



Particulate matters and gaseous pollutants in indoor environment and Association of ultra-fine particulate matters (PM₁) with lung function

Tanzina Akther¹ · Morshad Ahmed¹ · Mohammad Shohel^{1,2} · Farhana Khanom Ferdousi¹ · Abdus Salam¹

Received: 5 September 2018 / Accepted: 18 December 2018 / Published online: 4 January 2019
© Springer-Verlag GmbH Germany, part of Springer Nature 2019

Abstract

Real-time particulate matters (PM₁, PM_{2.5}, PM₄, PM₇, PM₁₀, and TSP) with AEROCET 531S (USA), gaseous pollutants (NO₂ and TVOC) with Aeroquel 500 gas sampler (NZ) were measured from the indoor air of houses at four residential locations in Dhaka, Bangladesh. PM₁₀ samples were collected on quartz filters with a dual channel dust sampler (IPM-FDS 2510, India) for selected trace metal determination from five houses of Dhaka. Respiratory function of the occupants was assessed by using a peak expiratory flow meter (Rossmax PF 120). Mean PM₁, PM_{2.5}, and PM₁₀ concentrations were 46.1 ± 13.4 , 76.0 ± 16.2 , and $203.9 \pm 44.8 \mu\text{g m}^{-3}$, respectively. Higher enrichment factors of Pb, Zn, and Ni were found for traffic, industrial, and constructional activities. The correlation between indoor and outdoor PM_{2.5} ($R^2 = 0.42$) and ratios ($I/O < 1$) suggesting indoor air was effected by outdoor air. The concentration of NO₂ (0.076 ± 0.007 ppm) and TVOC (90.0 ± 46.0 ppm) was found above than other studies. The average total hazard ratio (THR) in Dhaka was 9.06 and has the highest exposure to air pollutants (PM_{2.5}, PM₁₀, NO₂) in Khilkhet (THR 10.1) residents. A negative association between ultra-fine particles (PM₁) and peak flow rate measurements of the residents living in these houses indicates that inhalations of ultra-fine particles has great influence on the reduced lung efficiency.

Keywords Indoor air quality · Particulate matter · NO₂ and TVOC · Hazard ratio indicator · Peak flow rate · Lung function

Introduction

Air pollution is a major challenge for a sustainable development in the urban setting of any country (Stazi et al. 2017; Massey et al. 2012). Poor air quality can lead to rapid short-term effects including irritation in throat, eyes, and nose, dizziness, and headache (Dockery et al. 1993 and Koenig et al. 2005). The long-term effect can occur from particles having aerodynamic diameter less than $4 \mu\text{m}$ that can penetrate into lower respiratory tract (Brown et al. 2013) and particles with diameters smaller than $2.5 \mu\text{m}$ (PM_{2.5}) that can reach the alveoli of the lung (Valavanidis et al. 2008; Zhang et al.

2017). PM₁ has even worst effect on human health as it can easily pass through bloodstream and the whole body. Numerous scientific studies have linked particle pollution exposure to a variety of lung and cardiovascular diseases (Perez-Padilla et al. 2010; Uzoigwe et al. 2013; WHO 2011). A recent report by Lancet Commission on Pollution and Health stated that around 4.5 million die due to air pollution (Zhang et al. 2017) and Bangladesh has the worst records (Landrigan et al. 2017).

The effect of indoor air pollutant on health can surpass the outdoor pollutant as people spend most of their time in indoor environment, which made it one of the weightiest topics of air pollution research (Klepeis et al. 2001). Around 3.8 million people each year experience premature death arising from household air pollution caused by the inefficient use of solid fuels and kerosene for cooking purposes (WHO 2018). In perspective of Dhaka city, where most of inhabitant uses natural gas for cooking, there still can be other sources of indoor pollution, such as re-suspension of house dust, cigarette smoking, incense, toiletries, just to name a few (Mohammadyan et al. 2008; Nakai and Tamura 2008). Dhaka has a population density of $44,500 \text{ km}^{-2}$ with poor infrastructure and pollution

Responsible editor: Constantini Samara

✉ Abdus Salam
asalam@gmail.com

¹ Department of Chemistry, University of Dhaka, Dhaka 1000, Bangladesh

² Department of Chemistry, University of Iowa, Iowa City, IA 52242, USA

mitigation policy. In addition, the houses are built keeping in mind to accommodate as many people as possible rather than quality of living. Consequently, the dwellers of Dhaka city are at health risk due to high concentration of different gaseous and particulate matter pollutant in indoor environment (Nahar et al. 2016). Children, particularly under 5 years old who spend a lot of time indoor, are mostly prone to be affected by respiratory diseases in Dhaka (Khalequzzaman et al. 2007; Ram et al. 2014; Dherani et al. 2008). It was also observed that a switch in fuel from biomass to fossil does not necessarily improve the children's health living in low-income area of Dhaka, which implies that there are other emission source or pollutant involved that need further investigation (Khalequzzaman et al. 2007). Begum and Biswas (2009) observed higher concentration of particulate matter ($PM_{2.5}$ and PM_{10}) from indoor settings of a research center at Dhaka city. Different anthropogenic species (black carbon, organic carbon, Pb, and Zn) were also identified from particulate matters through chemical analysis (Begum and Biswas 2009). A seasonal variation of $PM_{2.5}$ with higher concentration during winter has been observed in the low-income areas of Dhaka city (Gurley et al. 2013). The previous studies done on indoor air quality of Dhaka only focused on a certain area and specific community. Variability of indoor air pollutants and their sources at different location are still unknown. There is also lack of studies about the diurnal variation of indoor pollutants at Dhaka city, which need to be accessed for mitigation policy. Furthermore, an extensive study on health impact of different pollutant yet needs to be done.

To address this issue, we have quantified atmospheric particulate matters (PM_1 to TSP), NO_2 gas, and total volatile organic compounds (TVOC) from residential houses at four different locations in mega city Dhaka, Bangladesh. This data was collected during the months August to October in the year 2017. The sources of such pollutants and its hourly variation were recorded. The total health hazard index of these air pollutants was also determined. A quartz filter was used to collect PM_{10} samples from which selected trace metal concentrations were also determined. The lung function of the occupants living in sampled residential houses was measured and correlated with ultra-fine particulate matters (PM_1).

Methods and materials

Meteorology of Dhaka, Bangladesh

Dhaka is the capital of Bangladesh located at $23^{\circ}42'N$ $90^{\circ}22'E$, on the eastern banks of the Buriganga river. It covers a total area of 306.38 km^2 and have a population around 20 million. The land is above sea level, characterized by tropical vegetation and moist soil. Bangladesh can be divided into four seasons: pre-monsoon (March–May), monsoon (June–

September), post-monsoon (October–November), and winter (December–February) (Shohel et al. 2017). Dhaka city is within the monsoon climate zone with an annual average temperature of maximum $34.5^{\circ}C$, minimum $11.5^{\circ}C$, and monthly means varying between $18^{\circ}C$ in January and $29^{\circ}C$ in August. Nearly 80% of the average annual rainfall (1931 mm) occurs between May and October and the average annual humidity is 70%.

Sampling locations

The residential houses were chosen from five different locations of Dhaka city (Fig. 1). First one was Khilkhet, which is a residential area located on the east by the polluted Turag river. This area has some garments and ice cream factories. The second suburb was Rampura, which is a moderately populated residential area with moderate traffic. The locality suffers from extensive construction activities taking place. The third area was Mirpur, which is a densely populated area and do have high traffic congestion. It is known for its business activities, several big industries, and vehicle repairing workshop. And, finally, we chose Dholaipar, which is located in the southern part of Dhaka city. It is a very crowded area with glass, plastic, and welding factories. Additionally, we have also done partial study at Tongi (only trace metal analysis), a northern industrial site of Dhaka housing the pharmaceutical, soap and detergent, cosmetics, garments, and food industries.

Experimental

Particulate matter measurement

The PM measurements were taken place at four sampling sites from 7:00 to 21:00 (15 h) for three consecutive days during the post-monsoon season of August to October, in 2017. Both offline and real-time measurements of PM were carried out in indoor environmental settings. PM_{10} was collected on pre-weighed and pre-combusted (6 h at $450^{\circ}C$) 47 mm diameter quartz filters (Tissu quartz filters from Pall Gelman) with IPM-FDS 2510 air sampler (dual channel dust sampler, Instrumex, flow rate: 16.65 L min^{-1} , accuracy $\pm 2\%$). The instrument was placed in the living room at least 1.5 m height from the floor (Blondeau et al. 2005) for indoor measurements (Table 1) and in balcony for outdoor measurements. A total of 15 PM filters were collected and covered with aluminum foil and stored in a refrigerator at about $-20^{\circ}C$ for trace metal analysis.

Simultaneous real-time measurements of PM in indoor were also recorded using Aerocet-531S (MetOne Inc.) at a flow rate of 2.83 L/min (accuracy $\pm 5\%$) for 15 h during the

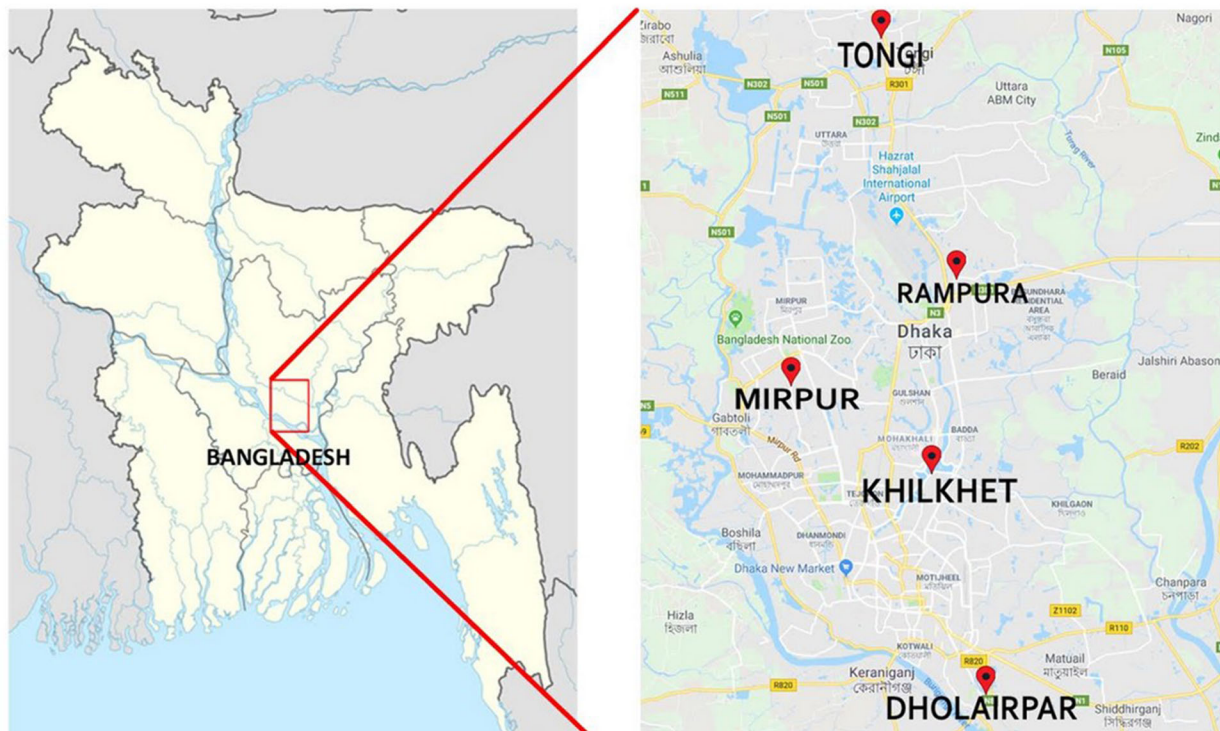


Fig. 1 a Map of Bangladesh. b Map of the five sampling locations in the Dhaka mega city (Khilkhet, Rampura, Mirpur, Dholairpar, Tongi)

sampling time. The Aerocet-531S is a real-time PM sampler which is capable of measuring six different sizes (PM_{1} , $PM_{2.5}$, PM_{4} , PM_{7} , PM_{10} , and TSP) at 1-min intervals. The instrument uses a laser diode light source which uses right angle scattering method at $0.78 \mu\text{m}$. The light reaches the collection system and detector where the instrument uses the information of scattered particles and calculate a mass per unit volume. A mean particle diameter is used to calculate a volume (cubic meters), for six different sizes and multiplied by the number of particles to get a generic density ($\mu\text{g m}^{-3}$). Finally, the mass is divided by the air volume sampled for a mass per unit volume ($\mu\text{g m}^{-3}$).

NO_2 and TVOC concentrations

The NO_2 and TVOC concentrations were measured in living room by low volume (0.5 L/min) Aeroqual 500 series NO_2 and TVOC monitor, respectively (Aeroqual Ltd., Auckland, New Zealand). The concentrations were recorded manually in each hour in the study period and recorded on a log sheet. Each sensor needs to warm up for 3 min to burn off any contaminants before recording the data. After completion of warm up, the monitor displays the current, average, maximum, and minimum reading in ppm level of the attached sensor.

Peak flow rate

A peak flow meter is a portable, hand held, inexpensive, plastic cylindrical device used to measure how fast air flows from the lungs or the ability to push air out of the lungs. Rossmax PF120 peak flow meter has been used for recording the peak flow rate of the occupants in standing position with a range of 60–800 L/min. This test was explained well to the subjects and several trials were attempted. After understanding the technique of the test correctly by the participants, highest three readings of the test were considered for each person. Although “normal” peak flow rate is based on a person’s sex, height, age, and race, we conducted our investigations only for 25 adults (age ranging from 20 to 60 years) from four houses in Dhaka due to the reluctance of the participants as a whole to participate in this experiment. All the occupants chosen were non-smokers, without breathing problems, and had no lung complications. This was intended to get a proper sample and calculate the normal flow rates.

Elemental analysis

Each filter was weighed twice before and after sample collection with balance (AS220.R2, Radwag; sensitivity 0.0001 g). The half portion of filter paper was placed in separate stopper

Table 1 Characteristics of the houses of the sampling sites (Tongi, Khilkhet, Rampura, Mirpur, Dholaipar) in greater Dhaka city, Bangladesh. There was no mechanical ventilation in these houses, only natural ventilation was available

Area	Floor	Building age (year)	Number of occupants	Smoking/covering material	Utensils inside houses	Vegetation	Characteristics of the sampling sites
Khilkhet	3rd	1.0	6	No/Plaster, tiles	Glass, wooden, metal	No vegetation	Influenced by heavy traffic from nearby highway
Rampura	1st	20	4	No/Plaster, mosaic floor	Glass, wooden, metal	Plants in both indoor and balcony	No intense traffic, constructional area
Mirpur	2nd	21	6	No/Plaster, cement floor	Glass, plastic, wooden, metal	No vegetation	Dense traffic, some rickshaw and automobile repairing workshops
Dholaipar	1st	24	5	No/Plaster, mosaic floor	Glass, plastic, wooden, metal	No vegetation, pets in balcony	Typical residential area with no traffic, some welding, glass factories
Tongi (only trace metal analyzed)	6th	1.5	4	No/Plaster, tiles	Glass, wooden, metal	No indoor plants	Industrial area with high traffic

bottle and 45 mL de-ionized water, and 15-mL 12% nitric acid (HNO₃) solution was added. The mixture was then placed into an automatic mechanical shaker at 95 °C for 90 min and then sonicated for 30 min. The mixture was then allowed to settle overnight and then filtered using filter paper. The filter was then used for the analysis of trace metals using Atomic Absorption Spectrophotometer (model: AAnalyst 800, Perkin Elmer, USA).

Quality control

The AEROCET 531S uses a proprietary algorithm to convert count data to mass measurements ($\mu\text{g m}^{-3}$). Fundamentally, it calculates a volume for each detected particle then assigns a standard density for the conversion. The standard density value is augmented by the K-Factor setting to improve measurement accuracy. The AEROCET 531S provides a separate K-Factor setting for each measurement range (PM₁, PM_{2.5}, PM₄, PM₇, PM₁₀, and TSP). These K-Factors is modified with Comet software. K-Factor values should be empirically derived via comparison with a reference unit. As a reference unit is unavailable, the recommended K-Factor setting is considered 3.0.

For trace metal in PM₁₀, filters were collected for three consecutive days. Blank filters were also collected for the same time period. Using similar procedure, sample blanks were also analyzed using AAS for quality assurance of analysis. Corrections were made by excluding their results from PM₁₀ samples. Standard solutions were prepared for individual elements for calibration. Calibration curves for each element were constructed from the data. Specific hollow cathode lamps were used with fixed wavelength to analyze the samples. Sometimes, the sample had to be diluted many folds to keep the results in the analytical range. De-ionized water and

high purity acid were used to prepare sample solution for AAS analysis.

NO₂ and TVOC were recorded every hour in each place from 7:00 to 21:00 (15 h) to maintain a consistency. Peak flow meter was washed regularly after sampling to provide accurate reading.

Total hazard ratio indicator determination

Total hazard ratio of different indoor locations was calculated using the following equation to find out the universal breathing exposure risk (Datta et al. 2017). Hazard ratio (HR) is the ratio of measured average concentration with reference values of a pollutant (Datta et al. 2017). The reference values for NO₂, PM_{2.5}, and PM₁₀ were taken as 0.04 ppm, 25, and 50 $\mu\text{g m}^{-3}$, respectively. The hazard ratio was calculated for each location and the summation of the HR of all the pollutants gives the THR indicator.

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

$$THR_{\text{site}} = \sum HR_i \quad (2)$$

where C_i is the measured average concentration of a pollutant and RfC_i is the reference concentration of that pollutant.

Results and discussion

Concentration of particulate matters

Measurements of PM₁, PM_{2.5}, PM₄, PM₇, PM₁₀, and TSP showed significant variation in concentration over the selected sampling sites of Dhaka city (Fig. 2). As no standard values for indoor PM have been yet set on ambient air quality, all the

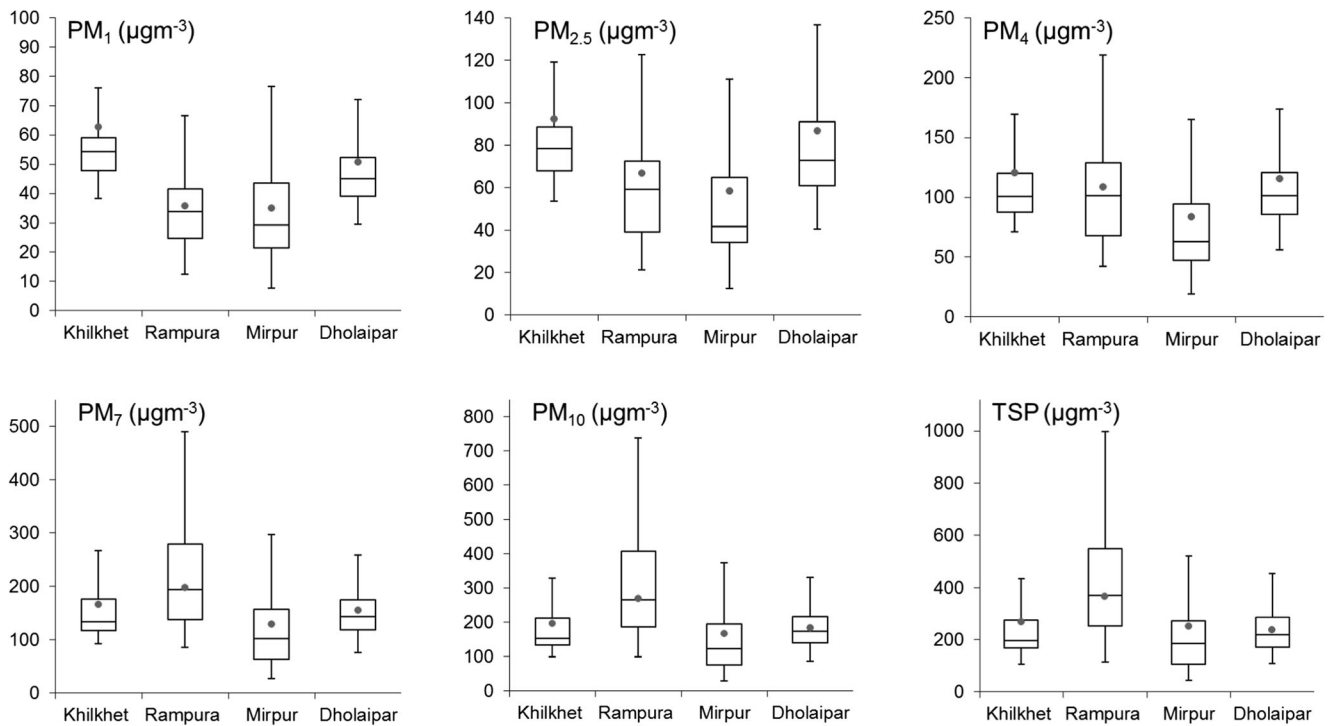


Fig. 2 Indoor particulate matters at different locations by using box and whisker plot. Y-axis indicates the particulate matter (PM) mass of each size fraction. The upper end and lower end of the box represent the third quartile and first quartile, respectively, and median is marked by a

horizontal line. The whisker represents the maximum (upper whisker) and minimum value (lower whisker). The dot is the average value of whole data set

values were compared with the outdoor limit value. The average PM₁ concentration in Dhaka during the study period was $46.1 \pm 13.4 \mu\text{g m}^{-3}$ with the highest concentration in Khilkhet ($62.8 \pm 13.1 \mu\text{g m}^{-3}$) and lowest in Mirpur ($34.9 \pm 20.8 \mu\text{g m}^{-3}$). In urban houses Palestine, PM₁ concentration ranged from 48 to $178 \mu\text{g m}^{-3}$ and annual average indoor PM₁ was 70.0 ± 19.1 , which was 1.5 times higher compared to our study area (Jodeh et al. 2018).

Average PM_{2.5} concentrations for Khilkhet, Rampura, Mirpur, and Dholaipar were 92.3 ± 27.3 , 66.6 ± 43.4 , and 58.2 ± 38.8 , $86.8 \pm 28.3 \mu\text{g m}^{-3}$, respectively, and were significantly higher than the Environmental Protection Agency (EPA) for 24-h period ($35 \mu\text{g m}^{-3}$) (EPA 2011) and World Health Organization (WHO) guideline ($25 \mu\text{g m}^{-3}$ over 24 h) (Liu et al. 2018). The highest PM_{2.5} concentration recorded in the house of Khilkhet may be attributed to particulate pollutants, gases originated from cooking performances, oily fumes, and some constructional works inside the building (Abt et al. 2000). These pollutants are the major sources of pollution in the residential environment. The lowest PM_{2.5} concentrations were recorded at Mirpur which was due to heavy rainfall during the sampling periods. The building constructional work at nearby sites and mosaic cleaning activities in the kitchen and bathroom was also responsible for noticeable high concentration of PM_{2.5} in Rampura ($21.3\text{--}418 \mu\text{g m}^{-3}$) (Abt et al. 2000). Many welding, glass, and plastic factories were located in Dholaipar. Further, the pets

in the balcony were the main factor considered for high air pollution ($40.7\text{--}246.9 \mu\text{g m}^{-3}$) (Wallace 1996).

Comparing our indoor PM_{2.5} concentrations with other countries shows that PM_{2.5} in Dhaka is 9.5, 7.0, and 1.7 times higher than in countries like UK (Jones et al. 2000), USA (Haller et al. 1999), and Kuwait (Yassin et al. 2012). Interestingly, it is eight times lower than India (Kulshreshtha and Khare 2010), five times lower than in Pakistan (Colbeck et al. 2010), and 1.8 times lower than Thailand (Feng et al. 2000). PM_{2.5} concentration in Palestine ($84.2 \mu\text{g m}^{-3}$) (Jodeh et al. 2018) was found similar to that of our study ($76.0 \mu\text{g m}^{-3}$). In essence, we can conclude that the concentration of particulate matter in developing countries (Bangladesh, India, Pakistan, Palestine, and Thailand) is relatively higher than in developed countries (UK, USA, and Kuwait).

The average indoor PM₁₀ concentration for Khilkhet ranged from 99.8 to $889.2 \mu\text{g m}^{-3}$ with a mean of $197.3 \mu\text{g m}^{-3}$, and, for Rampura, ranged from 82.2 to $3002.5 \mu\text{g m}^{-3}$ with a mean of $268.2 \mu\text{g m}^{-3}$. For Mirpur, PM₁₀ varied from 29.3 to $713.8 \mu\text{g m}^{-3}$ with a mean of $165.7 \mu\text{g m}^{-3}$ and, for Dholaipar, varied from 80.6 to $792.2 \mu\text{g m}^{-3}$ with a mean of $184.5 \mu\text{g m}^{-3}$. All these values were also higher than the WHO and EPA guideline limit value ($50 \mu\text{g m}^{-3}$ and $150 \mu\text{g m}^{-3}$) (Liu et al. 2018; EPA 2011).

Among four places, total suspended particulate (TSP) mass concentration was found highest in Rampura amounting to an

average of $363.9 \pm 327.1 \mu\text{g m}^{-3}$ and lowest in Dholaipar amounting to an average of $263.1 \pm 125.5 \mu\text{g m}^{-3}$.

Indoor-outdoor ratio of PM_{2.5}

Kulshreshtha and Khare (2011) state that indoor sources of pollution can be compared with that of the indoor/outdoor ratio (I/O) of particulate matter. The I/O ratios of PM_{2.5} were calculated and the impact of outdoor air and indoor sources on indoor air quality has been quantified. The I/O ratio is defined as the ratio C_{in}/C_{out} where C_{in} and C_{out} are the indoor and outdoor concentrations of PM, respectively (Chen and Zhao 2011). The measured result showed that the mean I/O ratio for all the sampling sites was 0.76 ± 0.22 when the outdoor concentration was more than $170 \mu\text{g m}^{-3}$, which indicates that indoor PM_{2.5} concentration could be dominated by outdoor sources. Former studies investigated I/O ratios of the sampling sites were less than one, indicating the PM produced from vehicular emissions from the neighboring crowded roads, invariably enter into the homes and elevate their concentration levels (Oosterlee et al. 1996). Hourly variation of I/O showed a dramatical change after 10:00 till the afternoon hour (that is by 14:00)—Fig. 3. Due to the increase of several indoor activities by occupants like cooking, dusting, and frisking, these variations were observed (Massey et al. 2012). In the afternoon, windows are kept mostly open; air pollutants from outdoors can go into these dwellings and increase the I/O ratio (Leung 2015).

A positive linear correlation is observed between the indoor and outdoor concentration of PM_{2.5} that shows a significant correlation ($p < 0.001$) but relatively weak relationship between indoor and outdoor data ($R^2 = 0.42$) (Fig. 4). This indicates that 42% of indoor air is influenced by outdoor contribution (Colbeck et al. 2010). This relatively weak indoor to outdoor PM association suggests that not only outdoor sources, but also several indoor sources and activities such as dusting, washing, cleaning, and resuspension are contributors for fine PM that are responsible for indoor air pollution.

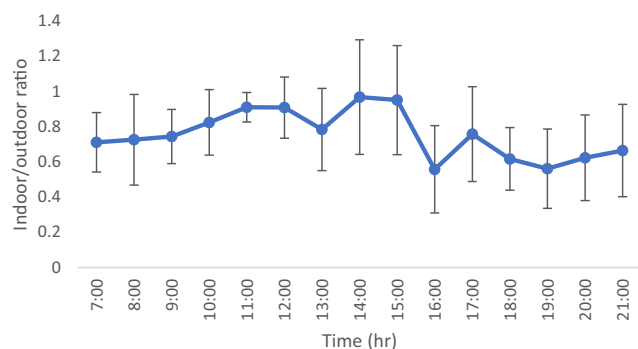


Fig. 3 Hourly variations of I/O ratio of PM_{2.5} in indoor environment in Dhaka, Bangladesh

Concentration of trace metals in PM₁₀

Concentration of Ca, Mg, and Fe was found higher in indoor PM₁₀ of all sampling sites, followed by Pb and Zn. Ni was determined only in Mirpur. EFs of metals were calculated to evaluate the degree of anthropogenic influence by using the following equation (Shohel et al. 2018; Ahmed et al. 2018):

$$EF = (X/Fe)_{aerosol} / (X/Fe)_{crust} \quad (1)$$

where X = concentration of species of interest and Fe = concentration of Fe .

The enrichment factors of Ca and Mg ($EF < 10$) suggested that they came from crustal sources.

Ca is also a tracer for construction dust (Pace and Watson 1987) and the principal ingredient of wall putty (calcium carbonate) used for finishing walls before painting. During sampling in Rampura, we encountered heavy constructional activity in nearby sites which included mosaic cleaning activity performed inside constructional sites. Zn was found moderately enriched in Mirpur and Khilkhet (Table 2). Zn is used during vulcanization of tyres (Sörme et al. 2001) and is an indicator of traffic-related emission (Harrison et al. 1996). The enrichment of Zn in Mirpur and Khilkhet was due to the closeness of the residential houses to nearby roads. Pb was found highly enriched ($EF > 100$) in all residential houses (Table 2). The average concentration of Pb was significant in Mirpur and Tongi compared to the other indoor environment except Dholaipar. Pb in indoor environments of Dhaka (0.7–3.3 ppb) was higher than the European cities and far East Asian cities like Taiwan (0.13 ppb) (Fung and Wong 1995). High concentration of Pb was observed due to the presence of several automobile repair shops, battery manufacturers, and recycle shops near the residential houses. The Pb species generated from those sources may be resuspended in the air because of traffic turbulence, construction, and abrasion activities (Srithawirat and Latif 2015; Laidlaw et al. 2012; Zahran

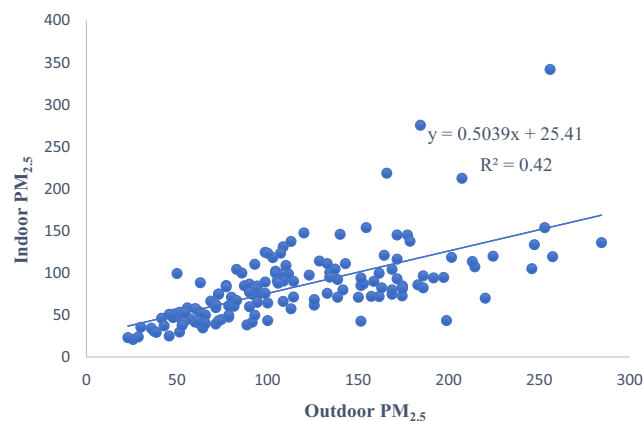


Fig. 4 Correlation between Indoor vs outdoor fine particle mass concentrations (PM_{2.5}) in Dhaka, Bangladesh measured with AEROCET 531S

Table 2 Concentrations (units are in $\mu\text{g m}^{-3}$) and enrichment factor of different metals at indoor environment, Dhaka, Bangladesh

Sites	Ca		Mg		Pb		Zn		Ni	
	Conc.	EF	Conc.	EF	Conc.	EF	Conc.	EF	Conc.	EF
Mirpur	17.3 ± 3.8	2.7 ± 1.0	8.8 ± 5.6	3.0 ± 0.7	3.3 ± 5.8	902 ± 630.6	17.5 ± 11.3	1551.7 ± 1309.4	1.0 ± 0.4	256.6 ± 23.4
Khilkeht	10.4 ± 2.1	1.8 ± 0.6	5.1 ± 0.8	1.9 ± 0.8	0.7 ± 1.1	196 ± 95.7	13.1 ± 15.1	1302.9 ± 1170.6	BDL	BDL
Rampura	54.0 ± 1.1	10 ± 16.9	8.3 ± 1.1	3.4 ± 0.8	0.7 ± 1.1	210 ± 99.3	8.9 ± 5.8	939.1 ± 406.6	BDL	BDL
Dholaipar	6.1 ± 1.8	1.3 ± 0.2	3.3 ± 0.1	1.6 ± 0.2	BDL	BDL	8.8 ± 5.5	1083.3 ± 898.7	BDL	BDL
Tongi	9.3 ± 2.1	1.7 ± 0.5	5.2 ± 0.7	2.0 ± 0.5	1.2 ± 2.0	363 ± 142.7	5.0 ± 1.8	507.3 ± 199.0	BDL	BDL

BDL below detection limit

et al. 2013). Further sources of Pb in houses could be due to use of lead-based paints applied on walls, toys, and furniture (Lin et al. 2009). Ni was found only in Mirpur with concentration higher than the limit value of outdoor environment (0.5 ppb) due to the presence of many vehicular repairing workshops in that area. Other factors such as paint and varnishes, telephone cable, and electrical equipment may also contribute to the sources of nickel (Salam et al. 2012).

NO₂ and TVOC concentrations

Hourly variation of NO₂ and TVOC was recorded in selected houses of Dhaka city (Fig. 5). Average NO₂ concentration was 0.076 ppm, which exceeds the limit value of NAAQS (0.04 ppm) for 24 h (Abrar et al. 2014). This increased concentration of NO₂ could be affected by both outdoor and indoor contributions. Previous studies have shown that NO₂ concentrations in the kitchen of New York and London homes with gas stoves (0.049 and 0.072 ppm, respectively) were higher than with electric stoves (0.0083 and 0.0095 ppm, respectively) (Arbex et al. 2007). In our study area, all the kitchens were equipped with gas stoves which attributed to high concentration of NO₂ in the living room and an increased value of NO₂ was especially observed in the afternoon

(14:00–15:00) due to cooking activities (Arbex et al. 2007). In Lahore, NO₂ concentration (0.11 ppm) was found 1.5 times higher than our study (Abrar et al. 2014).

There is no recognition for indoor air TVOC standard. Previous studies have shown that TVOC can be ranged from 1 to 4000 $\mu\text{g m}^{-3}$ and become a health concern whenever it exceeds 500 $\mu\text{g m}^{-3}$ (Wagdi et al. 2018). In our study, measured TVOC at all residential houses rose above this benchmark value and were found extremely high (90 ppm).

The decrease in VOC concentration was observed in morning hours; this may be due to the opening of doors and windows of the residential dwellings for the entry and exit purposes. This eventually diluted the VOC concentration inside the houses due to a temporary increase in ventilation. Additionally, dusting and pesticide spray (aerosols) inside the house also attribute to higher concentration of VOCs. It was observed that the floors were wiped with disinfectants after the lunch hour around 14:00—this might have attributed to a slight increase in the VOC concentration in the afternoon hours. Use of beauty care products and perfumes by the occupants of the house might have led to the increase of VOC concentration. Previous studies have also suggested that the use of these products gradually increases the VOC concentration in a poorly ventilated room (Wolkoff et al. 1992; Wolkoff 1995).

Fig. 5 Hourly variation of NO₂ and TVOC in indoor environment in Dhaka, Bangladesh measured with Aeroqual 500 series

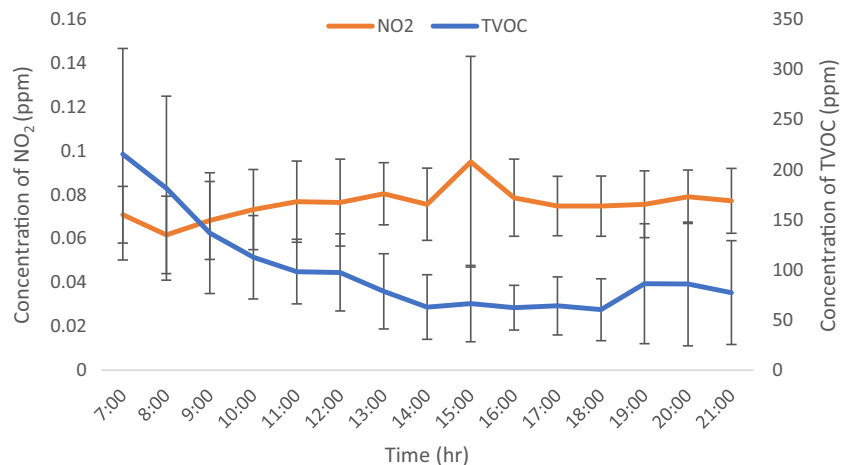
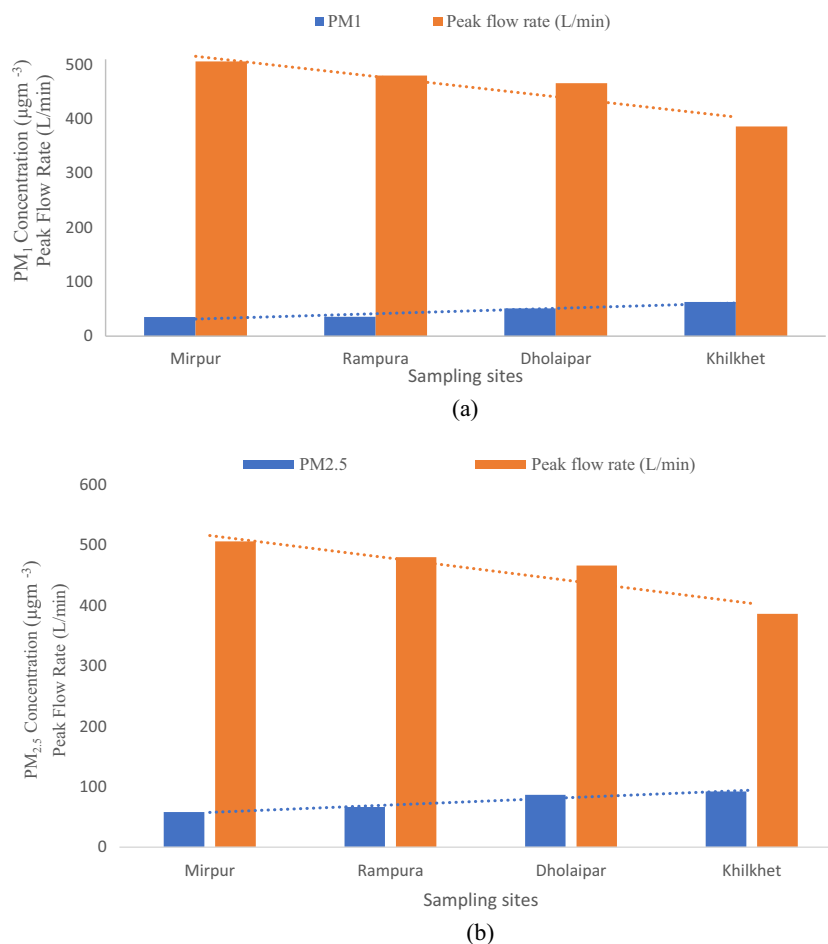


Fig. 6 Association of ultra-fine particulate matters **a** PM_{10} and **b** $PM_{2.5}$ with lung function measured with peak flow rate among the residents at five different locations in Dhaka, Bangladesh



Total hazard ratio indicator

Total hazard ratio (THR) was calculated using reference values of a pollutant in each site (Datta et al. 2017). The reference values for NO_2 , $PM_{2.5}$, and PM_{10} were taken as 0.04 ppm, 25, and $50 \mu\text{g m}^{-3}$, respectively. HR of each pollutant for 15-h exposure varies over sampling sites. HR of PM_{10} was relatively higher in Rampura than other pollutant in four different sites (Table 3). Nevertheless, an increased HR of $PM_{2.5}$ and NO_2

Table 3 Determination of total hazard ratio (THR) indicator of $PM_{2.5}$, PM_{10} , and NO_2 in Dhaka, Bangladesh

Locations	HRi ^a			THR indicator $\sum \text{HRi}^a (\text{PM}_{2.5} + \text{PM}_{10} + \text{NO}_2)$
	$PM_{2.5}$	PM_{10}	NO_2	
Khilkhet	3.69	3.95	2.46	10.10
Rampura	2.66	5.36	1.82	9.85
Mirpur	2.32	3.31	1.50	7.15
Dholaipar	3.47	3.69	1.99	9.15
Ave Dhaka	3.04	4.08	1.94	9.06

^a Mean of 3-day data (15 h per day) on each location for $PM_{2.5}$ and PM_{10} ; mean of 15-h data for NO_2

were observed in Khilkhet compared to other places (Table 3). Average THR was considerably higher in Khilkhet than other sites in our study. This may indicate that the residents in Khilkhet are more exposed to air pollutants than others. All the sampling locations have much higher $PM_{2.5}$ HR than previous studies Datta et al. 2017 and Gennaro de et al. 2013.

Association of fine particulate matter with peak flow rate

The associations between indoor 15-h averages of PM_{10} concentrations and lung function parameters within the household occupants suggested reduced lung function with increasing exposure (Fig. 6). Chan et al. (2015) also found a decrease in lung function with increased exposure of particulate matters. In Mirpur, PM_{10} concentration was $34.5 \mu\text{g m}^{-3}$ whereas the average peak flow rate of the residents was 506 L min^{-1} . With more inhalation of PM_{10} ($62.7 \mu\text{g m}^{-3}$), a reduced flow rate of 386 L min^{-1} was observed in Dholaipar. PM_{10} is a part of $PM_{2.5}$ and may have the adverse effect than $PM_{2.5}$, while exposure to dust as particles get sucked into and embedded deep in lungs. Similar trend is also observed in case of $PM_{2.5}$. With the increasing value of $PM_{2.5}$, the peak flow rate of the

residents was decreasing. Despite the availability of limited data, we found a negative relation between PM_{10} , $PM_{2.5}$, and peak flow rate of the residents, which suggested that high indoor PM levels and more inhalation of fine and ultrafine PM are blocking the airways and reducing lung efficiency.

Conclusion

Indoor particulate matter concentration measurement was conducted across the Dhaka mega city area in the post-monsoon season to evaluate the concentration of fine particulate matters and their association with lung functions. The study also investigated the sources responsible for such indoor air pollution. The average indoor PM_{10} , $PM_{2.5}$, and $PM_{1.0}$ concentration 46.1 ± 13.4 , 76.0 ± 16.2 , and $203.9 \pm 44.8 \mu\text{g m}^{-3}$, respectively, which exceed the WHO and EPA standard limits for all monitoring locations. Indoor $PM_{2.5}$ concentration was relatively weakly correlated with outdoor concentrations and suggested 42% outdoor PM penetrates to city home dwellings. Indoor/outdoor ratio of $PM_{2.5}$ was less than unity (0.75) due to the outdoor source arising from vehicular emissions. Several indoor activities like dusting, wiping of floors with detergents, cooking activities, and cleaning are responsible for increased levels of indoor PMs. Concentration of NO_2 and TVOC was 0.076 ± 0.007 ppm and 90 ± 46.0 ppm, respectively. This was much higher than the guideline value and previous studies. Enrichment factor analysis showed that anthropogenic source was responsible for Ni, Zn, and Pb and crustal source for Ca and Mg. A negative association was observed between PM_{10} and peak flow rate indicating a decreased lung function with elevated concentration of fine particles. Overall, the current study indicates that on average Dhaka has highly polluted indoor house atmospheric conditions compared with international data and causing high risk of several diseases among the city dwellers.

Acknowledgements Authors acknowledge the owner and residents of the houses who were helping during sampling and also participating in the lung function test experiments. Centre for Advanced Research in Sciences (CARS) for helping with trace metal analysis.

Funding information Authors acknowledge the financial support of the Ministry of Education, The Government Republic of Bangladesh (Project no.: PS 14138).

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

Abrar A, Sundas W, Perveen F, Habib M (2014) Air quality monitoring of some gaseous pollutants at selected points in Gullberg II, Lahore, Pakistan. *Int Res J Env Sci* 3:38–47

- Abt E, Suh HH, Allen G, Koutrakis P (2000) Characterization of indoor particle sources: a study conducted in the metropolitan Boston area. *Environ Health Perspect* 108:35–44
- Ahmed M, Hossain A, Akther T, Shohel M, Salam A (2018) Chemical composition and source identification of fog water at an indo-Gangetic plain (IGP) outflow location (coastal Bhola Island), Bangladesh. *J Environ Pollut Manag* 1:104
- Arbex MA, Martins LC, Pereira LAA, Negrini F, Cardoso AA, Melchert WR, Arbex RF, Saldiva PHN, Zanobetti A, Braga ALF (2007) Indoor NO_2 air pollution and lung function of professional cooks. *Braz J Med Biol Res* 40:527–534
- Begum AB, Biswas SK (2009) Characterization and apportionment of sources of indoor air particulate matter of aed campus, Dhaka. *J Bangladesh Acad Sci* 33:25–36
- Blondeau P, Iordache V, Poupard O, Genin D, Allard F (2005) Relationship between outdoor and indoor air quality in eight French schools. *Indoor Air* 15:2–12
- Brown JS, Gordon T, Price O, Asgharian B (2013) Thoracic and respirable particle definitions for human health risk assessment. *Fibre Toxicol* 10:12
- Chan CC, Chen BY, Cheng T-J, Guo YL (2015) Effects of particulate air pollution and ozone on lung function in non-asthmatic children. *Environ Res* 137:40–48
- Chen C, Zhao B (2011) Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor. *Atmos Environ* 45:275–288
- Colbeck I, Nasir ZA, Ali Z (2010) Characteristics of indoor/outdoor particulate pollution in urban and rural residential environment of Pakistan. *Indoor Air* 20:40–51
- Datta A, Suresh R, Gupta A, Singh D, Kulshrestha P (2017) Indoor air quality of non-residential urban buildings in Delhi, India. *Int J Sust Built Environ* 6:412–420
- Dherani M, Pope D, Mascarenhas M, Smith KR, Weber M, Bruce N (2008) Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: a systematic review and meta-analysis. *Bull World Health Organ* 86:390–398
- Dockery DW, Pope CA 3rd, Xu X, Spengler JD, Ware JH, Fay ME, Ferris BG Jr, Speizer FE (1993) An association between air pollution and mortality in six U.S. cities. *N Engl J Med* 329:1753–1759
- Feng CT, Kirk RS, Nuntavarn V-V, Bart DO, Lauraine GC, Nipapun K (2000) Indoor/outdoor PM_{10} and $PM_{2.5}$ in Bangkok, Thailand. *J Expo Anal Environ Epidemiol* 10:15–26
- Fung YS, Wong LWY (1995) Apportionment of air pollution sources by receptor models in Hong Kong. *Atmos Environ* 29:2041–2048
- Gennaro de G, Farella G, Marzocca A, Mazzone A, Tutino M (2013) Indoor and outdoor monitoring of volatile organic compounds in school buildings: indicators based on health risk assessment to single out critical issues. *Int J Environ Res Public Health* 10:6273–6291
- Gurley ES, Salje H, Homaira N, Ram PK, Haque R, Petri WA Jr, Bresee J, Moss WJ, Luby SP, Breyse P, Azziz-Baumgartner E (2013) Seasonal concentrations and determinants of indoor particulate matter in a low-income community in Dhaka. *Bangladesh Environ Res* 121:11–16
- Haller L, Claiborn C, Larson T, Koenig J, Norris G, Edgar R (1999) Airborne particulate matter size distributions in an arid urban area. *J Air Waste Manag Assoc* 49:161–168
- Harrison RM, Smith DJT, Pio CA, Castro LM (1996) Source apportionment of atmospheric polycyclic aromatic hydrocarbons collected from an urban location in Birmingham, UK. *Environ Sci Technol* 30:825–832
- Jodeh S, Hasan AR, Amarah J, Father J, Salghi R, Lgaz H, Jodeh W (2018) Indoor and outdoor air quality analysis for the city of Nablus in Palestine: seasonal trends of PM_{10} , $PM_{5.0}$, $PM_{2.5}$ and $PM_{1.0}$ of residential homes. *Air Qual Atmos Health* 11:229–237

- Jones NC, Thornton CA, Mark D, Harrison RM (2000) Indoor/outdoor relationships of particulate matter in domestic homes with roadside, urban and rural locations. *Atmos Environ* 34:2603–2612
- Khalequzzaman M, Kamijima M, Sakai K, Chowdhury NA, Hamajima N, Nakajima T (2007) Indoor air pollution and its impact on children under five years old in Bangladesh. *Indoor Air* 17:297–304
- Klepeis NE, Nelson WC, Ott WR, Robinson JP, Tsang AM, Switzer P, Behar JV, Hern SC, Engelmann WH (2001) The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J Expo Sci Environ Epidemiol* 11:231–252
- Koenig JQ, Mar TF, Allen RW, Jansen K, Lumley T, Sullivan JH, Trenga CA, Larson T, Liu LJ (2005) Pulmonary effects of indoor- and outdoor-generated particles in children with asthma. *Environ Health Perspect* 113:499–503
- Kulshreshtha P, Khare M (2010) A comparative study of indoor air pollution and its respiratory impacts in Delhi, India. *WIT Trans Ecol Environ* 136:287–296
- Kulshreshtha P, Khare M (2011) Indoor exploratory analysis of gaseous pollutants and respirable particulate matter at residential homes of Delhi, India. *Atmos Pollut Res* 2:337–350
- Laidlaw MAS, Zahran S, Mielke HW, Taylor MP, Filippelli GM (2012) Re-suspension of lead contaminated urban soil as a dominant source of atmospheric lead in Birmingham, Chicago, Detroit and Pittsburgh, USA. *Atmos Environ* 49:302–310
- Landrigan J, Richard F, Nereus BE, Acosta JR, Olusoji A, Arnold R, Niladri, Bertollini R (2017) The lancet commission on pollution and health. *Lancet* 391:462–512
- Leung D (2015) Outdoor-indoor air pollution in urban environment: challenges and opportunity. *Front Environ Sci* 2:1–7
- Lin GZ, Peng RF, Chen Q, Wu ZG, Du L (2009) Lead in housing paints: an exposure source still not taken seriously for children lead poisoning in China. *Environ Res* 109:1–5
- Liu HY, Dunea D, Iordache S, Pohoata A (2018) A review of airborne particulate matter effects on young Children's respiratory symptoms and diseases. *Atmosphere* 9:150
- Massey D, Kulshreshtha A, Masih J, Taneja A (2012) Seasonal trends of PM₁₀, PM_{5.0}, PM_{2.5} & PM_{1.0} in indoor and outdoor environments of residential homes located in north-Central India. *Build Environ* 47:223–231
- Mohammadyan M, Ashmore M, Shabankhani B (2008) Indoor PM_{2.5} concentrations in the office, café, and home. *J Occup Environ Hyg* 2:57–62
- Nahar M, Khan MH, Ahmad SA (2016) Indoor air pollutants and respiratory problems among Dhaka City dwellers. *Arch Community Med Public Health* 2:32–36
- Nakai S, Tamura K (2008) Relationship between indoor and outdoor particulate matter concentrations in Japan. *Asian J Atmos Environ* 2:68–74
- Oosterlee A, Drijver M, Lebret E, Brunekreef B (1996) Chronic respiratory symptoms in children and adults living along streets with high traffic density. *Occup Environ Med* 53:241–247
- Pace TG, Watson JG (1987) Protocol for applying and validating the CMB model. Report No. EPA 450/4-87-010. US Environmental Protection Agency, Research Triangle Park, NC
- Perez-Padilla R, Schilman A, Riojas-Rodriguez H (2010) Respiratory health effects of indoor air pollution. *Int J Tuberc Lung Dis* 14:1079–1086
- Ram PK, Dutt D, Silk BJ, Doshi S, Rudra CB, Abedin J, Goswami D, Fry AM, Brooks WA, Luby SP, Cohen AL (2014) Household air quality risk factors associated with childhood pneumonia in urban Dhaka, Bangladesh. *Am J Trop Med Hyg* 90:968–975
- Salam A, Mamoon HA, Ullah MB, Ullah SM (2012) Measurement of the atmospheric aerosol particle size distribution in a highly polluted mega-city in Southeast Asia (Dhaka-Bangladesh). *Atmos Environ* 59:338–343
- Shohel M, Simol HA, Reid E, Reid JS, Salam A (2017) Dew water chemical composition and source characterization in the IGP outflow location (coastal Bhola, Bangladesh). *Air Qual Atmos Health* 10:981–990
- Smith K (2003) Fuel combustion, air pollution exposure, and health: the situation in developing countries. *Annu Rev Energy Environ* 18:529–566
- Sörme L, Bergbäck B, Lohm U (2001) Goods in the anthroposphere as a metal emissions source: a case study of Stockholm, Sweden. *Water Air Soil Pollut* 1:213–227
- Srithawirat T, Latif MT (2015) Concentration of selected heavy metals in the surface dust of residential buildings in Phitsanulok, Thailand. *Environ Earth Sci* 74:2701–2706
- Stazi F, Naspi F, Ulpiani G, Perna CD (2017) Indoor air quality and thermal comfort optimization in class rooms developing an automatic system for windows opening and closing. *Energy Build* 139:732–746
- United States Environment Protection Agency (US EPA) (2011). The Screening Level (RSL) Tables (Last updated June 2011)
- Uzoigwe JC, Prum T, Bresnahan E, Garelnabi M (2013) The emerging role of outdoor and indoor air pollution in cardiovascular disease. *N Am J Med Sci* 5:445–453
- Valavanidis A, Fiotakis K, Vlachogianni T (2008) Airborne particulate matter and human health: toxicological assessment and importance of size and composition of particles for oxidative damage and carcinogenic mechanisms. *J Environ Sci Health C Environ Carcinog Ecotoxicol Rev* 26:339–362
- Wagdi D, Tarabieh K, Zeid MNA (2018) Indoor air quality index for preoccupation assessment. *Air Qual Atmos Health* 11:445–458
- Wallace L (1996) Indoor particles: a review. *J Air Waste Manag Assoc* 46:98–126
- Wolkoff P (1995) Volatile organic compounds – sources, measurements, emissions and the impact on indoor air quality. *Indoor Air* 3:1–73
- Wolkoff P, Johnsen CR, Franck C, Wilhardt P, Albrechtsen O (1992) A study of human reactions to office machines in a climatic chamber. *J Expo Anal Environ Epidemiol Suppl*(7):1–97
- World Health Organization (2011) Methods for monitoring indoor air quality in schools: report of a meeting, Bonn, Germany, 4–5 April 2011. WHO Regional Office for Europe. <http://www.who.int/iris/handle/10665/108596>. Accessed 24 Dec 2018
- World Health Organizations (WHO) (2018) Household air pollution and health (link: <http://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health>). Accessed 24 Dec 2018
- Yassin M, AlThaqeb BEY, Al-Mutiri EAE (2012) Assessment of indoor PM_{2.5} in different residential environments. *Atmos Environ* 56:65–68
- Zahran S, Laidlaw MA, McElmurry SP, Filippelli GM, Taylor M (2013) Linking source and effect: resuspended soil lead, air lead, and children's blood lead levels in Detroit, Michigan. *Environ Sci Technol* 47:2839–2845
- Zhang Q, Jiang X, Tong D, Davis SJ, Zhao H, Geng G, Feng T, Zheng B, Lu Z, Streets DG, Ni R, Brauer M, van Donkelaar A, Martin RV, Huo H, Liu Z, Pan D, Kan H, Yan Y, Lin J, He K, Guan D (2017) Transboundary health impacts of transported global air pollution and international trade. *Nature* 543:705–709