Jurnal Serambi Engineering JSE
Volume X, No.1, Januari 2025 Hal 11846 - 11853
p-ISSN : 2528-3561
e-ISSN : 2541-1934

Assessment of Black Carbon in University: Emphasis on Different Indoor Microenvironment, Infiltration Factor, and Exposure

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Received: November 28, 2024 Approved: December 5, 2024

Abstract

Black carbon (BC), a harmful air pollutant, poses significant risks to human health. As students spend most of their time indoors and a third in school, the educational environment deserves special attention; however, most previous research has focused on the assessment of the pollutant itself in the classroom. Therefore, this work aims to extend the characterisation of BC in universities by considering different indoor microenvironments, infiltration factors and estimating exposures for healthy children and adults. In this study, BC concentrations were measured in four room types: cafeteria, gym, office room and classroom. The average BC observed in the cafeteria (599 ng m^{-3}), gymnasium (987 ng m^{-3}), office (830 ng m^{-3}) and classroom (548 ng m^{-3}) were. Of these, the gymnasium had the highest mean concentration, consistent with its high indoor/outdoor (I/O) ratio of 1.11, indicating significant indoor sources of BC. Exposure levels correlated directly with BC concentrations, with adults having higher deposition rates compared to children. These results provide insights into the spatial variation of BC in indoor environments, with implications for air quality control and health risk assessment for occupants.

Keywords: *black carbon, exposure assessment, infiltration factor, university microenvironment*

Abstrak

Black carbon (BC) adalah polutan udara berbahaya yang dapat memberikan dampak negatif signifikan terhadap kesehatan manusia. Mengingat siswa menghabiskan sebagian besar waktunya di dalam ruangan, termasuk sepertiga waktu mereka di sekolah, lingkungan pendidikan memerlukan perhatian khusus. Namun, sebagian besar penelitian sebelumnya hanya berfokus pada penilaian polutan di ruang kelas. Oleh karena itu, penelitian ini bertujuan untuk memperluas karakterisasi BC di universitas dengan mempertimbangkan berbagai mikro lingkungan dalam ruangan, faktor infiltrasi, dan estimasi paparan pada anak-anak dan orang dewasa yang sehat. Penelitian ini mengukur konsentrasi BC di empat jenis ruangan: kafetaria, gym, ruang kantor, dan ruang kelas. Rata-rata konsentrasi BC yang teramati adalah 599 ng m^{-3} di kafetaria, 987 ng m^{-3} di gym, 830 ng m^{-3} di ruang kantor, dan 548 ng m^{-3} di ruang kelas. Di antara semua lokasi, gym memiliki konsentrasi rata-rata tertinggi, yang sejalan dengan rasio indoor/outdoor (I/O) sebesar 1,11, menunjukkan adanya sumber BC dari dalam ruangan. Tingkat paparan secara langsung berkorelasi dengan konsentrasi BC, dengan tingkat deposisi pada orang dewasa lebih tinggi dibandingkan anak-anak. Temuan ini memiliki implikasi untuk penilaian risiko kesehatan penghuni, menekankan perlunya pengendalian sumber polutan dalam ruangan untuk menciptakan lingkungan pendidikan yang lebih sehat.

Kata Kunci: *black carbon, exposure assessment, faktor infiltrasi, lingkungan mikro universitas*

1. Introduction

People residing in urban environments are constantly exposed to traffic-related air pollutants (TRAP) in their daily lives, with black carbon (BC) widely recognized as a reliable marker for assessing such exposure [1], [2]. BC, a harmful component of fine particulate matter, is particularly concerning due to its ability to infiltrate indoor spaces through various pathways, including air filtration systems, ventilation, and infiltration from outdoor sources [3], [4]. Given that students spend a significant portion of their time indoors, including nearly one-third in educational settings, the indoor environment in schools and universities warrants special attention.

While several studies have addressed BC concentrations in educational institutions, they have primarily focused on classrooms [3], [4], [5]. This approach overlooks other indoor environments that may contribute to exposure. Hence, this study was designed to evaluate BC levels within a university, emphasizing different indoor microenvironments, identifying sources, and exploring infiltration factors that influence exposure.

Indoor air pollution is affected by various factors, including outdoor infiltration, emissions from indoor sources, and chemical reactions occurring within enclosed spaces[6]. Activities such as cooking, smoking, incense burning, and candle use are known contributors to indoor BC and particulate matter [7]. Additionally, vehicles and nearby combustion sources, particularly in urban areas close to highways, significantly influence indoor BC levels. Compared to outdoor sources, indoor sources often play a more substantial role in personal exposure to fine particles and BC aerosols due to the proximity and longer exposure duration [8]. The distribution and persistence of BC indoors are further influenced by airflow dynamics, which depend on ventilation systems, room configurations, and heating or cooling mechanisms. Understanding these factors is critical for identifying the contribution of outdoor and indoor sources and assessing the extent of exposure.

Emerging evidence underscores the significant health risks posed by BC exposure. Both adults and children exposed to elevated BC levels have been linked to adverse health outcomes, including reduced lung function, acute respiratory inflammation, asthma exacerbation, cognitive decline, and attention deficits [9]. Given these risks, a detailed analysis of BC concentrations across different indoor microenvironments in universities is essential to provide insights into exposure dynamics, health implications, and opportunities for effective air quality management

2. Material and Methods

Overview of Study Sites

This study was conducted at a university located in Zhongli District, Taoyuan City, Taiwan. Measurements focused on different indoor microenvironments within the university, including a classroom, office, gym, cafeteria, and an outdoor reference site. These locations were selected to represent a variety of indoor settings commonly occupied by students and staff, each with distinct characteristics and potential pollution sources. The classroom, designed for teaching and learning activities, is equipped with basic ventilation and experiences occupancy fluctuations based on class schedules. The office serves as a workspace for students with a small room size, closed windows and door, featuring air conditioning, and consistent occupancy patterns. The gym is located below ground level with an average of 15 to 35 visitors at a time. The ventilation system used in the gym room is air conditioning, the gym used for physical activities. The semi-open system cafetaria, is located below ground level with an average footfall of 15 to 40 people. The ventilation system used in the canteen is a large exhaust machine with the brand teco. The average temperature in the cafeteria is 27°C with a relative humidity of 75%. The main source of pollution in the cafeteria comes from the cooking process, including emissions from heating devices and stoves. Lastly, the outdoor reference site was chosen to capture ambient air quality and assess the contribution of outdoor pollution to indoor environments. These sampling sites were selected to reflect a diversity of conditions, including differences in room size, ventilation systems, occupant activities, and potential infiltration from outdoor sources.

Measurement Campaigns

Rolling sampling method which consisted of 4 weeks of measurement activities were conducted at four corresponding sampling sites. The measurement activities were rolled out on 1 – 25 July 2024 in a warm period. Daily measurement for BC mass concentration, meteorological conditions, and room observations were conducted in shifts from site to site every 1.5 hours by single personnel. The daily measurement durations were 7-hours (09.00 AM – 16.00 PM) and pollutant concentration were collected at 1-minute measurement interval.

Measurement Instruments and Calibrations

Several high-time-resolution measurement instruments for BC and meteorological data were put in housing platform which has been fixed at each indoor microenvironment prior to daily monitoring activities. The measurement inlet was 150 cm above ground (breathing height of average Asian adults). All instruments have been calibrated according to their factory standards. The BC mass concentration (ng m^{-3}) was measured by utilizing portable Aethalometer (MicroAeth AE51). This instrument ment estimates the BC concentration through the light absorption principle. Briefly, BC was estimated by dividing the value of attenuated light intensity (I) with the amount of light intensity which is passing through the clean filter paper (I_0), as written in:

$$ATN = 100\, ln\, (I_0/I)$$

The estimated equivalent BC mass concentration value was then calculated by MicroAeth AE51 instrument by the infrared light attenuation at 880 nm wavelength. 1-minute interval of meteorological conditions data including relative humidity (RH) and temperature were obtained using IoT sensor instrument then collected via instrument's website.

Data Analysis

Descriptive statistic method was used to organize all collected data and visualize the measured BC mass concentration. Obtained data were dynamically averaged at 1-minute time resolution. In addition, I/O ratio analysis was used to measure infiltration indication in each location by using Eq. (1).

$$(1)\ Rasio_{I/O} = \frac{C_{in}}{C_{out}}$$

Where, C_{in} = Indoor BC concentration; C_{out} = Outdoor BC concentration[10]

Initial exposure assessment was calculated, focused on quantifying inhaled and deposited BC at each sector. The assessment was emphasized for healthy adults and children who are more likely to spend most of their time in an educational environment. The respiratory parameters for adult and children subjects used to calculate the UFPs PNC exposure dose were adapted from other studies [11], [12], [13] and summarized in **Table 1**. The amounts of inhaled UFPS PNC dose were calculated by using Eq. (2) & Eq. (3) and total deposition dose was calculated by using Eq. (4). Figures and statistical analysis results were generated from OriginPro software (OriginLab, v2024b)

$$(2)\ Total\ inhaled\ volume\ (TIV)\ = TV\ \times BF\ \times 30$$

Where, TIV = Total Inhaled Volume in 30 min (cm^3); TV = Tidal Volume per breath (cm^3); BF = Breathing Frequency (breath/min)

$$(3)\ Inhaled\ Dose\ (ID)\ = \frac{1}{n}\sum_{i=1}^{n} x_i\ \times TIV$$

Where, ID = Inhaled Dose per 30 min (ng/30min); x_i = 30 min average BC concentration (ng/cm^3); n = Total sampling time.

$$(4)\ Total\ Deposited\ Dose\ (TDD)\ = \frac{1}{n}\sum_{i=1}^{n} ID_i\ \times TD$$

Where, TDD = Total Deposited Dose per 30 min (ng/30min); ID = Inhaled Dose (ng/30min); n = total sampling time; TD = Total Deposition Factor.

Table 1. Respiratory & Deposition Parameters for BC Exposure Dose Calculation

Subject Respitory Profile	**Subject Condition**	
	Adults	**Children**
BF - Breathing Frequency (breath/min)	16±8*	16±7**
TV - Tidal Volume per breath (liter)	0.5±0.1***	0.39±0.03**
Minute ventilation (VE) = Breathing Frequency x tidal volume (L.min-1)	8	6.24
Respitory Flowrate (L/s)	0.15*	0.25**
Duration (min)	30	60
Inhaled Volume Per Hour (Liter)	480	374.4
Inhaled Volume Per 30 mins (Liter)	240	187.2
BCs Deposition Factors		
Total Deposition (TD)	0.22****	0.24*****

*[13] **[11] ***[12] ****[14] *****[15]

3. Results and Discussion

This study focused on assessing BC concentration among different indoor microenvironments in university including cafeteria, gym, office, and classroom. The data were collected in an organized manner according to established procedures, and the collection process went smoothly without any significant obstacles. In this chapter, the measurement results will be presented in detail, with the analysis focusing on BC concentration and infiltration indication at each site. In addition, the potential exposure to pollutants in each microenvironment will be discussed through an initial exposure assessment.

BC Concentration

Initially, the overall concentration of BC throughout the whole measurement campaigns were varied between four corresponding sampling sites. The measurement results of Black Carbon (BC) concentrations in four locations (office room, classroom, cafeteria, gym) showed significant variations between research locations. Each location had a unique distribution pattern, indicating differences in pollution sources and environmental conditions that affect pollutant levels in each room. The results of BC concentration measurements at the study sites are presented in **Figure 1** which shows that the highest BC concentration was found in the gym (987 ng m^{-3}), followed by the office room (830 ng m^{-3}), cafeteria (599 ng m^{-3}), and the lowest in the classroom (548 ng m^{-3}). BC concentrations do not yet have specific standards issued by the WHO, but the WHO has provided general guidance in the 2021 updated document WHO Global Air Quality Guidelines which discusses practical statements on other PM types such as BC in Chapter 4 of the document.

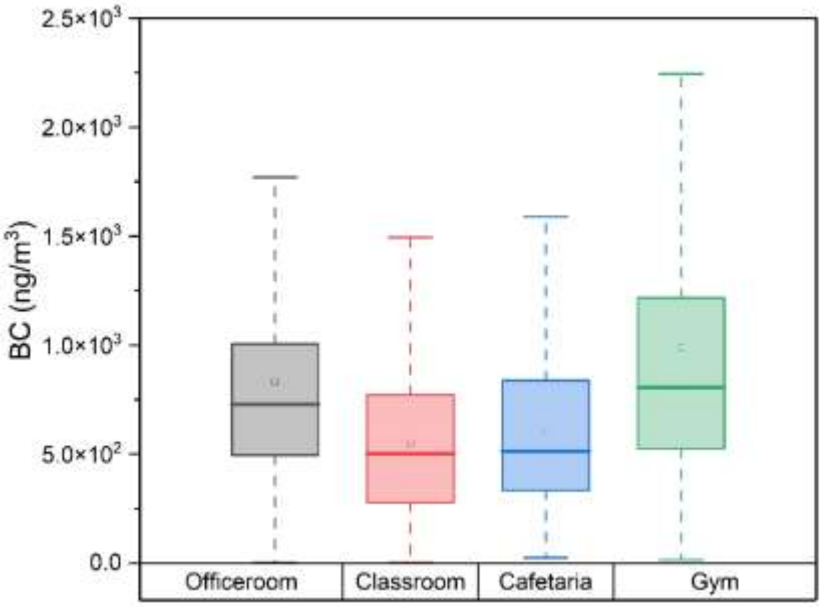

Figure 1. Distribution of average BC concentration

Based on WHO Global Air Quality Guidelines, it is suggested that in epidemiological studies BC ranges from 6.5×10^2 to 3.9×10^3 ng/m^3 and statistically has a relationship to health if it ranges from 1.08×10^3 to 1.15×10^3 ng/m^3. Based on this, the results of BC measurements in indoor microenvironments can be categorized into low concentrations [16]. Although the WHO through the GDG does not yet have quantitative guidance on UFPs and BC, it recognizes that these particles have negative health impacts, that reducing emissions will provide health and climate benefits, and that measurement and exposure assessment can be used as practical measures to assess impacts [16].

Room characteristics and ventilation systems also affect pollutant concentrations in the cafeteria, as in the findings of this study that exhaust fans were more effective in reducing BC concentration, resulting in lower BC concentrations in the cafeteria. And the semi-open room system also influenced reducing BC concentrations during cooking [17]. Meanwhile, the highest BC concentrations were in the gym, indicating high physical activity that causes particle resuspension and a limited ventilation system. Moreover, the friction of gym equipment during physical activity is also expected to increase BC concentrations in this location.

Table 2. Summary of Average Pollutant Concentration Measurement Results

Measured Parameter	Office room	Classroom	Cafetaria	Gym
BC (ng m^{-3})	830	548	599	987
Temperature (°C)	22	24	27	26
Relative Humidity (%)	61	72	75	74

Figure 2 shows the average variation of black carbon in one week (Monday-Thursday). The results show no significant fluctuations in the concentration of each pollutant on each day. This is because during the sampling period, the activities that occurred at the four indoor locations were normal and did not have a significant increase in activity intensity during weekday room operations. In **Figure 2**, it can also be found that the office room and cafeteria have the highest fluctuation rate, indicating that in these locations the intensity of activity changes from the location with the highest pollutant level to the same as the pollutant level in other locations.

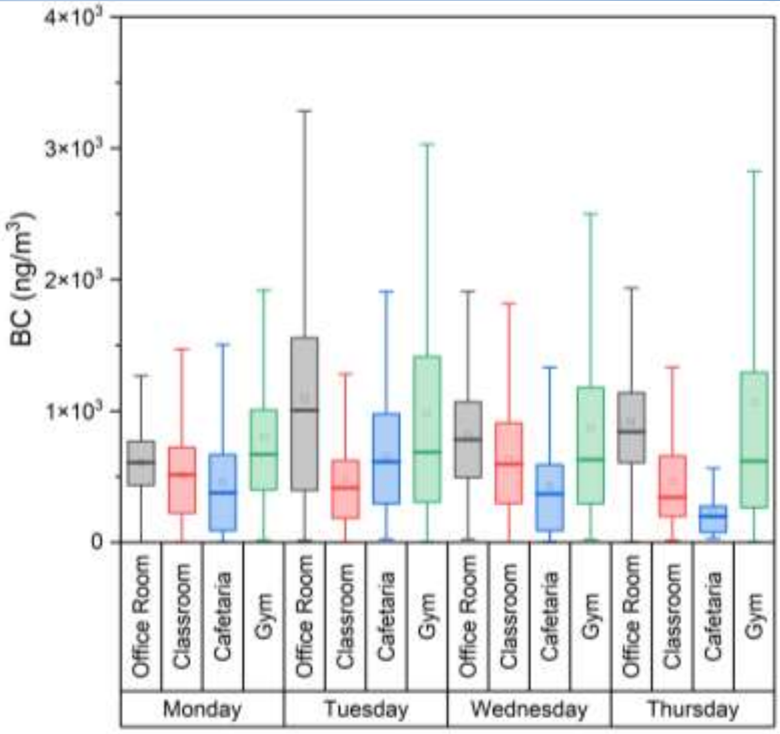

Figure 2. Weekly variation distribution of average BC concentration

Infiltration Factor via I/O Ratio

Indications of infiltration based on the I/O ratio for black carbon in the gym have the highest BC I/O ratio value with a value of 1.11 which indicates that the gym has its own BC source in the room, followed by the office room, classroom, and cafeteria with values of 0.98, 0.73, and 0.56, respectively. In the gym, the minimum ventilation rate makes the black carbon concentration accumulate in the room for a long time, thus increasing the concentration [18]. BC concentrations in the indoor environment are influenced by outdoor sources and indoor activities. Studies have found I/O ratios for BC ranging from 0.35 to 0.79 in residential environments [19]. In classrooms, the I/O ratio for BC was observed to be 0.56, which is relatively similar to a South Korean study of 0.68 [3]. Proximity to the highway also affected indoor BC concentrations, with classrooms closer to the highway having higher levels during peak hours [3].

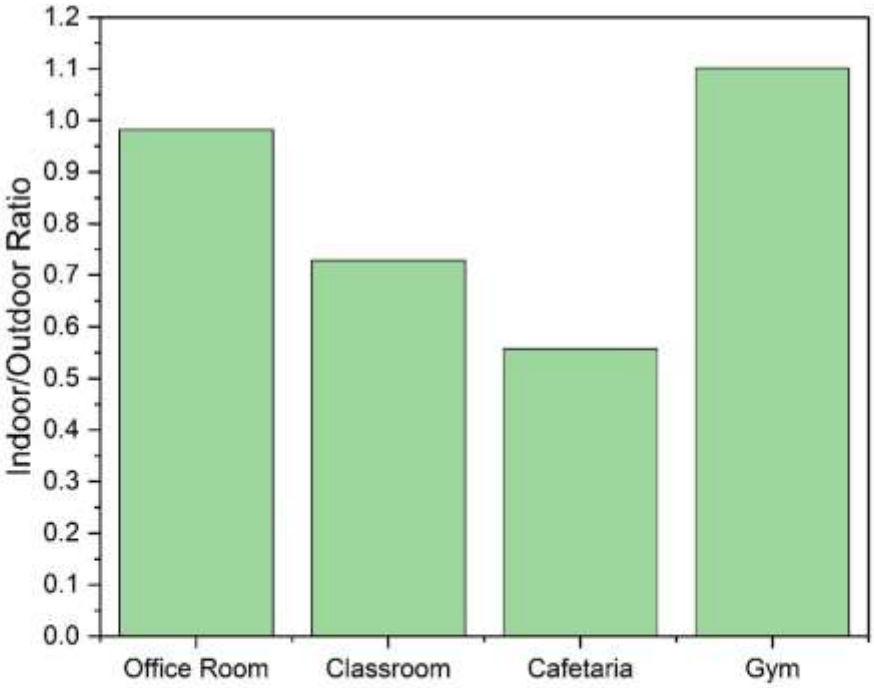

Figure 3. I/O Ratio for infiltration indication

Initial Exposure Assessment

The amount of black carbon (BC) inhaled and deposited in adults and children is proportional to the BC concentration at the corresponding location. In this study, it was found that adults inhaled and deposited more BC compared to children. For example, in the gym, the average inhaled BC per 30 minutes during the measurement period was 2.2×10^2 ng for adults and 1.7×10^2 ng for children. The BC deposition dose also varied among the four sectors studied, with the highest results recorded in the gym, at 48.64 ng/30 min for adults and 41.42 ng/30 min for children. This difference could be attributed to the higher respiratory capacity per minute and tidal volume in adults, who inhale more air and pollutants than children [11], [12]. On the other hand, this difference also reflects the physiological characteristics of the respiratory systems of children and adults, where deposition rates in children are lower for BC than in adults.

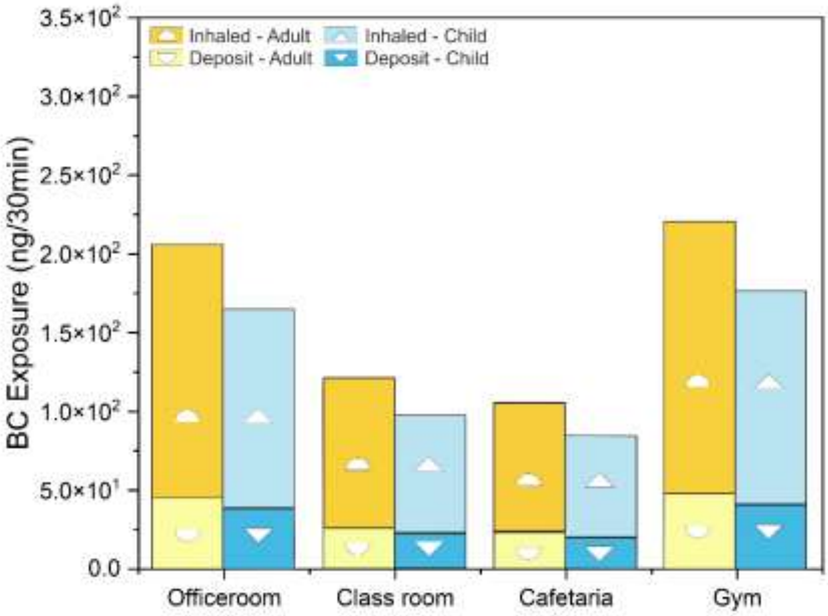

Figure 4. Total BC Exposure

4. Conclusion

This study revealed significant variations in black carbon (BC) concentrations across different indoor microenvironments within the university. The gym exhibited the highest BC concentration (987 ng m^{-3}), followed by the office room (830 ng m^{-3}), cafeteria (599 ng m^{-3}), and classroom (548 ng m^{-3}). Weekly concentration fluctuations indicated stable patterns, reflecting consistent daily activities in these environments. The gym also demonstrated the highest indoor/outdoor (I/O) ratio for BC (1.11), suggesting the presence of significant indoor sources of BC. This was followed by the office room (0.98), classroom (0.73), and cafeteria (0.56). These findings highlight the varying contributions of indoor and outdoor sources to BC levels in each location. Exposure levels were found to be proportional to BC concentrations at each site, with distinct differences in inhalation and deposition capacities between adults and children. Adults generally experienced higher BC inhalation and deposition rates compared to children, emphasizing the importance of evaluating both concentration levels and physiological factors when assessing health risks associated with BC exposure in indoor environments.

5. Acknowledgment

The authors would like to express their gratitude to Professor Sheng-Jie You and Professor Ya-Fen Wang for their guidance and support as advisors for this research at the Circular Society Laboratory, Chung Yuan Christian University, which facilitated and directed this study.

6. Abbreviations

BC	Black carbon
I/O	Indoor per outdoor
Ng/m3	Nano gram per cubic meter
WHO	World Health Organization
GDG	Guideline Development Group

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