Salam, Light absorption properties of black carbon and brown carbon emitted from biomass combustion at the typical rural cooking stoves in Bangladesh, Air Qual. Atmos. Heal. (2023), https://doi.org/10.1007/s11869-023-01302-7.

[13] S.U. Zaman, M. Yesmin, M.R.S. Pavel, F. Jeba, A. Salam, Indoor air quality indicators and toxicity potential at the hospitals' environment in Dhaka, Bangladesh, Environ. Sci. Pollut. Res. 28 (n.d.) 37727–37740. https://doi.org/10.1007/S11356-021-13162-8.

[14] S.U. Zaman, M.R.S. Pavel, K.S. Joy, F. Jeba, M.S. Islam, S. Paul, M.A. Bari, A. Salam, Spatial and temporal variation of aerosol optical depths over six major cities in Bangladesh, Atmos. Res. 262 (2021) 105803, https://doi.org/10.1016/j.atmosres.2021.105803.

[15] S.U. Zaman, M.R.S. Pavel, R.I. Rani, F. Jeba, M.S. Islam, M.F. Khan, R. Edwards, A. Salam, Aerosol climatology characterization over Bangladesh using ground-based and remotely sensed satellite measurements, Elem Sci Anth 10 (2022) 63.

[16] M.A. Hossain, S.U. Zaman, S. Roy, M.S. Islam, I. Zerin, A. Salam, Emission of particulate and gaseous air pollutants from municipal solid waste in Dhaka City, Bangladesh, J. Mater. Cycles Waste Manag. (2023), https://doi.org/10.1007/s10163-023-01855-w.

[17] S. Roy, S.U. Zaman, K.S. Joy, F. Jeba, P. Kumar, A. Salam, Impact of fine particulate matter and toxic gases on the health of school children in Dhaka, Bangladesh, Environ. Res. Commun. 5 (2023), https://doi.org/10.1088/2515-7620/acb90d.

[18] A. Salam, T. Hossain, M.N.A. Siddique, A.M. Shafiqul Alam, Characteristics of atmospheric trace gases, particulate matter, and heavy metal pollution in Dhaka, Bangladesh, Air Qual. Atmos. Heal. 1 (2008) 101–109, https://doi.org/10.1007/s11869-008-0017-8.

[19] P.G. Satsangi, S. Yadav, Characterization of PM2.5 by X-ray diffraction and scanning electron microscopy-energy dispersive spectrometer: its relation with different pollution sources, Int. J. Environ. Sci. Technol. 11 (2014) 217–232, https://doi.org/10.1007/s13762-012-0173-0.

[20] M. Ahmed, M. Das, T. Afser, M. Rokonujjaman, T. Akther, A. Salam, Emission of carbonaceous species from biomass burning in the traditional rural cooking stove in Bangladesh, Open J. Air Pollut. 07 (2018) 287–297, https://doi.org/10.4236/ojap.2018.74014.

[21] M.I. Haque, K. Nahar, M.H. Kabir, A. Salam, Particulate black carbon and gaseous emission from brick kilns in Greater Dhaka region, Bangladesh, Air Qual. Atmos. Heal. 11 (2018) 925–935, https://doi.org/10.1007/s11869-018-0596-y.

[22] W. Lin, J. Dai, R. Liu, Y. Zhai, D. Yue, Q. Hu, Integrated assessment of health risk and climate effects of black carbon in the Pearl River Delta region, China, Environ. Res. 176 (2019) 108522, https://doi.org/10.1016/j.envres.2019.06.003.

[23] U.S. Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment, U.S. EPA, Health assessment document for diesel engine exhaust (final 2002). https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=29060, 2002.

[24] F. Jeba, M. Riad, S. Pavel, S.U. Zaman, Health risk assessment of high-level particulate matter exposure in different environments in mega city Dhaka, Bangladesh. www.baasbd.org, 2021.

[25] C.P. Information, Diesel exhaust particulate collectors, 10–12, https://patents.google.com/patent/US20170211440A1/en, 2016.

[26] A. Schmidt, B. Ostro, K.S. Carslaw, M. Wilson, T. Thordarson, G.W. Mann, A.J. Simmons, Excess mortality in Europe following a future Laki-style Icelandic eruption, Proc. Natl. Acad. Sci. U. S. A. 108 (2011) 15710–15715, https://doi.org/10.1073/pnas.1108569108.

[27] P. Crippa, S. Castruccio, S. Archer-Nicholls, G.B. Lebron, M. Kuwata, A. Thota, S. Sumin, E. Butt, C. Wiedinmyer, D.V. Spracklen, Population exposure to hazardous air quality due to the 2015 fires in Equatorial Asia, Sci. Rep. 6 (2016) 1–9, https://doi.org/10.1038/srep37074.

[28] A. Salam, A. Andersson, F. Jeba, I. Haque, D.H. Khan, O. Gustafsson, Wintertime Air Quality in Megacity Dhaka , Bangladesh Strongly A Ff Ected by in Fl Ux of Black Carbon Aerosols from Regional Biomass Burning, 2021.

[29] B. de Foy, M.G. Saroar, A. Salam, J.J. Schauer, Distinguishing air pollution due to stagnation, local emissions, and long-range transport using a generalized additive model to analyze hourly monitoring data, ACS Earth Sp. Chem. 5 (2021) 2329–2340, https://doi.org/10.1021/acsearthspacechem.1c00206.

[30] Y. Liu, C. Yan, M. Zheng, Source apportionment of black carbon during winter in Beijing. https://doi.org/10.1016/j.scitotenv.2017.11.053, 2018.

[31] V. Singh, K. Ravindra, L. Sahu, R. Sokhi, Trends of atmospheric black carbon concentration over United Kingdom, Atmos. Environ. 178 (2018) 148–157, https://doi.org/10.1016/j.atmosenv.2018.01.030.

[32] O. Peralta, A. Ortínez-Alvarez, R. Basaldud, N. Santiago, H. Alvarez-Ospina, K. de la Cruz, V. Barrera, M. de la Luz Espinosa, I. Saavedra, T. Castro, A. Martínez-Arroyo, V.H. Páramo, L.G. Ruíz-Suárez, F.A. Vazquez-Galvez, A. Gavilán, Atmospheric black carbon concentrations in Mexico, Atmos. Res. 230 (2019) 104626, https://doi.org/10.1016/j.atmosres.2019.104626.

[33] T.K. Sankar, B. Ambade, D.K. Mahato, A. Kumar, R. Jangde, Anthropogenic fine aerosol and black carbon distribution over urban environment, J. Umm Al-Qura Univ. Appl. Sci. 9 (2023) 471–480, https://doi.org/10.1007/s43994-023-00055-4.

[34] EPA, Science Policy Council Handbook: Risk Characterization, 2000, p. 31.

[35] Q. Li, M. Kim, Y. Liu, C.K. Yoo, Quantitative assessment of human health risks induced by vehicle exhaust polycyclic aromatic hydrocarbons at Zhengzhou via multimedia fugacity models with cancer risk assessment, Sci. Total Environ. 618 (2018) 430–438, https://doi.org/10.1016/j.scitotenv.2017.11.084.

[36] M.A. Bari, W.B. Kindzierski, Ambient volatile organic compounds (VOCs) in Calgary, Alberta: sources and screening health risk assessment, Sci. Total Environ. 631–632 (2018) 627–640, https://doi.org/10.1016/j.scitotenv.2018.03.023.

[37] M.S. Islam, S.U. Zaman, M.S. Islam, S. Roy, M. Yesmin, S.C.C. Lung, A. Salam, Particulate matter exposure to street vendors in Dhaka city and associated health risk study, Air Qual. Atmos. Heal. (2024), https://doi.org/10.1007/s11869-024-01666-4.

[38] M.M. Rahman, B.A. Begum, P.K. Hopke, K. Nahar, J. Newman, G.D. Thurston, Cardiovascular morbidity and mortality associations with biomass- and fossil-fuel-combustion fine-particulate-matter exposures in Dhaka, Bangladesh, Int. J. Epidemiol. (2021), https://doi.org/10.1093/ije/dyab037.

[39] A. Dewan, S. Shahid, M. Asaduzzaman, F. Faruque, An exploratory study to examine abundance of PM 2.5 and associated disease burden in Bangladesh, ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. 3 (2022) 627–633.

[40] S. Siregar, N. Idiawati, W.C. Pan, K.P. Yu, Association between satellite-based estimates of long-term PM2.5 exposure and cardiovascular disease: evidence from the Indonesian Family Life Survey, Environ. Sci. Pollut. Res. 29 (2022) 21156–21165, https://doi.org/10.1007/s11356-021-17318-4.