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Indoor $PM_{2.5}$ Exposure During Haze and Non-haze Episodes in a Residential Microenvironment of Dhaka: A Comparative Study

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Abstract

Haze is a common meteorological phenomenon during winter in Dhaka. This study was conducted to evaluate the exposure variation of fine particulate matter i.e. $PM_{2.5}$ in a residential home of Dhaka under haze and non-haze weather. Indoor $PM_{2.5}$ samples were collected during January- February, 2020, using a filter- based air sampler. Six heavy metals (Fe, Mn, Cu, Zn, Pb and Cr) were analysed using atomic absorption spectrophotometer. The 24- hour average haze- time indoor $PM_{2.5}$ concentration was 139 ± 57.7 μgm^{-3}, whereas that during non- haze period was 96.3 ± 17.7 μgm^{-3}, both significantly exceeding the WHO guideline value. Haze- time $PM_{2.5}$ concentration in the sampling home was 1.44 times higher than its non- haze counterpart, suggesting that outdoor $PM_{2.5}$ particles probably entered the household via ventilation and infiltration, thereby degrading the indoor air quality. The concentration of heavy metals increased by 1.32 to 71.3 times during haze, with Zn contributing the highest to $PM_{2.5}$. Hazard index (HI) for children and adults during haze was 31.19 and 13.68, respectively, indicating severe non- carcinogenic risk. Total cancer risk during haze (6.22×10^{-4}) and non- haze (4.66×10^{-4}) exceeded the USEPA threshold (1×10^{-4}). Exposure to elevated indoor $PM_{2.5}$ levels during haze increased the probability of cancer incidence from 1 in 2146 individuals, to 1 in 1608 individuals. Backward air mass trajectory analysis suggested that transboundary source contributed to aerosols during haze formation. Findings of this study revealed the severity of indoor air pollution in Dhaka, emphasizing effective control strategies.

Keywords: Haze, Indoor, Fine particulate matter ($PM_{2.5}$), Heavy metals, Total cancer risk

I. Introduction

Fine particulate matter ($PM_{2.5}$) refers to the solid particles or liquid droplets having an aerodynamic diameter of 2.5 μm or less, that are suspended in the air. $PM_{2.5}$ is regarded as a hazardous air pollutant because of its ability to enter deeper into the lung, and cause various respiratory and cardiovascular diseases[1]. Since people stay more than 90% of their time indoors (home, office, school, restaurant, commercial spaces etc.), they are exposed to indoor $PM_{2.5}$ for a prolonged period, hence they are at elevated risk to develop carcinogenic and non- carcinogenic health hazards[2]. Indoor $PM_{2.5}$ can originate from various indoor sources, like cooking, cleaning, vacuuming, dusting, smoking, cosmetics and consumer products, residents' activities, building materials, etc.[3,4,5] Moreover, outdoor $PM_{2.5}$ can penetrate into an indoor environment via the open windows, and cracks and fine lines of a building, therefore, outdoor sources can also contribute to the increase of indoor $PM_{2.5}$ level[2,5]. Ji & Zhao[6] reported that outdoor source contribution to residential $PM_{2.5}$ can reach >92%, and 54- 63%, when windows are open and closed, respectively. Consequently, indoor air quality (IAQ) usually deteriorates during winter, as outdoor $PM_{2.5}$ can remain suspended in the dry, ambient air for prolonged period, and greater number of outdoor particles can enter the indoor environment via ventilation and infiltration[5].

Outdoor air quality of a region is often severely compromised due to acute air pollution episodes e.g. excessive biomass burning, dust storms, forest fires, which drastically increase ambient $PM_{2.5}$ concentration, leading to a meteorological phenomenon known as "haze" [6,8]. Haze is characterized by dry climate, low wind speed, relative humidity of <80%, unusually high $PM_{2.5}$ concentration, horizontal visibility reduction of <10 km, and obscure sky[2,3]. Therefore, winter is the most favourable season for haze formation, and so, haze is a common phenomenon in South Asia from November till April[9].

Over the past few decades, Dhaka has been burdened with alarming levels of air pollution, posing serious threat to the public health. Although the detrimental consequences of outdoor air pollution are well recognized, indoor air pollution continues to be overlooked. Owing to continuous exposure to household $PM_{2.5}$, Dhaka residents are suffering from multiple health hazards[10]. Women, children, and elderly people are the worst sufferers, as they mostly stay at home. The situation worsens during winter, when haze is formed, comprising of high loads of outdoor $PM_{2.5}$, originating from local or transboundary sources. During a haze event, high loadings of $PM_{2.5}$ can be transported from outdoor to indoor, leading to the degradation of IAQ, as well as increasing the health risk towards the residents[11].

Several studies have been conducted focusing on the PM pollution of Dhaka city during winter. Saha et al.[12] carried out continuous monitoring of indoor and outdoor $PM_{2.5}$ in 17 homes of Dhaka city during monsoon and winter seasons, and observed that, dry climate substantially increased outdoor $PM_{2.5}$ concentration during winter, which eventually entered indoors via ventilation and infiltration, thereby deteriorating the IAQ of sampling homes. Yasmin et al.[13]

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reported that the daily average indoor $PM_{2.5}$ concentration exceeded the World Health Organization (WHO) air quality guidelines in 43 homes of Dhaka city during the summer season in 2022- 2023, and infiltration of outdoor air was found to be the most significant contributor to indoor $PM_{2.5}$ levels. Kumar et al.[14] employed low- cost sensors for the continuous monitoring of $PM_{2.5}$ in five homes of Dhaka during April- June (pre- monsoon season), 2021, and observed that, poor ventilation and extensive frying during cooking elevated the indoor $PM_{2.5}$ concentrations. These studies underscore the pronounced effect of infiltrated outdoor $PM_{2.5}$ particles on the degradation of IAQ in Dhaka homes. However, such approaches are mostly sensor- based, and do not address the chemical characterization of indoor $PM_{2.5}$ in residential microenvironments of Dhaka, which is critical for identifying its sources and assessing the health implications. Moreover, existing studies do not involve high-pollution winter haze episodes, when atmospheric stagnation and regional pollutant transport can substantially alter $PM_{2.5}$ levels and its chemical profiles. To address these gaps, the present study systematically compares indoor $PM_{2.5}$ levels under haze and non-haze conditions in a residential microenvironment of Dhaka, using filter- based sampling, coupled with a well- established gravimetric analysis of heavy metals. In addition, health risk assessment of $PM_{2.5}$ was conducted to evaluate the potential non-carcinogenic and carcinogenic risks. Furthermore, NOAA-HYSPLIT backward trajectory analysis was employed to elucidate potential regional transport pathways, contributing to haze formation. Such combined approach offers novel insights into the chemical composition, source influences, and health implications of indoor $PM_{2.5}$ in a residential setting of urban Dhaka during regional haze episodes.

II. Materials and Methods

Sampling

In Bangladesh, winter generally spans from December till February[15]. This study was carried out during winter season of 2020 in a residential home (Latitude: 23.8031˚ N, Longitude: 90.3950˚ E) at Cantonment in the Dhaka Metropolitan Area. The population density of Cantonment (9113/km^2) is much lower than that of the whole Dhaka city (34,000/km^2) (Population and Housing Census, 2022)[16]. Cantonment area is characterized by military governance, minimal traffic, no industry, developed urbanization, and ample vegetation[2]. Therefore, local emission sources in Dhaka Cantonment are less pronounced, contributing to its improved air quality, as compared to the rest of Dhaka.

This study was conducted in two phases- a) haze episode (29- 31 January, 2020), characterized by reduced visibility, an unusual increase in $PM_{2.5}$ concentration, relative humidity of 62- 77%, and an average wind speed of 11.2 km h^{-1}; and b) non- haze episode (23- 25 February, 2020), characterized by comparatively clear sky, average wind speed of 18.4 km h^{-1}, and relative humidity of 82 – 89%. Meteorogical data were collected from the Bangladesh Meteorological Department.

24- hour sampling of indoor $PM_{2.5}$ was conducted at the living room of the sampling home for three consecutive days using an air sampler (Model: SIBATA, MP- ∑500 NII, flow rate of 3.00 L min^{-1}, flow accuracy: ±5%). The sampler was leak- tested and calibrated before sampling. The sampler was positioned 1.5 meter off the ground, and was kept reasonably far from the windows and walls. Indoor $PM_{2.5}$ was accumulated on quartz filters (pre-combusted at 800˚C for 4 hours). After sampling, each $PM_{2.5}$- loaded filter was preserved in clean petri dishes. A microbalance (sensitivity 0.0001g) was used to weigh each filter thrice before and after sampling. The difference between the two measurements corresponded to 24- hour $PM_{2.5}$ mass. Blank sampling was also carried out to maintain accuracy in the measurements.

Extraction and chemical analysis

Half of each filter paper was treated with 24 mL deionized water along with 8 mL of 12% nitric acid, for extracting the $PM_{2.5}$. After proper shaking and ultra sonication, each mixture was filtered. Each filtrate was used to determine the concentration of six metals- Pb, Cr, Zn, Fe, Cu, and Mn, by flame atomic absorption spectrophotometer (Model: AA240FS, Varian, Australia). The concentrations of different elements in the $PM_{2.5}$ samples were determined using the calibration curve of standard solutions. Reagent blanks were also analysed by the same manner.

Data processing methods

Hazard ratio of indoor $PM_{2.5}$

The hazard ratio (HR_i) of a particular species, i, refers to the ratio of its average concentration (C_i) to its reference concentration (R_fC_i), expressed by the following equation[17]:

$$HR_i = C_i / R_fC_i \quad (1)$$

A HR value >1 indicates adverse health risk, whereas HR< 1 is associated with no health risk. The 24- hour average reference concentration for $PM_{2.5}$ is 15 μgm^{-3}, according to the WHO guideline value[18].

Health risk assessment

Health risk assessment signifies the possible health effects arising from the exposure to carcinogenic and non-carcinogenic species. In this study, indoor $PM_{2.5}$ – bound metals e.g. Pb, Cr, Zn, Cu, and Mn were recognized as potential hazardous species, posing a serious threat to human health[19]. Pb and Cr are potential carcinogens[19]. The main exposure pathway for indoor $PM_{2.5}$ to enter the human body, is inhalation[20], so this exposure route was considered for both non- carcinogenic and carcinogenic risk assessment.

Average daily dose (ADD) (mg kg^{-1} day^{-1}) for inhalation pathway was calculated using the following equation[21]:

$$\text{Average daily dose, ADD} = \frac{C \times InhR \times EF \times ED}{BW \times AT} \quad (2)$$

The definition, unit and reference values of these parameters were obtained from the Department of Environmental Affairs (DoEA)[22], and presented in Table 1.

Table 1. Definition and reference values of the exposure parameters used to calculate the average daily dose (ADD) of indoor $PM_{2.5}$- bound heavy metals

Parameter	Definition	Unit	Child	Adult
C	Heavy metal concentration	mgm^{-3}		
InhR	Inhalation rate	$m^3\ day^{-1}$	10	20
EF	Exposure frequency	days $year^{-1}$	350	350
ED	Exposure duration	years	6	30
BW	Average body weight	kg	15	70
AT	Averaging time period	days		
	For non- carcinogens:		365 × ED	365 × ED
	For carcinogens:		365 × 70	365 × 70

Non- carcinogenic risk assessment

The term 'Hazard Quotient (HQ)' is used for the characterization of non- carcinogenic risk. HQ is expressed by equation (3)[23]:

$$HQ = \frac{ADD}{RfD} \quad (3)$$

Where ADD is the average daily dose of a specific heavy metal taken by an individual, and R_fD is the chronic reference dose (mg kg^{-1} day^{-1}) of that metal. The chronic reference dose values of the heavy metals are mentioned in Table 2.

Hazard Index (HI) is expressed by equation (4):

$$\text{for n number of heavy metals, } HI = \sum_i^n HQ \quad (4)$$

When HI ≤ 1, the exposed community does not suffer from any adverse health effects. If HI >1, then the exposed residents may be subjected to non- carcinogenic effects[19].

Carcinogenic risk assessment

Carcinogenic risk signifies the possibility of cancer incidence in an individual from lifelong exposure to a carcinogenic species. Incremental lifetime cancer risk (ILCR) is calculated using equation (5)[21]:

$$ILCR = LADD \times SF \quad (5)$$

Where LADD is the lifetime average daily dose (mg kg^{-1} day^{-1}) of a carcinogenic heavy metal; and SF is the cancer slope factor (mg kg^{-1} $day^{-1})^{-1}$. LADD was evaluated by equation (6)[21]:

$$LADD = \frac{C \times EF}{AT}\left(\frac{InhR\ child \times ED\ child}{BW\ child} + \frac{InhR\ adult \times ED\ adult}{BW\ adult}\right) \quad (6)$$

The SF values of carcinogenic heavy metals (Pb and Cr) are presented in Table 2.

The total cancer risk, R_t of all the heavy metals was evaluated by equation (7)[24]:

$$\text{for n number of heavy metals, } R_t = \sum_i^n ILCR \quad (7)$$

Ferreira- Baptista & De Miguel reported that, the acceptable value for carcinogenic risk is from 10^{-6} to 10^{-4}. Cancer risk less than 10^{-6} is negligible, and that greater than 10^{-4} is considered unacceptable[23].

Table 2. Reference dose (R_fD) and slope factor (SF) values for investigated heavy metals

Heavy metal	R_fD (mg kg^{-1} day^{-1})	References	SF (mg kg^{-1} $day^{-1})^{-1}$	References
Pb	3.52E- 03	26	4.20E- 02	22
Cr (VI)	2.86E- 05	25	4.10E+ 01	19
Zn	3.00E- 01	26		
Cu	4.02E- 02	26		
Mn	1.43E- 05	25		

Statistical analysis

Due to small sample size and non- normal distribution of data, differences in indoor $PM_{2.5}$- bound heavy metal concentrations in the sampling household during haze and non- haze days were analysed using the non- parametric Mann- Whitney U test. All analyses were conducted using a two- tailed test, with statistical significance defined as $p < 0.05$.

III. Results and Discussion

Daily average indoor $PM_{2.5}$ concentration

The 24- hour average haze- time indoor $PM_{2.5}$ concentration was 139.0 ± 57.7 μgm^{-3}, whereas the corresponding non-haze concentration was 96.3 ± 17.7 μgm^{-3}, the haze- time $PM_{2.5}$ level being 1.44 times higher than its non- haze counterpart. Both these concentrations exceeded the 24-hour average WHO threshold (15 μgm^{-3}) by 9.3 and 6.4

times, respectively. The observed values were also higher than the DoE (Department of Environment) recommended guideline (65 μgm^{-3}) for Bangladesh[27]. Exposure to $PM_{2.5}$ level exceeding the guideline values can lead to various health complications.

While conducting this study, simultaneous monitoring of $PM_{1.0}$, $PM_{2.5}$, and PM_{10} was carried out using a sensor- based device (Model: IGERESS air quality monitoring detector) in the sampling household. One sensor was placed in the living room beside the SIBATA air sampler, and the other sensor was put in the balcony. Our previous study[2] reported the findings of the real- time PM measurement, which was conducted simultaneously in the indoor and outdoor of the Cantonment household over the same sampling period. It was found that, 85 to 89% indoor $PM_{2.5}$ originated from outdoor sources, the infiltration factor being 0.95 (i.e. 95% effective infiltration). Only 11- 14% indoor $PM_{2.5}$ had individual indoor origin. Therefore, it was evident that, infiltration, ventilation, or transportation of outdoor particles into an indoor household, could result in elevated indoor PM concentration, like that in Cantonment household. The situation worsened during haze episodes, since the outdoor PM concentration was extremely high, and infiltration of such high loadings of $PM_{2.5}$ severely degraded the IAQ, consequently compromising the health of the residents. In 2015, the smoke haze episode in Indonesia and Singapore was responsible for the deterioration of IAQ, due to the penetration of outdoor PM into the buildings[28]. Hence, despite being an outdoor meteorological phenomenon, haze can affect IAQ adversely.

Probable indoor sources of $PM_{2.5}$ in the sampling home could be cooking, sweeping, movement of the residents, building materials, resuspension of dust etc[3,4,5]. On the other hand, outdoor PM emitting from sources like vehicular exhaust and road dust could enter the indoor environment via the cracks and fine lines, or open windows of a building, thereby contributing to the indoor $PM_{2.5}$ composition[5]. Agarwal et al.[29] reported that outdoor haze particles could be responsible for deteriorating the IAQ, and these haze particles could originate from transboundary sources e.g. biomass burning and forest fires. He found that transboundary haze particles formed by a forest fire in Indonesia during October, 2015, severely polluted the outdoor and indoor air of Singapore and Malaysia.

Table 3 depicts the 24- hour average indoor $PM_{2.5}$ concentration in various indoor microenvironments across different global cities during haze and non- haze episodes. In all the cities, indoor $PM_{2.5}$ concentration on haze days was significantly higher than that on non- haze days. Household concentration of $PM_{2.5}$ in Dhaka and Beijing was found to be similar under both weather conditions. Given that Dhaka and Beijing are densely populated megacities, increased $PM_{2.5}$ level in indoor settings is attributed to high population density, compact buildings, intense urban traffic, and extensive industrial activities. However, indoor $PM_{2.5}$ level in Bangkok and Chiang Mai was considerably lower than that of Dhaka and Beijing, owing to greater reliance on cleaner energy, and humid climate, thereby reducing the ambient $PM_{2.5}$ level.

Table 3. 24- hour average $PM_{2.5}$ concentration in various indoor settings across global cities

City	Setting	Haze	Non- haze	References
Dhaka, Bangladesh	Residential	139.0 ± 57.7	96.3 ± 17.7	Present study
Beijing, China	Residential	210	104	30
Bangkok, Thailand	Residential	19.85	11.4	31
Chiang Mai, Thailand	Residential	106.8	5.52	31
Nanjing, China	Non- residential	292 ± 70	55 ± 16	32
Malaysia	School	30.04 ± 7.82	4.86 ± 2.44	33

Indoor $PM_{2.5}$ - bound heavy metals during haze and non-haze episodes

Six heavy metals (Pb, Cr, Fe, Zn, Cu, and Mn) were quantified in the indoor $PM_{2.5}$ samples, collected from the Cantonment household during haze and non- haze days. ∑(heavy metals) was 8.25 μgm^{-3} on haze days, and 4.20 μgm^{-3} on non- haze days, implying that the contribution of these 6 heavy metals to the total indoor $PM_{2.5}$ concentration was approximately 4- 5%. The differences in the heavy metal levels under the two weather conditions were found to be statistically insignificant ($p > 0.05$), which was attributable to the small sample size. Nevertheless, the metals exhibited higher concentrations during haze, indicating the influence of outdoor haze on the chemical composition of indoor $PM_{2.5}$.

Fig. 1 illustrates the concentration of indoor $PM_{2.5}$- bound heavy metals in the sampling home under haze and non- haze weather. Fig. 1 depicts that, concentration of the heavy metals increased by 1.32 to 71.3 times because of the haze influence, though their sources might vary based on indoor and outdoor characteristics. Under both weather conditions, Zn recorded the highest concentration among the investigated heavy metals (haze concentration: 3449.0 ngm^{-3}, non- haze concentration: 3018.0 ngm^{-3}). Cooking was a major indoor source of Zn emission, whereas outdoor Zn sources could probably be road dust, vehicular exhaust etc.[5,6] The heavy metal concentration order during haze days was: Zn> Fe>

Pb> Mn> Cu> Cr. However, the order for non- haze days was: Zn> Fe> Pb> Cr> Cu> Mn. Concentration of Mn during haze was 71.3 times higher than that during the non- haze episode. Apart from crustal sources, Mn might originate from anthropogenic sources like gasoline and diesel combustion, and resuspended road dust[5,20].

During haze, toxic metals like Pb, Cr, Cu, and Mn exceeded their corresponding WHO guideline values (Pb: 500 ngm^{-3}; Cr: 20 ngm^{-3}; Cu: 70 ngm^{-3}; Mn: 150 ngm^{-3})[35]. On the non-haze days, these metals were within the WHO threshold, except Cr.

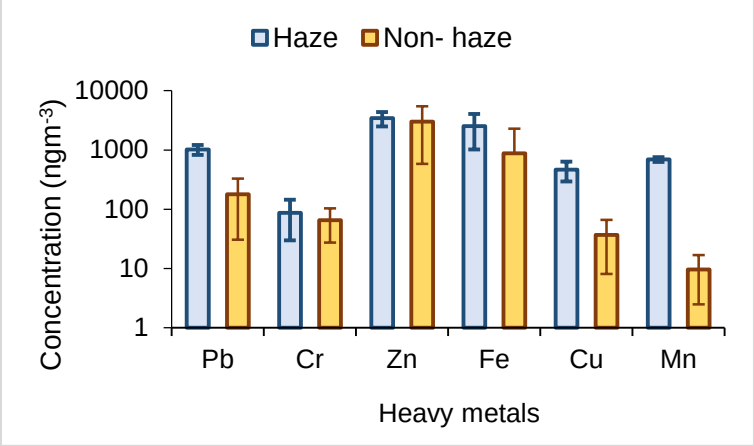


Fig. 1. 24- hour average concentration of indoor $PM_{2.5}$- bound heavy metals in Cantonment home

Hazard ratio of indoor $PM_{2.5}$

Fig. 2 depicts the hazard ratio (HR) of indoor $PM_{2.5}$ in Dhaka Cantonment home under haze and non- haze phenomena. The average HR of indoor $PM_{2.5}$ was 9.27 and 6.42 during haze and non- haze weather, respectively, both exceeding the HR threshold of 1.0. Hence, the residents of Cantonment household were at adverse health risk caused by indoor $PM_{2.5}$. Moreover, as hazard ratio varies proportionally with $PM_{2.5}$ concentration, health implications of $PM_{2.5}$ can be severe during a haze episode. For instance, the haze- time HR of indoor $PM_{2.5}$ was approximately 1.5 times higher than the non- haze time HR. Since people mostly stayed at indoors, they were exposed to increased $PM_{2.5}$ level during haze, and such prolonged exposure could bring about various health complications.

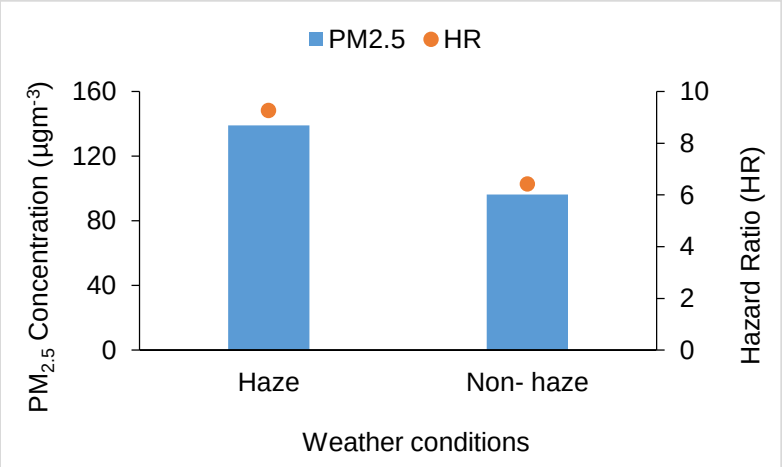


Fig. 2. Variation of Hazard Ratio (HR) with indoor $PM_{2.5}$ level at Dhaka Cantonment household

Health risk assessment of indoor $PM_{2.5}$ - bound heavy metals

Non- carcinogenic risk assessment

Table 4 represents the hazard index (HI) values of indoor $PM_{2.5}$ - bound heavy metals in the Cantonment household during haze and non- haze episodes. HI for child (31.19) and adult (13.68) during haze exceeded the threshold value of 1.0, implying severe non- carcinogenic risk. On the contrary, HI during non- haze days was < 1 for both child and adult, therefore, no carcinogenic risk was imposed. It found that, haze increased the non- carcinogenic risk among child and adult by 55 and 29 times, respectively, as compared to the non- haze weather. Moreover, children were at greater risk than adults because of their lower body weight, and greater average daily dose[21].

Table 4. Hazard index (HI) of indoor $PM_{2.5}$ - bound heavy metals in th8 sampling home

Weather condition	Receptor	Hazard quotient (HQ) of heavy metals					Hazard index, HI
		Pb	Cr	Zn	Cu	Mn	
Haze	Child	1.59E-02	1.67E-01	7.35E-03	7.43E-03	3.10E+01	31.19
	Adult	3.41E-02	3.58E-01	3.15E-03	3.18E-03	1.33E+01	13.68
Non- haze	Child	2.80E-03	1.26E-01	6.43E-03	5.88E-04	4.34E-01	0.57
	Adult	6.00E-03	2.70E-01	2.76E-03	2.52E-04	1.86E-01	0.47

Fig. 3 depicts the percentage contribution of individual heavy metals to the total HI. It was evident that, Mn recorded the highest contribution (~ 99%) to the HI in residential environment of Dhaka Cantonment during haze days. On non- haze days, maximum contribution was observed for Mn and Cr. Wang et al.[24] also reported about the highest contribution of indoor $PM_{2.5}$- bound Mn to the total HI inside a university canteen in Nanjing, China. Owing to high indoor concentration i.e. increased average daily dose (ADD), and low chronic reference dose (R_fD) value, HQ of Mn was substantial, resulting in its maximum contribution to HI.

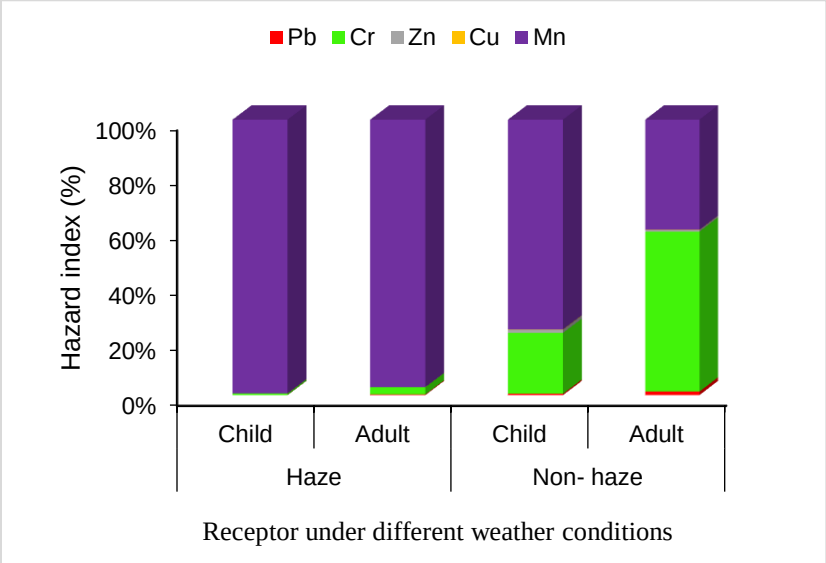


Fig. 3. Percentage contribution of indoor $PM_{2.5}$ - bound heavy metals to the total HI in the sampling home during haze and non- haze episodes

Carcinogenic risk assessment

Table 5 represents the total cancer risk (R_t) imposed by indoor $PM_{2.5}$ - bound carcinogenic heavy metals (e.g. Pb and Cr) in the Cantonment home during haze and non- haze events. The average R_t in Cantonment home was 6.22×10^{-4} and 4.66×10^{-4} during haze and non- haze days, respectively, which were six and four times higher than the USEPA threshold (1×10^{-4}). The haze- time R_t was 1.33 times greater than its non- haze equivalent. It implied that, exposure to elevated indoor $PM_{2.5}$ levels during haze might have raised the probability of cancer incidence from 1 in 2146 individuals, to 1 in 1608 individuals, which suggested that the carcinogenic risk of indoor $PM_{2.5}$ could be significantly increased by haze.

Table 5. Total cancer risk of indoor $PM_{2.5}$ - bound carcinogenic metals in the sampling home

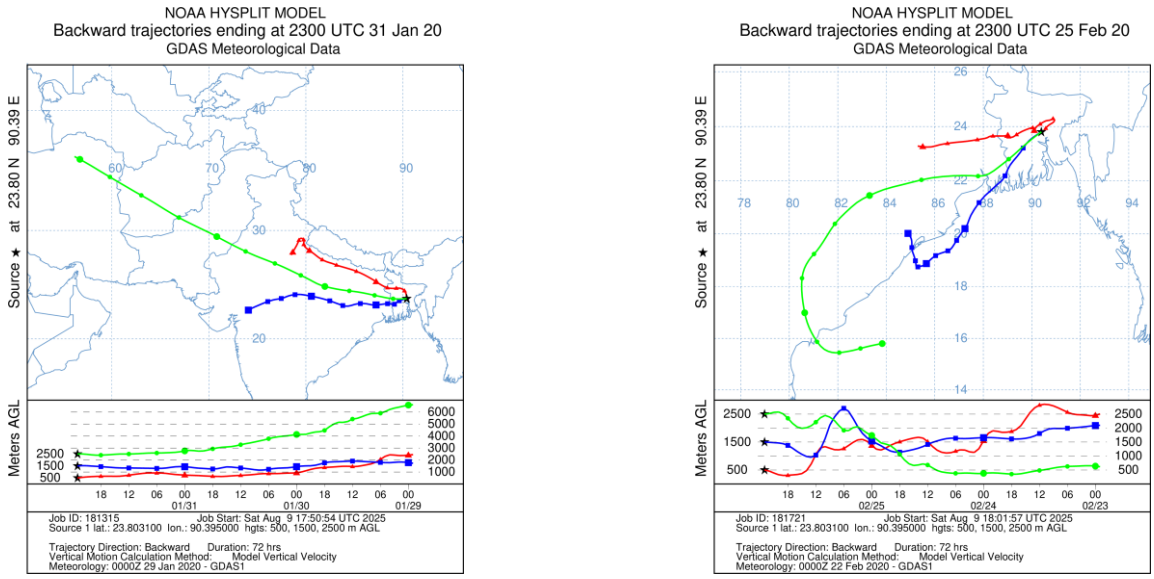
Weather condition	Incremental lifetime cancer risk (ILCR) for heavy metals		Total cancer risk, R_t	Inference based on USEPA guideline value
	Pb	Cr		
Haze	7.39E-06	6.15E-04	6.22E-04	Not acceptable
Non- haze	1.30E-06	4.65E-04	4.66E-04	Not acceptable

It is evident from Table 5 that, the residents of Cantonment home experienced higher ILCR values for Cr, than Pb. The total cancer risk was almost fully contributed (~ 99%) by Cr under both weather conditions. Acute and chronic exposure to indoor $PM_{2.5}$- bound Cr might result in lung cancer and other health hazards[32].

Backward air mass trajectory analysis

Haze events are common during winter in South Asian countries, therefore, outdoor haze particles may originate from local sources, as well as transboundary sources. Since indoor $PM_{2.5}$ had dominant contribution from outdoor sources in this study, it is essential to analyze the transboundary effects, along with the local sources. While passing over a polluted region, air mass can carry pollutants, and transport them to neighboring areas, which can consequently deteriorate the air quality of downwind regions. Backward air mass trajectory analysis indicates the source and pathway of airmass at different altitudes over a certain period of time.

Fig. 4 represents the backward air mass trajectories reaching Dhaka Cantonment site on haze and non- haze days. Ali et al.[34] reported that air mass trajectories arriving at Bangladesh often originate from India, Pakistan, Nepal, Iran, and the Bay of Bengal. Fig. 4(a) illustrates that, North Iran was the point of origin for the 72- hour backward trajectory at 2500 m AGL (Above Ground Level) during haze days, and air mass traversed the IGP (Indo- Gangetic Plain) region before reaching Dhaka Cantonment from the north- western direction. During winter, IGP is burdened with excessive anthropogenic emissions, including biomass burning, fossil fuel combustion, and industrial activities, which can severely affect regional air quality[35,35]. Moreover, crop residue burning during winter causes substantial PM emissions in North India, which may also contribute to the transboundary transport of aerosols to Dhaka[7]. On the contrary, it is evident from Fig. 4(b) that, air mass originating at 2500 m and 1500 m AGL flowed over the Bay of Bengal before arriving at Dhaka Cantonment on non- haze days, therefore, relatively cleaner air was transported to the sampling site from the south-western direction[34,35]. Hence, the trajectory patterns indicate that, long range transport of air mass over the highly polluted IGP region during winter could influence haze formation in Dhaka, whereas non- haze weather was associated with marine airflow, thereby underscoring the observed differences in $PM_{2.5}$ concentrations in Dhaka Cantonment under contrasting weather conditions. However, though backward trajectory analysis provides qualitative supporting evidence for transboundary air pollution, it does not represent the quantitative source apportionment of $PM_{2.5}$. The application of multivariate receptor models such as- PMF or PCA was not feasible in this study due to the limited number of samples. Future studies incorporating large scale sampling and receptor models are recommended to quantitatively resolve source contributions to aerosols during haze episodes.



(a) (b)

Fig. 4. Backward air mass trajectories reaching Dhaka Cantonment site during (a) haze, and (b) non- haze episodes, retrieved by NOAA- HYSPLIT

IV. Conclusion

This study was designed with the goal of observing the effect of haze on the IAQ of a residential home located at Dhaka Cantonment, which usually experiences low outdoor air pollution. Both the haze- time and non- haze time indoor $PM_{2.5}$ concentration exceeded the WHO guideline value, indicating elevated health risk to the exposed residents. Infiltration and ventilation of outdoor fine particles into the indoor environment probably resulted in a degraded IAQ at the sampling home. Haze increased both the non-carcinogenic and carcinogenic risk of indoor $PM_{2.5}$- bound heavy metals, and children were found to be the worst sufferers in such case. Backward air mass trajectory analysis suggested significant contributions from transboundary sources during the haze episode. Overall, the outcomes of this study indicated that outdoor air pollution in Dhaka could adversely affect the IAQ and occupants' health in residential homes, especially during high air pollution events like haze. Hence, awareness campaigns on indoor air pollution should be enhanced, and resilient building designs should be encouraged.

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