Environmental Challenges 17 (2024) 101046

Contents lists available at ScienceDirect

Environmental Challenges

journal homepage: www.elsevier.com/locate/envc

# Personal Exposure to Black Carbon: Impact of Time-Activity Patterns and Environmental Factors on Exposure Levels

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A R T I C L E I N F O

*Keywords:*
Black carbon
Personal exposure
Inhaled dose
Time-activity patterns
Wildfire smoke

A B S T R A C T

Black carbon (BC) is a critical environmental pollutant with significant implications for human health. This study aims to quantify personal exposure to BC by focusing on the influence of microenvironments and time-activity patterns in the Rio Grande Valley (RGV) region of South Texas, USA. Over eight days in March and April 2023, a portable aethalometer and GPS tracking instruments were used to measure BC exposure among a study participant, alongside recording the time spent in various microenvironments. The BC measurements were correlated to the time activity patterns to calculate BC inhaled dosage values thereby elucidating its impact on human health. The mean values for different hours ranged from the lowest,0.26 μg/m$^3$ ± 0.29 at 02:00, to the highest, 1.07 μg/m$^3$ ± 1.40 at 17:00. The study also identified peak BC levels in areas near major roadways and airports. Outdoor activities accounted for 31% - 33% of the BC inhaled dosage on weekends, which was much higher than the 0.10% - 1.42% contribution observed on weekdays. The results also reflect a negative impact of Mexican wildfire activities on black carbon in this border region. This research provides insights into one of the first black carbon measurement studies conducted in the South Texas, U.S.– Tamaulipas State, Mexico border region.

## 1. Introduction

Black carbon (BC), a light-absorbing fraction of fine particulate matter ($PM_{2.5}$), is primarily produced by the incomplete combustion of fossil fuels, biomass, and other organic materials (Lei et al., 2016; Coppola et al., 2022). Often referred as soot, BC has the dual ability to absorb and scatter solar radiation, contributing significantly to atmospheric warming and the acceleration of the ablation of glaciers by reducing the surface albedo of snow and ice surfaces (Ramanathan & Carmichael, 2008; Tiwari et al. 2021; Wang et al., 2023). With an atmospheric lifetime of 4-12 days, BC is the second largest anthropogenic contributor to global warming, following carbon dioxide (Bond et al., 2013; Cape et al., 2012).

The health and environmental impacts of BC are profound and multifaceted. Being part of $PM_{2.5}$, the properties like the large surface-carrying capacity of toxic compounds (Henri Hakkarainen et al., 2022) and inflammation-inducing ability (Niranjan & Thakur, 2017) are closely linked to adverse health effects (Lei et al., 2016). Black carbon has also been proven to cause inflammation of the placental tissue, thereby leading to preterm birth, low birth weight, and pre-eclampsia (Goriainova et al., 2022). Out of 1,000 deaths caused by exposure to $PM_{2.5}$ globally, 35 were linked to BC (Chowdhury et al., 2022). 1,436, 957 premature deaths were attributed to BC exposure in China in the year 2013 alone (Wang et al., 2021). A study by Li et al., 2016 in the United States assessed the public health burden associated with black carbon and estimated that 13,910 deaths (0.6% of the total deaths) were attributed to ambient BC levels in 2010.

In developing regions, biofuels like firewood and agricultural residues are major sources of BC, while in industrialized countries, emissions are dominated by heavy-duty diesel vehicles (Rana et al., 2019; Brown-Steiner et al., 2016). In Latin America and the Caribbean, vehicular traffic, biomass burning from deforestation, and cooking are the primary sources (Blanco-Donado et al., 2022). Apart from deforestation and damage to ecosystems, wildfires emit greenhouse gases (GHGs) and aerosols, such as black carbon and organic carbon (Cruz Núñez et al., 2014; Liu et al., 2023) into the environment. The United States accounts for about 8 percent of global black carbon emissions, primarily from diesel engines, biomass burning (including wildfires),

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https://doi.org/10.1016/j.envc.2024.101046
Received 2 September 2024; Received in revised form 4 November 2024; Accepted 7 November 2024
Available online 9 November 2024

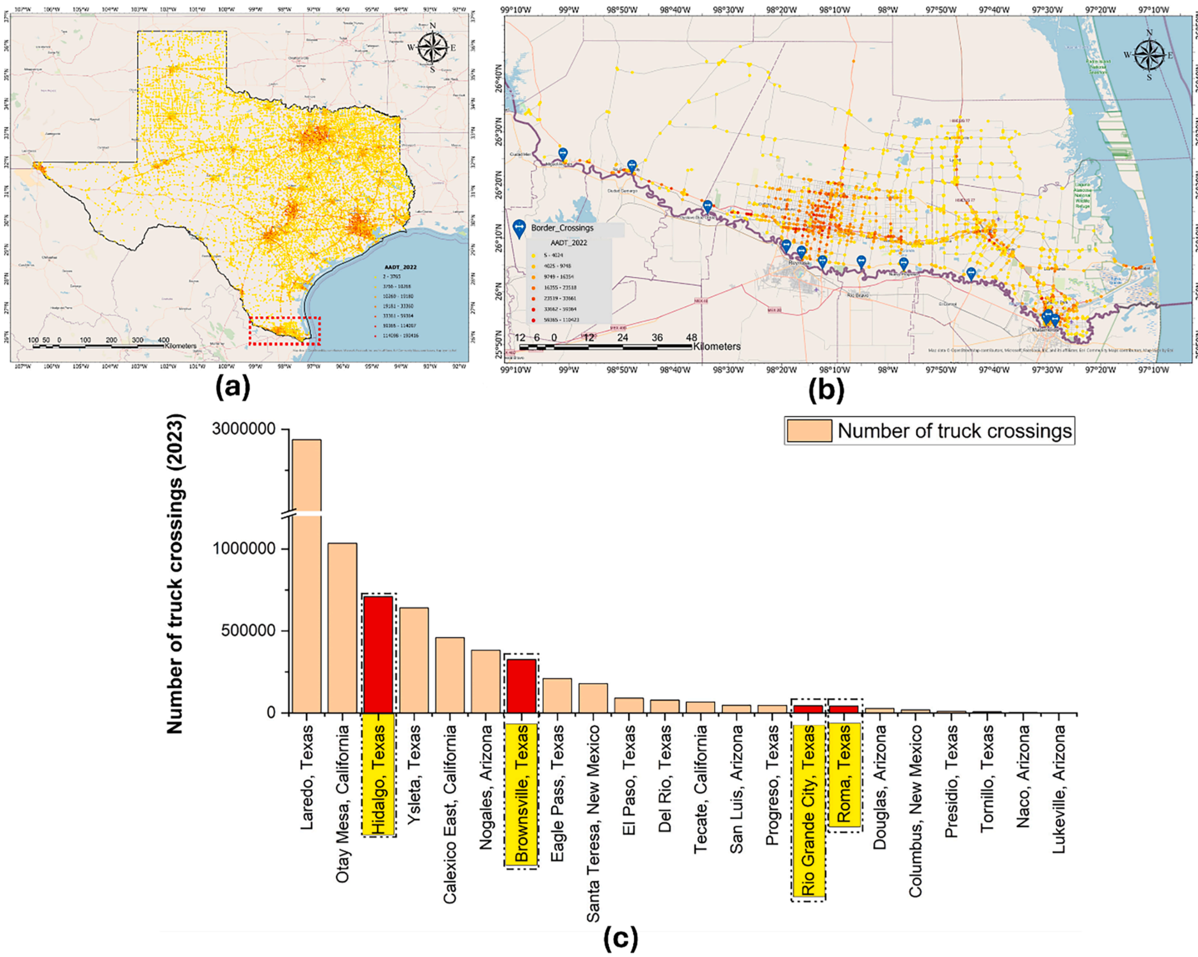


**Fig. 1. a** shows the AADT values for the state of Texas, while **Fig 1. b** shows the AADT for the RGV along with the ports of entry in the region. **Fig 1. c** shows the number of trucks that cross various ports of entry across the US-Mexico border, highlighting the ones through RGV.

and industrial activities (Cho, 2016). Wildfires in Mexico, which peak between February and May (NASA Earth Observatory, 2024), are another significant source of BC in the United States, with an average annual emission of 5955 Mg of BC from 2000 to 2012 (Cruz Núñez et al., 2014). Multiple studies have been conducted documenting the impact of biomass burnings in Central Mexico and their impact on air quality in the states of the U.S. (Bravo et al., 2002; Rios et al., 2023; Carabalí et al., 2021). However, to our knowledge, no studies have been conducted in the Rio Grande Valley region, which is impacted by smoke from the other side of the border.

Heavy-duty diesel vehicles (HDDVs) are significant sources of diesel particulate matter and nitrogen oxide emissions (Ruehl et al., 2021). BC is a major marker of diesel emissions (Song et al., 2012; Wu et al., 2022). At the US-Mexico border, the high passenger vehicular and commercial truck traffic and rigorous security inspections at the international ports of entry between the two countries results in long lines of idling vehicles on both sides, exacerbating these emissions (Olvera et al., 2013). For example, several studies have been conducted regarding air pollutant emissions near the ports of entry on the U.S-Mexico border. A study by Quintana et al., 2018 at the San Ysidro, California Port of Entry (SYPOE) between San Diego, California, USA, and Tijuana, Baja California, Mexico, documented that waiting in line at SYPOE accounts for approximately 62.5% of ultrafine particles exposure and 44.5% of exposure to black carbon while traveling northbound (from Mexico to the United States). Quintana et al., 2014 assessed the impact of San Ysidro Port of Entry's wait times on the air quality in the community. Their study findings showed that living near the border crossing might increase the exposure to traffic-related pollutants in the community. In contrast, Li et al., 2023 in their study at the U.S.–Mexico Bridge of the Americas (BOTA) port of entry between El Paso, Texas, USA, and Ciudad Juarez, Chihuahua, Mexico, documented that the traffic emissions did not result in elevated levels of air pollutant concentrations compared to the concentrations measured in the nearby residential community. Till date, no studies have been conducted in the Rio Grande Valley region of South Texas, which is home to 13 of the 28 international U.S.-Mexico border crossings in the state of Texas. (TABC, 2024). The bilateral commerce trading between these two countries results in cross-border heavy vehicular activities, including the Rio Grande Valley (RGV) region (Mendez et al., 2022). According to the Texas Department of Transportation (TxDOT), the mean Annual Average Daily Traffic (AADT) in the RGV surged from a median of 570 in 2003 to 6,667.5 in 2022 (TxDOT, 2023). Fig. 1. a shows the AADT values for Texas, and Fig. 1. b shows the AADT values for the RGV region. The ports of entry at Hidalgo and Brownsville are also one of the busiest across this border region (Fig. 1. c). 708726 trucks passed through the port of entry at Hidalgo, making it the busiest in the RGV region (Bureau of Transportation Statistics, 2024). The increase in AADT in this region in contrast to previous years underscores the critical need to study the associated environmental impacts on the community and the corresponding personal exposures.

This study is the first to measure personal exposure to BC in the RGV region. Data was collected over eight days between March and April 2023 to assess individual BC exposures. The primary aim of this study was threefold: (1) to analyze the spatial and temporal variations in

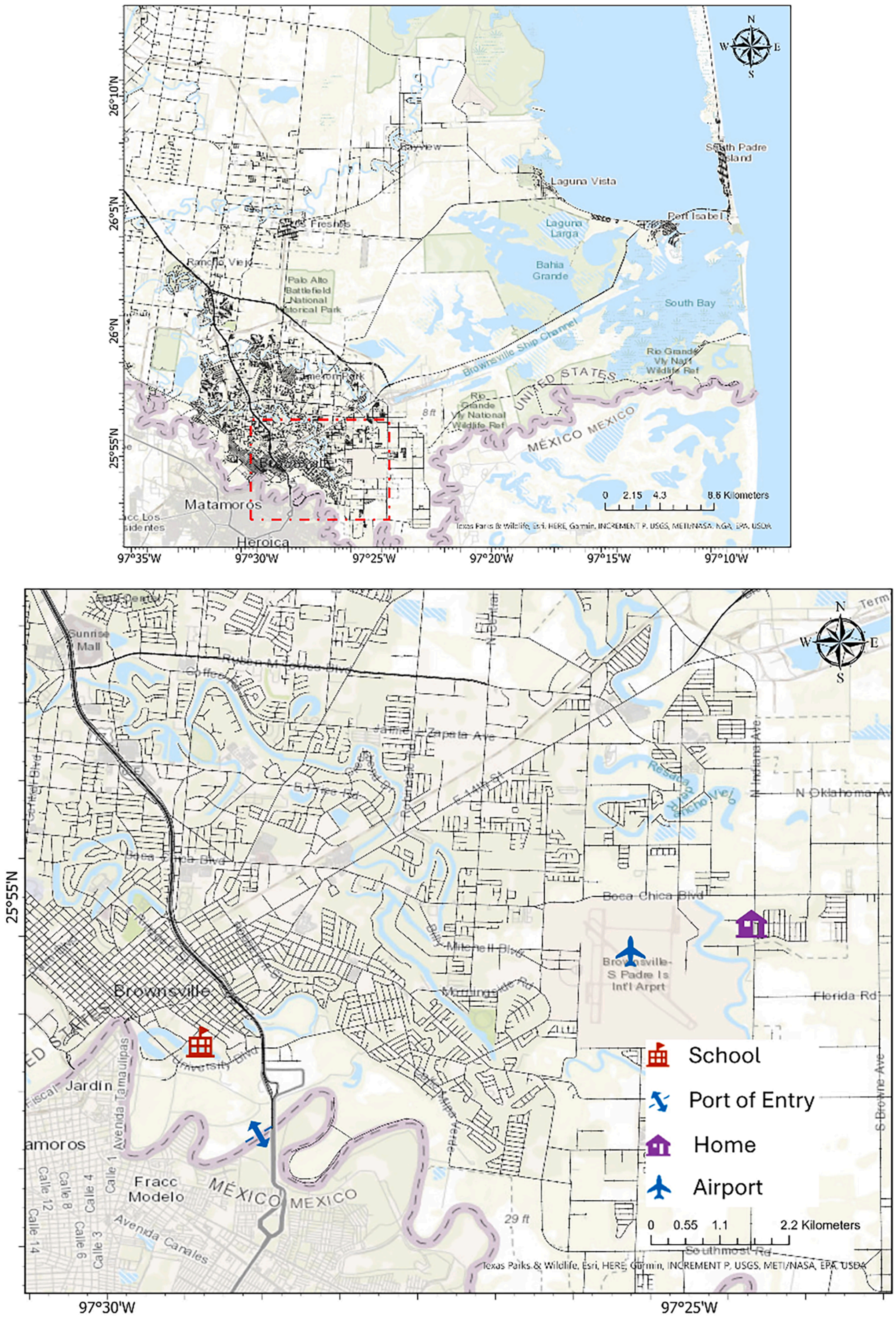


**Fig. 2.** Area of interest with the road network. Enlarged image showing the major points of interest in the study region.

personal exposures to BC, (2) to quantify the contributions of various microenvironments to BC exposure and inhaled dosage, and (3) to examine the sources influencing BC levels in the region.

## 2. Materials and Methods

### 2.1. Study area

The study was conducted in the lower Rio Grande Valley (RGV) region of Texas, mainly covering the cities of Brownsville and Port Isabel/ South Padre Islands from March 30, 2023 to April 7, 2023. Traffic emissions, diesel engine emissions, and industrial emissions are the

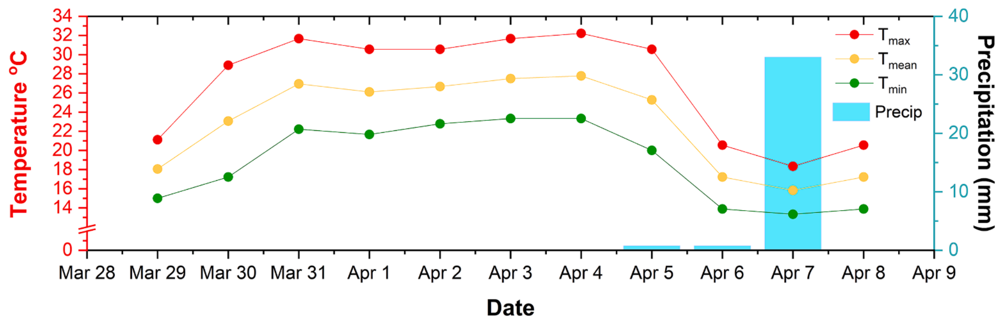


**Fig. 3.** Time series of Temperature and Precipitation in the region

major sources of particulate matter (PM) in this area (Karnae & John, 2019). PM basically comprises of a mixture of solid particles and liquid droplets in air and comes in many sizes and shapes. For example, particles with diameters less than 10 micrometers and smaller are classified as $PM_{10}$, whereas particles with diameters 2.5 micrometers and less are called $PM_{2.5}$ (USEPA, 2024). BC is typically a component of $PM_{2.5}$. The study was mainly focused on Brownsville city, and the main points of interest are illustrated in Fig. 2.

### 2.2. Meteorological Conditions

Summers in this region are hot and humid, with average daily temperatures exceeding 32.2°C, while winters rarely see temperatures drop below freezing, and snowfall is infrequent (Pinakana et al., 2023). The dominant wind directions are south and southeastern. The meteorological data for Brownsville city was collected from the National Weather Service (NWS) (National Weather Service, 2023). During the study period, temperatures in the region experienced a noticeable fluctuation, with maximum daily temperatures ranging from 18.3°C to 32°C, and minimum temperatures between 13.3°C and 23.3°C as shown in Fig. 3. The average daily temperature fluctuated from 15.8°C to 27°C. While the first seven days observed no precipitation, there was a sharp increase in rainfall starting on April 5, with a notable peak of 33.02 mm on April 7.

### 2.3. Study Design and Instrumentation

The study participant, an undergraduate Hispanic/Latino male student in his early twenties was recruited to participate in this study. He attended classes at the University of Texas Rio Grande Valley (UTRGV) Brownsville campus, which is located 1.2 kilometers from the nearest port of entry and 0.8 kilometers from the Interstate 69E Highway. He also traveled to Port Isabel/South Padre Islands often for leisure, and other entertainment activities. South Padre Islands is a major tourist hotspot in this region with beautiful beaches and a vibrant nightlife. The study participant's home in Brownsville was located 0.72 kilometers from the Brownsville/South Padre Island International Airport (BRO) and 7.58 kilometers from the Brownsville/Veterans-Los Tomates International Port of Entry.

The study participant was instructed on how to use the device and was explained the important objectives of the study. The participant was also instructed to record his daily activities and time. A portable aethalometer microAeth® AE51 (AethLabs, San Francisco, CA, USA) was used to assess personal BC exposures. This instrument has been used in several studies, including Quang et al., 2022 in Vietnam, Uzun et al., 2022 in Turkey, Williams & Knibbs, 2016 in Brisbane, Australia, and Lin et al., 2020 in Beijing, China, to measure individuals' exposure to BC. The instrument collects aerosol samples using T60 (Teflon-coated borosilicate glass fiber filter material) at an optical wavelength of 880 nm, which represents Black Carbon. The measurement time base was set at 60 seconds. One of the study's objectives was to analyze the influence of the surrounding environment on BC exposure levels. However, as the portable aethalometer did not have an inbuilt GPS, QStarz (BT-Q1000XT, Qstarz International Co, Taipei, Taiwan), a real-time GPS tracker was used simultaneously. This device was used predominantly for studies that tracked the location of participants in the study (Breen et al., 2014; Koehler et al., 2019). The participant was instructed to carry the GPS instrument and the portable aethalometer to record both the location, and the BC levels, simultaneously. Personal measurements included all daily activities related to transportation, home, university, and outdoor activities.

**Table 1**
Different microenvironments and respective inhalation rates ($m^3/h$) for the age group 19 – 40 years

| Activities | Inhalation rate (Age group 19 – 40 years) |
|---|---|
| Sleeping | 0.36 |
| School | 0.45 |
| Sedentary Activities | 0.45 |
| Transport | 0.60 |
| Outdoor Environments | 0.94 |

### 2.4. Correcting loading effects of Aethalometer data

The data obtained from the aethalometer necessitates substantial post-processing for accurate analysis (Apte et al., 2011). The percent attenuation (ATN) derived by the aethalometer relies on both scattering and absorption of light by the sample that builds up on the filter matrix. Various studies have concluded that with the increased filter loading, i.e., the ATN value, BC concentration is underestimated, and it is crucial to adjust the filter loading accurately when assessing personal exposure to black carbon using an Aethalometer (Good et al., 2016; Jimenez et al., 2007).

Hence, a procedure to correct the loading effects of aethalometer data proposed by Aki Virkkula et al., 2007 was followed in this study. The formula is as follows:

$$BC_{corrected} = (1 + k \cdot TN) \cdot BC_{noncorrected}$$

where ATN is the attenuation, and BC is the black carbon value recorded by the aethalometer.

### 2.5. Contribution of microenvironments to time, daily personal exposures, and inhaled dose

The participant's activity records were manually checked and compared with GPS data to prevent errors in classifying microenvironments. Additionally, the roadway inventory from TxDOT (Texas Department of Transportation, 2020) was utilized to accurately categorize the black carbon data from the transport microenvironment within the entire dataset. The data was then classified into the following: a) Sleeping, i.e., time spent at home for this activity; b) Sedentary activities, i.e., time spent at home other than sleeping time; c) School, i.e.,

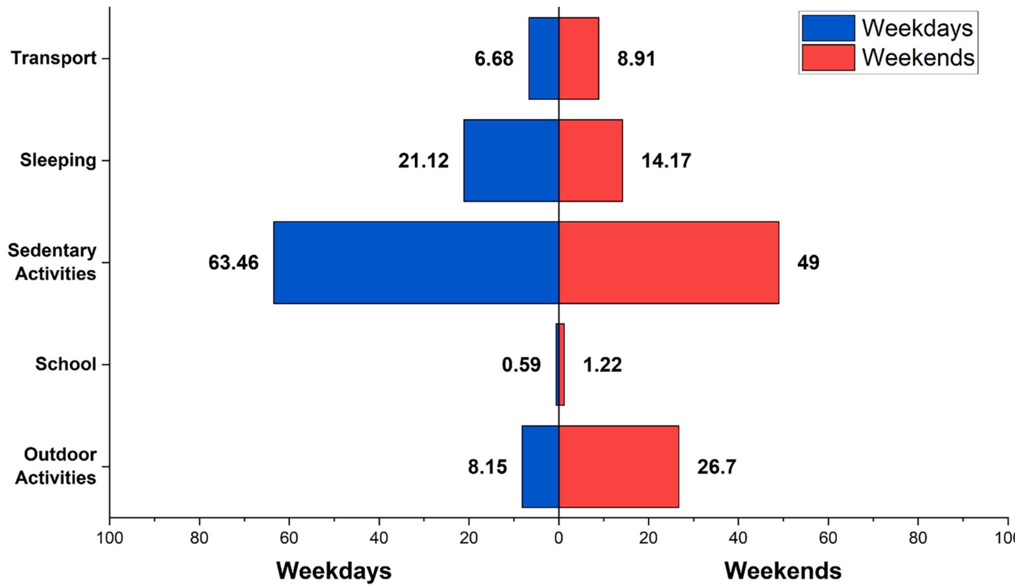


**Fig. 4.** Percentage of time spent in each microenvironment on weekdays and weekends.

time spent at school; d) Transport, i.e., time spent traveling and e) Outdoor activities, i.e., all the activities in outdoor microenvironments other than traveling.

The inhalation rate values for the age group 19-40 from Buonanno et al., 2011 were used in calculating the BC inhaled dosages, as shown in Table 1. BC exposure concentrations were calculated for various hours and days across multiple microenvironments to analyze their contributions to daily exposure levels. BC inhaled dose values (Eq. 1) and their contributions to daily dosage levels (Eq. 2) were also calculated using the following (Cunha-Lopes et al., 2019; Uzun et al., 2022):

$$\text{BC inhaled dose} = \sum_{j=1}^{m} C_{ij} * t_{ij} * IR_{ij} \tag{1}$$

$$\text{BC exposure contribution} = \frac{\left(C_{ij} * t_{ij}\right)}{\left(\sum_{j=1}^{m} C_{ij} * t_{ij}\right)} \tag{2}$$

where,

- $C_{ij}$ – Arithmetic mean of BC concentration in the microenvironment ($j$) exposed by personal ($i$) (μg/m$^3$)
- $t_{ij}$ – Time spent by personal ($i$) in microenvironment/activity, ($j$) (hours)
- $m$ – Total number of microenvironments, $\sum_{j=1}^{m} t_{ij} = 24$ h
- $IR$ - the inhalation rate (m$^3$/h)

### 2.6. Statistical Analysis

For the final analysis, we considered the days with at least 70% data completeness. Hourly, daily, and descriptive data statistics were performed using Microsoft Excel (v.16.06, Microsoft Inc., Redmond, WA, USA). The spatial maps were generated using ArcGIS pro v3.2 (Esri, USA). Differences in BC concentrations on different hours, days, and microenvironments were compared using the Kruskal-Wallis (K-W) ANOVA, a nonparametric test. A p-value $< 0.05$ was considered statistically significant. Cluster analysis is a useful multivariate method to find grouping patterns of pollutants; therefore, a Hierarchical Cluster Analysis was conducted, and results were visualized as a dendrogram. Origin Pro (Origin Lab Corporation, Northampton, MA, USA; Version 2024) was used to plot the graphs and perform all statistical analysis on the collected data.

**Table 2**
Descriptive statistics of BC personal exposure values during the study period

| Day | Data Completeness | Mean ± SD | Minimum | Median | Maximum |
|---|---|---|---|---|---|
| **30-March** | 72.08 % | 0.60 ± 2.07 | 0.003 | 0.33 | 60.56 |
| **31-March** | 98.94 % | 0.47 ± 1.11 | 0.001 | 0.25 | 17.32 |
| **01-April** | 100 % | 0.74 ± 1.66 | 0.001 | 0.26 | 28.81 |
| **02-April** | 100 % | 1.01± 2.35 | 0.001 | 0.56 | 36.00 |
| **03-April** | 100 % | 0.54 ± 0.48 | 0.006 | 0.45 | 8.02 |
| **04-April** | 75.08 % | 0.49 ± 0.37 | 0.003 | 0.45 | 1.91 |
| **05-April** | 99.72 % | 0.50 ± 0.35 | 0.001 | 0.44 | 1.85 |
| **06-April** | 99.69 % | 0.29 ± 0.31 | 0.003 | 0.20 | 3.88 |

## 3. Results

### 3.1. Time-activity patterns

Daily time-activity patterns were collected from the participant's daily log, and GPS data was used to minimize misclassifications. Fig. 4 illustrates the breakdown of time spent in each microenvironment on weekends and weekdays. The data shows notable differences in time activity patterns between weekdays and weekends. Most of the time (63.46%) on weekdays was spent on sedentary activities, while sleeping accounted for 21.12%. On weekends, outdoor activities significantly increased, rising to 26.7% of the time, indicating more leisure or recreational activities. The percentage of time spent sleeping decreased to 14.17% during the weekends, indicating that the study participant was more active during this time.

A major portion of the time, 85.17%, was spent indoors during the weekdays, compared to the amount spent outdoors on weekends, 64.39%. In summary, weekends involved more outdoor activities, and less time spent on sedentary tasks and sleep compared to weekdays, indicating a shift towards more active and diverse routines during weekends. The patterns observed in this study were similar to previous studies and surveys, where Thorp et al., 2012 found that participants

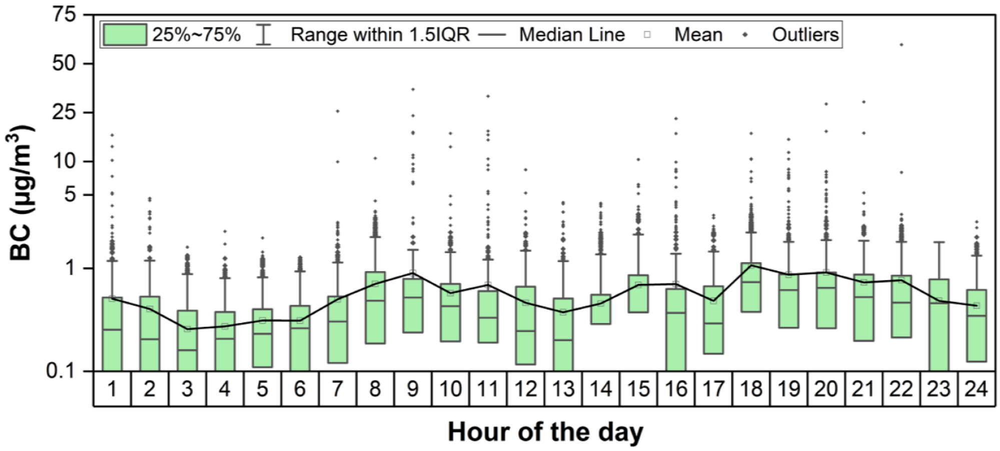


**Fig. 5.** Box plots for BC values measured at different hours of the days during study period.

**Table 3**
Descriptive statistics of BC personal exposure values during different hours of the day for the whole study period

| Hour of the day | Mean± SD | Minimum | Median | Maximum |
|---|---|---|---|---|
| **00:00** | 0.51 ± 1.30 | 0.003 | 0.25 | 16.75 |
| **01:00** | 0.40 ± 0.60 | 0.003 | 0.20 | 4.62 |
| **02:00** | 0.26 ± 0.29 | 0.003 | 0.16 | 1.60 |
| **03:00** | 0.27 ± 0.27 | 0.003 | 0.20 | 2.26 |
| **04:00** | 0.31 ± 0.30 | 0.001 | 0.23 | 1.95 |
| **05:00** | 0.31 ± 0.27 | 0.001 | 0.26 | 1.26 |
| **06:00** | 0.50 ± 1.37 | 0.006 | 0.30 | 25.63 |
| **07:00** | 0.71 ± 0.81 | 0.022 | 0.48 | 10.68 |
| **08:00** | 0.90 ± 2.50 | 0.012 | 0.52 | 36.00 |
| **09:00** | 0.58 ± 1.09 | 0.001 | 0.43 | 17.31 |
| **10:00** | 0.69 ± 2.14 | 0.002 | 0.33 | 32.56 |
| **11:00** | 0.46 ± 0.65 | 0.009 | 0.24 | 8.47 |
| **12:00** | 0.38 ± 0.54 | 0.007 | 0.20 | 4.24 |
| **13:00** | 0.46 ± 0.66 | 0.004 | 0.28 | 4.17 |
| **14:00** | 0.69 ± 1.11 | 0.004 | 0.37 | 10.44 |
| **15:00** | 0.70 ± 1.73 | 0.001 | 0.36 | 22.58 |
| **16:00** | 0.48 ± 0.53 | 0.003 | 0.29 | 3.22 |
| **17:00** | 1.07 ± 1.40 | 0.057 | 0.73 | 17.32 |
| **18:00** | 0.87 ± 1.46 | 0.006 | 0.61 | 15.44 |
| **19:00** | 0.91 ± 1.85 | 0.005 | 0.64 | 28.81 |
| **20:00** | 0.73 ± 1.68 | 0.006 | 0.52 | 29.80 |
| **21:00** | 0.77 ± 2.82 | 0.003 | 0.46 | 60.56 |
| **22:00** | 0.48 ± 0.42 | 0.005 | 0.46 | 1.78 |
| **23:00** | 0.44 ± 0.42 | 0.010 | 0.34 | 2.79 |

spent 10.7 hours in sedentary activities on workdays. On non-workdays, such as weekends, they spent 8.6 hours being sedentary. The American Time Use Survey, 2023, also reported an increase in leisure and sports activities on weekends compared to weekdays.

### 3.2. *Temporal and Spatial Characteristics of BC Exposure*

The recorded BC exposure concentrations varied both temporally and spatially. The daily descriptive statistics are summarized in Table 2. The highest daily mean BC concentration of 1.01 μg/m³ was observed on April 2, while the lowest mean of 0.29 μg/m³ was observed on April 6. The range of black carbon exposure values also varied widely, with maximum levels reaching up to 60.56 μg/m³ on March 30 and dropping to 3.88 μg/m³ on April 6. It is crucial to understand the exposure patterns during different hours of the day. Fig. 5 visualizes the box plots of BC personal exposure values for each hour, offering insights into the hourly fluctuations. The outliers, which were data points falling beyond 1.5 times the interquartile range (IQR) of the data, were also shown to characterize the peak values at different hours. Descriptive statistics for each hour are summarized in Table 3.

The values in different hours were found to be significantly different from each other ($p$-value $<$ 0.05). The mean values range from the lowest of 0.26 ± 0.29 μg/m³ at 02:00 to the highest of 1.07 ± 1.40 μg/m³ at 17:00. The data presents a clear pattern of fluctuations in BC concentrations, which are closely tied to vehicular and industrial activities. The outdoor movement of the participant during rush hours increased the BC exposure levels to these activities. The lowest concentrations occurred during the early morning hours, 02:00 to 05:00 when the daily activities were minimal. Conversely, the higher concentrations mainly were observed during the morning hours of 07:00 to 09:00 and evening hours of 17:00 to 19:00, corresponding with peak traffic times and high industrial activities. Multiple studies have explained a similar increase in BC exposure levels. Cunha-Lopes et al. (2019) concluded that BC concentrations from 00:00 to 07:30 were constant and low, associated primarily with low traffic emissions. Krecl et al., 2016 Targino et al., 2017a and Bista et al., 2022 also highlighted the increase of BC concentrations during peak rush hours, especially in the morning and evening time periods.

The spatial map of BC concentrations during the study period is shown in Fig. 6. Green indicates less BC exposure, while red indicates a high BC exposure. The maps show that the higher BC exposure values are mostly recorded on roads while transporting and at the participant's residence. The roadway where some of the highest BC concentrations were recorded is 0.19 kilometers from the BRO Airport. The recordings were as high as 8.16 μg/m³. High values of up to 32.56 μg/m³ were also recorded at the participant's residence, only 0.72 km from the airport. This implies there might be a negative impact on the local air quality, especially black carbon, primarily due to airport activities and/or associated road traffic. A vast amount of research has been conducted on the impact of the aviation industry on air quality worldwide (Bajgai & Shrestha, 2023; Trebs et al., 2023; Xu et al., 2023; Bendtsen et al., 2021; Riley et al., 2021; Hudda et al., 2020; Lammers et al., 2020; Zhang et al., 2020; Targino et al., 2017b; Zhu et al., 2011; Westerdahl et al., 2008; Carslaw et al., 2012) also corroborates our research results. Hudda et al., 2020 found that black carbon levels were 1.3 times higher during winds coming from the impact sector compared to winds from the non-impact sector at a residence located 1.3 kilometers from the airport in 2017. Another study by Westerdahl et al., 2008 recorded elevated BC at take-off downwind of LAX - Los Angeles International Airport, CA.

### 3.3. *Microenvironment contribution in daily and hourly BC exposures*

As illustrated in Fig. 7, measurements were collected in several microenvironments during the whole study period. The mean concentrations of BC ranged from 0.11 ± 0.12 μg/m³ to 2.17 ± 0.30 μg/m³, with the highest levels observed during sedentary activities at 06:00 and the lowest while driving at 16:00. Maximum BC concentrations vary

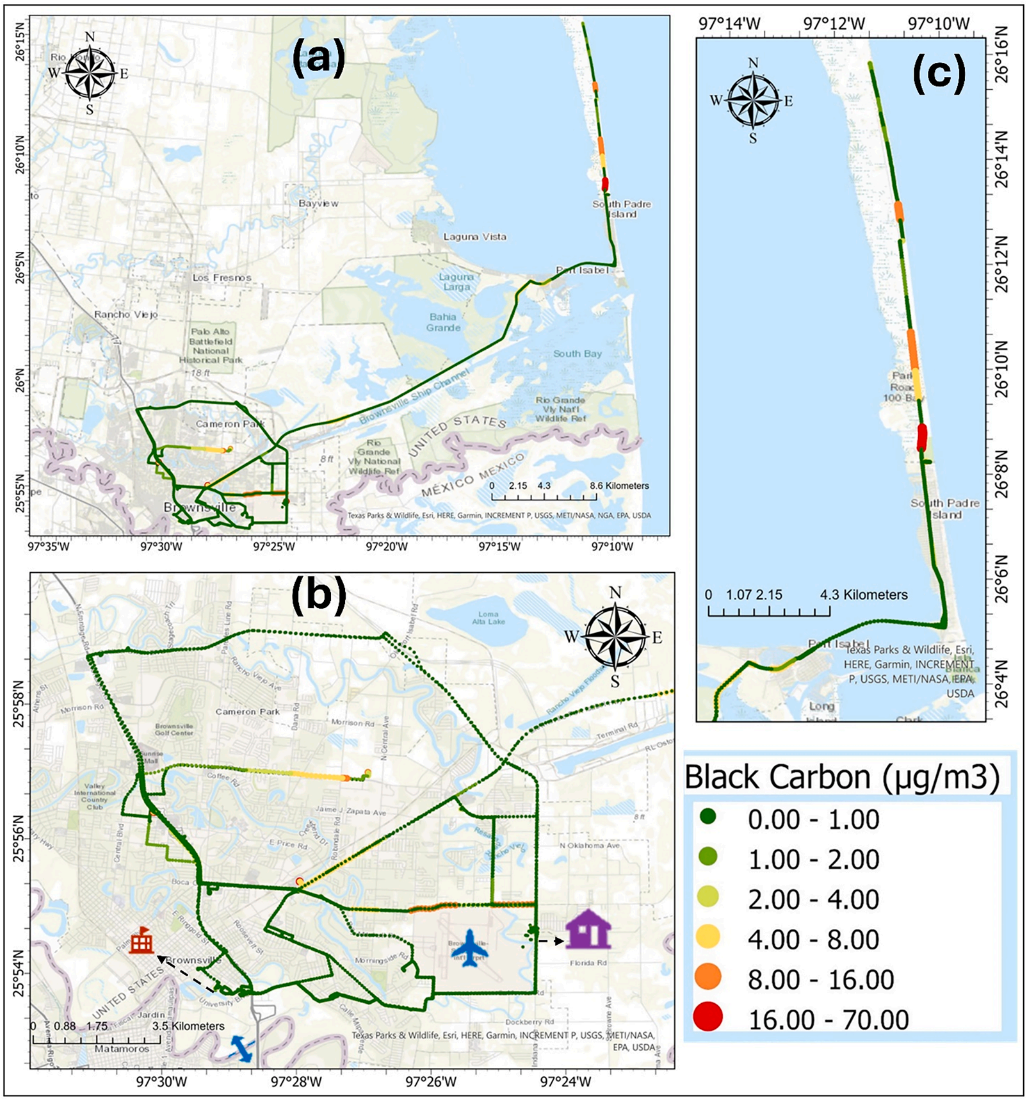


**Fig. 6.** Spatial variation in measured BC values (a) across the study period (b) enlarged version highlighting Brownsville area (c) enlarged version highlighting South Padre Island area

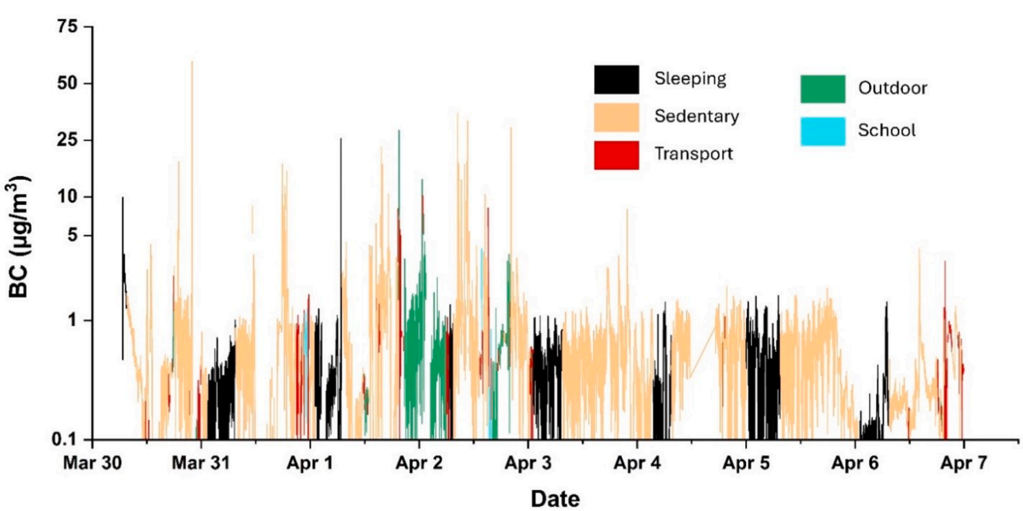


**Fig. 7.** BC time series for the measured values, with multiple colors indicating different microenvironments.

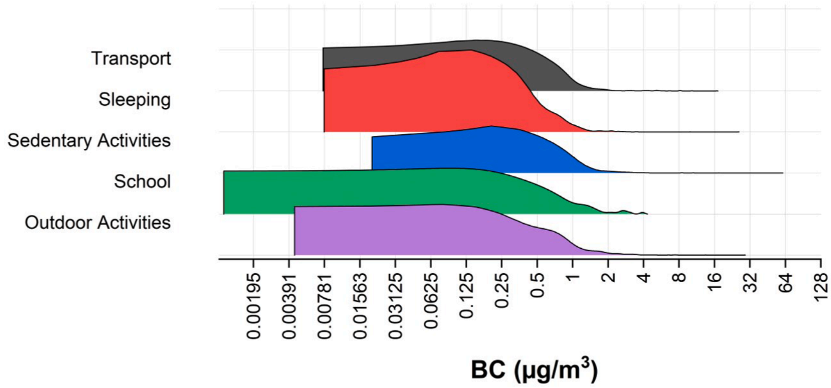


**Fig. 8.** Ridgeline charts of black carbon concentration (μg/m$^3$) by microenvironment.

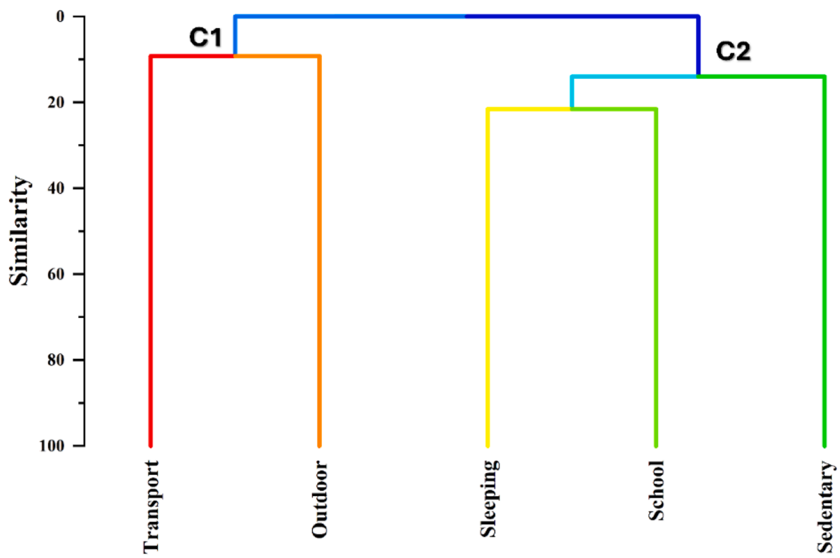


**Fig. 9.** Dendrogram of microenvironments' impact on BC exposure measurements.

significantly, from 0.28 μg/m$^3$ to 60.57 μg/m$^3$, with the highest spike occurring during sedentary activities at 21:00. Minimum BC levels were often recorded at 0.01 μg/m$^3$, indicating negligible exposure at certain hours across all microenvironments. Maximum values ranged from 0.52 μg/m$^3$ (recorded at 5:00 while traveling) to 60.56 μg/m$^3$ (sedentary activity at home). Fig. 8 shows the ridgeline charts of the BC personal exposures in the different microenvironments.

BC exposures during outdoor activities vary throughout the day. The mean concentrations range from 0.12 ± 0.21 μg/m$^3$ to 1.58 ± 3.66 μg/m$^3$, with notable increases in the evening. The maximum recorded values suggest that engaging in outdoor activities during specific hours may increase the risk of exposure to BC, for example, reaching 28.82 μg/m$^3$ at 19:00 . The sharp fluctuations at 01:00 and between 06:00 - 08:00 demonstrate the impact of rush hour traffic on BC exposure levels. When the daily trends were observed, it was noted that the mean values of BC during outdoor activities on the weekend days of April 1 and 2 were slightly higher than on weekdays, with values of 0.67 ± 1.94 μg/m$^3$ and 0.55 ± 0.94 μg/m$^3$, respectively.

Findings from our study mirror similar studies, including Koehler et al., 2019 study, which showed that mean personal exposures during transit and at eateries tended to be higher than exposures at home. Fig. 9 shows the variations of BC exposure values using a dendrogram, highlighting the source similarity of BC during indoor activities. While the transport and outdoor activities were classified into one cluster, indoor activities were classified into another.

The descriptive statistics of personal BC concentrations in different microenvironments during the measurement campaign are shown in Table 4, offering a comprehensive overview of black carbon concentration fluctuations across various microenvironments and times of day. The amount of data in the school environment is relatively less compared to other microenvironments. They were recorded for 13:00, 15:00, and 16:00, reflecting the study participant's school schedule. While the highest mean value of 1.42 ± 1.21 μg/m$^3$ was recorded at 13:00, the lowest value of 0.15 ± 0.21 μg/m$^3$ was recorded at 15:00. The school is located only 1.2 kilometers from the nearest port of entry and 0.8 kilometers from Interstate 69E Highway, which may contribute to the observed variability due to outdoor air infiltration in the indoor microenvironment. The mean values of BC exposures during sedentary activities ranged from 0.25 ± 0.24 μg/m$^3$ at midnight, a time of minimal human activity, to a peak of 2.17 ± 0.30 at 06:00. A sudden increase was observed in mean values from 17:00 to 21:00 hours, possibly due to traffic rush hours. During weekends, BC exposure levels increased compared to weekdays: 0.94 ± 1.65 μg/m$^3$ and 1.44 ± 3.08 μg/m$^3$.

BC concentrations displayed moderate variability during sleeping hours, with mean values ranging from 0.20 μg/m$^3$ to 0.72 μg/m$^3$. With no active source of BC in indoor environments during the sleeping hours, the standard deviation is also relatively low, ranging from 0.17 μg/m$^3$ to 0.37 μg/m$^3$, indicating more consistent exposure levels during these hours. The maximum value recorded at 6:00 was 25.63 μg/m$^3$ could be attributed to indoor sources. The daily averages indicate similar trends

**Table 4**
Descriptive statistics of BC concentrations in different hours of the day at microenvironments (μg/m$^3$)

| Hours | Outdoor activities | | | School | | | Sedentary Activities | | | Sleeping | | | Transport | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean ± SD | Min | Max | Mean ± SD | Min | Max | Mean ± SD | Min | Max | Mean ± SD | Min | Max | Mean ± SD | Min | Max |
| **00:00** | 1.11 ± 2.11 | 0.137 | 13.47 | - | - | - | 0.25 ± 0.24 | 0.003 | 1.09 | 0.66 ± 0.37 | 0.026 | 1.44 | 1.19 ± 3.16 | 0.079 | 16.76 |
| **01:00** | 1.16 ± 1.43 | 0.174 | 4.63 | - | - | - | 0.31 ± 0.32 | 0.003 | 1.19 | 0.31 ± 0.29 | 0.015 | 1.25 | 0.42 ± 0.11 | 0.20 | 0.57 |
| **02:00** | 0.16 ± 0.26 | 0.02 | 1.29 | - | - | - | 0.14 ± 0.12 | 0.003 | 0.48 | 0.30 ± 0.30 | 0.007 | 1.60 | - | - | - |
| **03:00** | 0.41 ± 0.40 | 0.026 | 2.27 | - | - | - | 0.72 ± 0.23 | 0.242 | 1.25 | 0.20 ± 0.17 | 0.003 | 0.83 | - | - | - |
| **04:00** | 0.41 ± 0.45 | 0.035 | 1.96 | - | - | - | - | - | - | 0.30 ± 0.27 | 0.001 | 1.32 | - | - | - |
| **05:00** | 0.38 ± 0.36 | 0.001 | 1.26 | - | - | - | - | - | - | 0.30 ± 0.25 | 0.003 | 1.20 | 0.52 ± 0.00 | 0.517 | 0.52 |
| **06:00** | 0.38 ± 0.34 | 0.516 | 0.63 | - | - | - | 2.17 ± 0.30 | 1.882 | 2.46 | 0.50 ± 1.43 | 0.006 | 25.63 | 0.42 ± 0.31 | 0.012 | 1.21 |
| **07:00** | - | - | - | - | - | - | 0.74 ± 0.89 | 0.056 | 10.69 | 0.66 ± 0.71 | 0.022 | 3.53 | - | - | - |
| **08:00** | - | - | - | - | - | - | 0.90 ± 2.50 | 0.012 | 36.01 | - | - | - | - | - | - |
| **09:00** | - | - | - | - | - | - | 0.58 ± 1.09 | 0.001 | 17.32 | - | - | - | - | - | - |
| **10:00** | - | - | - | - | - | - | 0.69 ± 2.14 | 0.002 | 32.56 | - | - | - | 0.29 | 0.291 | 0.29 |
| **11:00** | 0.17 ± 0.09 | 0.106 | 0.36 | - | - | - | 0.50 ± 0.68 | 0.009 | 8.47 | - | - | - | 0.18 ± 0.09 | 0.070 | 0.36 |
| **12:00** | 0.20 ± 0.04 | 0.109 | 0.28 | - | - | - | 0.41 ± 0.58 | 0.007 | 4.24 | - | - | - | 0.14 ± 0.08 | 0.026 | 0.28 |
| **13:00** | 0.59 ± 0.18 | 0.427 | 0.75 | 1.42 ± 1.21 | 0.353 | 3.91 | 0.42 ± 0.62 | 0.004 | 4.17 | - | - | - | 0.42 ± 0.22 | 0.245 | 0.83 |
| **14:00** | - | - | - | - | - | - | 0.70 ± 1.13 | 0.004 | 10.44 | - | - | - | 0.43 ± 0.52 | 0.324 | 1.73 |
| **15:00** | 0.14 ± 0.21 | 0.057 | 0.62 | 0.15 ± 0.21 | 0.057 | 0.85 | 0.69 ± 1.78 | 0.001 | 22.59 | - | - | - | 1.34 ± 1.66 | 0.072 | 8.23 |
| **16:00** | 0.12 ± 0.21 | 0.003 | 1.27 | 0.19 | 0.194 | 0.19 | 0.59 ± 0.55 | 0.008 | 3.22 | - | - | - | 0.11 ± 0.12 | 0.15 | 0.35 |
| **17:00** | 0.40 ± 0.25 | 0.084 | 1.83 | - | - | - | 1.21 ± 1.52 | 0.057 | 17.32 | - | - | - | 0.72 ± 0.63 | 0.206 | 2.33 |
| **18:00** | 0.55 ± 0.33 | 0.171 | 0.93 | - | - | - | 0.98 ± 1.59 | 0.006 | 15.44 | - | - | - | 0.26 ± 0.27 | 0.016 | 1.67 |
| **19:00** | 1.58 ± 3.66 | 0.114 | 28.82 | - | - | - | 0.73 ± 1.10 | 0.019 | 17.98 | - | - | - | 1.13 ± 1.88 | 0.005 | 8.16 |
| **20:00** | 0.55 ± 1.00 | 0.192 | 3.33 | - | - | - | 0.77 ± 1.85 | 0.01 | 29.80 | - | - | - | 0.63 ± 0.85 | 0.006 | 5.22 |
| **21:00** | 0.41 ± 0.54 | 0.007 | 2.24 | - | - | - | 0.92 ± 3.34 | 0.003 | 60.57 | - | - | - | 0.42 ± 0.33 | 0.01 | 1.11 |
| **22:00** | 0.47 ± 0.51 | 0.005 | 1.67 | - | - | - | 0.48 ± 0.42 | 0.01 | 1.78 | - | - | - | 0.51 ± 0.28 | 0.111 | 1.22 |
| **23:00** | 0.57 ± 0.68 | 0.010 | 2.79 | - | - | - | 0.43 ± 0.34 | 0.04 | 1.69 | - | - | - | 0.32 ± 0.32 | 0.019 | 1.65 |

SD - standard deviation, Min - minimum, Max - maximum, - - data not available

of BC exposure values, which are usually low and consistent. Dons et al., 2012; and Uzun et al., 2022 also concluded that personal exposure to BC is usually the lowest while sleeping when compared to other microenvironments. The BC exposure data for commuting/traveling suggests that individuals are exposed to higher BC levels during certain hours of transport, particularly during late-night and early-morning commutes. The mean values range from the highest value of 1.34 ± 1.66 μg/m$^3$ recorded at 15:00 to the lowest value of 0.11 ± 0.12 μg/m$^3$ recorded at 16:00. The BC exposure's daily mean during weekends was noticed to be higher, i.e., 0.85 ± 1.62 μg/m$^3$, when compared to weekdays,0.88 ± 1.92 μg/m$^3$. Table 5 shows the descriptive statistics of personal BC measurements on various days in several microenvironments.

### 3.4. Daily Inhaled Doses and Contribution by Microenvironment

Table 6 presents the daily inhaled doses of black carbon and the contribution of various microenvironments to overall BC exposures. Since the study participant spent most of their time in sedentary and outdoor activities, these two environments contributed the most to daily BC exposures. Sedentary activities accounted for 50% to 89.14% of daily exposures, while outdoor activities contributed between 0.1% and 33.34%. Sleep contributed to an inhaled dosage range of 0.12 μg to 1.24 μg during the study period. This variability in the dosage of sleeping and sedentary activities suggests that indoor air quality might impact health albeit a bit less during sleep due to the decreased inhalation rate. The total dosage peaked on April 2, which was a weekend. The majority of the day's inhaled dose contribution is attributed to sedentary activities. The contribution from school environments to total black carbon (BC) exposure is generally lower than that of other microenvironments. The highest contribution was observed on March 31st at 2.11%, with other values being consistently below 2%. This suggests that while schools contribute to BC exposures, their impact is relatively minor compared to other environments. Transport has a moderate impact on daily BC exposures, ranging from 2.55% to 26.26%. The highest contribution of transport to the daily dosage was observed on April 6$^{th}$ at 26.26%. As shown in Fig. 10, outdoor activities contributed 31% and 33% of the inhaled dosage on weekends, which is higher than the 0.10% - 1.42% contribution on weekdays.

**Table 5**
Descriptive statistics of BC concentrations on different days at microenvironments (μg/m$^3$)

| Day | Outdoor activities | | | School | | | Sedentary Activities | | | Sleeping | | | Transport | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean ± SD | Min | Max | Mean ± SD | Min | Max | Mean ± SD | Min | Max | Mean ± SD | Min | Max | Mean ± SD | Min | Max |
| **Mar 30** | 0.13 ± 0.2 | 0.005 | 1.83 | 0.19 | 0.193 | 0.19 | 0.58 ± 2.24 | 0.003 | 60.57 | 2.23 ± 1.29 | 0.471 | 9.96 | 0.29 ± 0.47 | 0.018 | 2.33 |
| **Mar-31** | - | - | - | 0.49 ± 0.41 | 0.137 | 1.32 | 0.59 ± 1.37 | 0.004 | 17.32 | 0.23 ± 0.19 | 0.001 | 1.01 | 0.38 ± 0.38 | 0.009 | 1.65 |
| **Apr-1*** | 0.67 ±1.94 | 0.007 | 28.82 | - | - | - | 0.94 ± 1.65 | 0.001 | 22.59 | 0.37 ± 1.38 | 0.004 | 25.63 | 0.85 ± 1.62 | 0.015 | 8.16 |
| **Apr-2*** | 0.55 ±0.94 | 0.001 | 13.47 | 0.68 ± 1.01 | 0.056 | 3.91 | 1.44 ± 3.08 | 0.007 | 36.01 | 0.41 ± 0.32 | 0.021 | 1.35 | 0.88 ± 1.92 | 0.011 | 16.76 |
| **Apr-3** | 0.37 ± 0.1 | 0.17 | 0.53 | - | - | - | 0.61 ± 0.55 | 0.01 | 8.02 | 0.41 ± 0.23 | 0.006 | 1.10 | 0.39 ± 0.12 | 0.079 | 0.60 |
| **Apr-4** | 0.78 ±0.14 | 0.569 | 0.85 | - | - | - | 0.56 ± 0.37 | 0.003 | 1.91 | 0.24 ± 0.29 | 0.003 | 1.43 | 0.78 ± 0.25 | 0.254 | 1.07 |
| **Apr-5** | - | - | - | - | - | - | 0.52 ± 0.36 | 0.001 | 1.85 | 0.46 ± 0.35 | 0.014 | 1.61 | - | - | - |
| **Apr-6** | 0.18 ±0.12 | 0.105 | 0.74 | 0.69 | 0.69 | 0.69 | 0.32 ± 0.32 | 0.005 | 3.89 | 0.18 ± 0.21 | 0.003 | 1.44 | 0.46 ± 0.35 | 0.005 | 3.11 |

SD - standard deviation, Min - minimum, Max - maximum, - - data not available, *weekend days

**Table 6**
Daily inhaled doses of BC and the contribution values of various microenvironments.

| | BC $_{inhaled\ dose}$ (μg) | | | | | | Daily BC exposure contribution | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Outdoor Activities | School | Sedentary Activities | Sleeping | Transport | Total Dosage | Outdoor Activities | School | Sedentary Activities | Sleeping | Transport |
| **Mar 30** | 0.0663 | 0.0001 | 3.6271 | 0.6531 | 0.3310 | 4.67 | 1.42% | 0.002% | 77.54% | 13.96% | 7.08% |
| **Mar-31** | - | 0.1059 | 3.9979 | 0.5044 | 0.4227 | 5.03 | - | 2.11% | 79.46% | 10.03% | 8.40% |
| **Apr-1*** | 2.9557 | - | 4.8115 | 0.7978 | 1.0377 | 9.60 | 30.78% | - | 50.11% | 8.31% | 10.81% |
| **Apr-2*** | 4.6842 | 0.1783 | 7.8836 | 0.1298 | 1.1746 | 14.05 | 33.34% | 1.27% | 56.11% | 0.92% | 8.36% |
| **Apr-3** | 0.0541 | - | 4.6045 | 0.9342 | 0.1464 | 5.73 | 0.94% | - | 80.23% | 16.28% | 2.55% |
| **Apr-4** | 0.0040 | - | 3.4991 | 0.3380 | 0.0844 | 3.92 | 0.10% | - | 89.14% | 8.61% | 2.15% |
| **Apr-5** | - | - | 3.8468 | 1.2492 | - | 5.09 | - | - | 75.49% | 24.51% | - |
| **Apr-6** | 0.0099 | 0.0021 | 2.0256 | 0.4055 | 0.8699 | 3.31 | 0.30% | 0.07% | 61.14% | 12.24% | 26.26% |

- - this data is not available, *weekend days

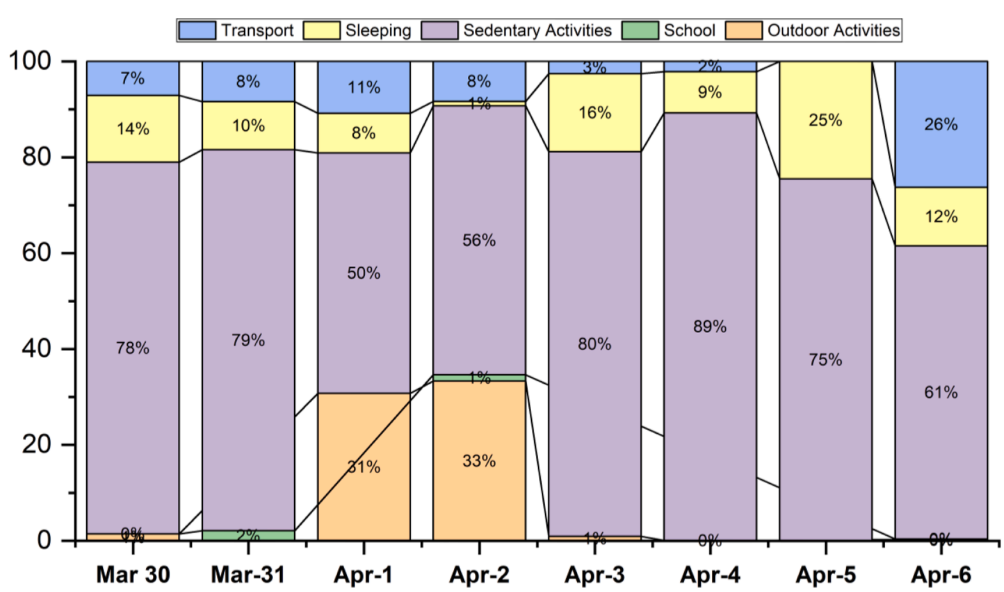


**Fig. 10.** Stack plot of contributions of microenvironments to inhaled dosage

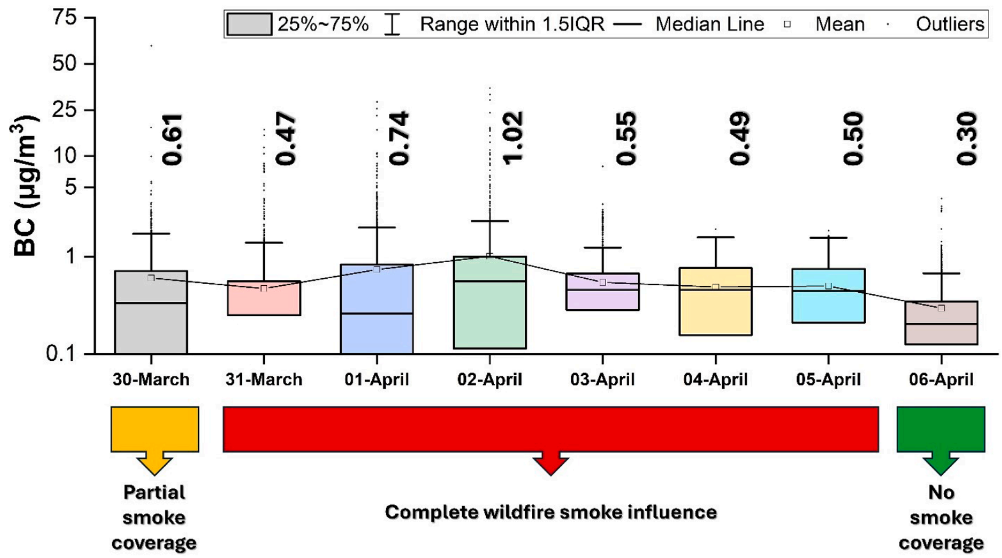


**Fig. 11.** Boxplots of BC exposure measurements with the mean value on different days with respect to smoke coverage in the area

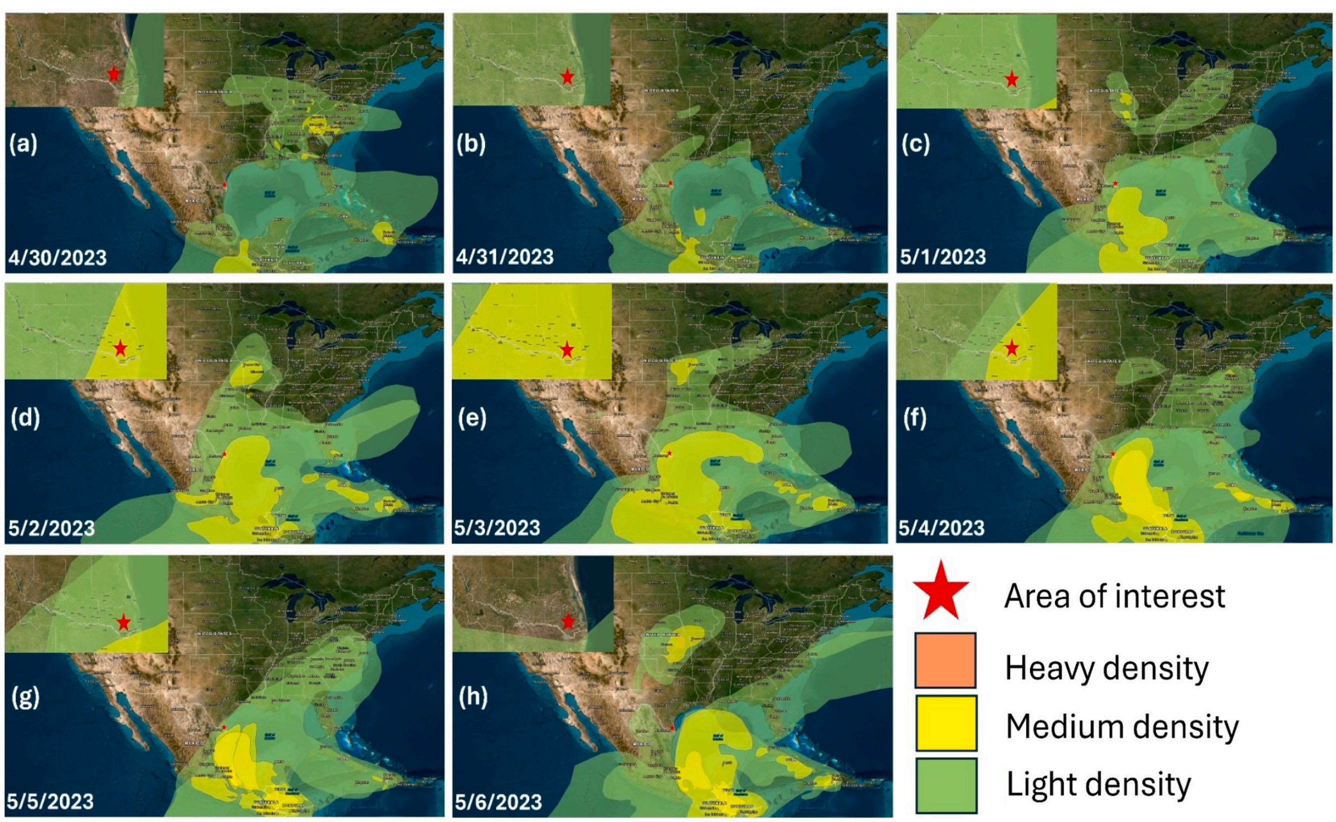


**Fig. 12.** Representative NOAA HMS smoke maps for the study period days under partial wildfire smoke influence: (a) 30 April; under complete wildfire smoke influence (b) 31 April, (c) 01 May, (d) 02 May, (e) 03 May, (f) 04 May, (g) 05 May; under no wildfire smoke influence; (h) 06 May. Inset enlarges the region of interest to clearly display smoke influence on the field site, shown as a star.

### *3.5. Impact of wildfires on the BC exposure measurements*

During the data collection period, active Mexican wildfires on the other side of the border produced smoke plumes that impacted the local air quality in the region. It is probable that personal BC exposure levels were impacted due to these fires. Exposure to wildfire smoke leads to worsened respiratory diseases like asthma and chronic obstructive pulmonary disease, poorer birth outcomes, and increased cardiovascular events (D'Evelyn et al., 2022; Matz et al., 2020; Aguilera et al., 2021), which accentuates the importance of studying spikes in BC levels due to wildfire events in this region. The 24-hour average values for BC were calculated and compared to the area's Hazard Mapping System (HMS) smoke coverage status. HMS is a blended product of the Geostationary Operational Environmental Satellite (GOES) Imager, the Polar Operational Environmental Satellite (POES) Advanced Very High-Resolution Radiometer (AVHRR), Moderate Resolution Imaging

Spectroradiometer (MODIS), and the Visible Infrared Imaging Radiometer Suite (VIIRS) (Pouliot et al., 2017; Gunsch et al., 2018; Pinakana et al., 2024). Fig. 11 illustrates the variation in BC measurements on different days in relation to smoke coverage in the area. Fig. 12 illustrates the smoke from Mexican wildfires using the HMS smoke product in the Rio Grande Valley, specifically focusing on the study area. The 24-hour mean BC concentrations ranged from 0.30 ± 0.31 to 1.02 ± 2.35 μg/m$^3$ over the eight days. The highest concentration was observed on April 2$^{nd}$, with a value of 1.02 μg/m$^3$, during a period classified as "Complete smoke." The lowest concentration was recorded on April 6$^{th}$, with a mean of 0.30 μg/m$^3$, during a "no smoke" period. A plethora of research has been conducted elucidating the impacts of wildfires on air quality (Carreras-Sospedra et al., 2024; Bravo et al., 2002; Gupta et al., 2018), particularly black carbon (Chakrabarty et al., 2023; Wu et al., 2020; Ditas et al., 2018; Kruger et al., 2023). We noticed that the presence of smoke, whether partial or complete, had a noticeable effect on the mean BC concentrations. On days with either partial or complete smoke, personal BC exposure ranged from 0.47 ± 0.31 μg/m$^3$ to 1.02 ± 2.35 μg/m$^3$. Mean BC concentrations were consistently higher during "Complete smoke" periods than "No smoke" days.

## 4. Limitations

Our study does have some limitations. The study was conducted for a limited number of days and over just one season. Also, we could measure the personal exposure patterns of just one study participant because of the dearth of multiple portable units of AE51. BC concentrations from this study were correlated with other datasets such as HMS and proximity to roadways to elucidate potential sources. A major limitation of our research endeavor was the inability to conduct a source apportionment analysis due to the usage of a single-wavelength instrument. Future studies in this region could use instruments with multiple wavelength measurements to study source apportionment. Also, conducting the study over different seasons as well as increasing the number of study participants of all ages to establish baseline characteristics of time activity patterns in different microenvironments is recommended to extrapolate the exposure levels to a larger population in the region. Nevertheless, we feel our study provides an essential dataset of BC exposures and inhaled dosage values of BC in a US-Mexico border area, which is impacted by both anthropogenic and natural sources of air pollution. Continued monitoring and research are essential to develop effective strategies for mitigating black carbon's environmental and health impacts in the Rio Grande Valley.

## 5. Conclusions

Personal exposure to BC was investigated in the region of Rio Grande Valley using a portable aethalometer, focusing on the influence of microenvironments and time-activity patterns. This is the first dataset on black carbon emanating from this region. The study participant spent 84.58% of the time at home on weekdays and 63.17% on weekends. Outdoor activities on weekends increased to 26.7% from 8.15% on weekdays. Due to the proximity of the resident's home to the airport, a potential impact on air quality and BC concentrations was observed. BC values were also recorded to be high on the roadways near the airport. The contributions of different microenvironments to daily BC exposure and inhaled dose were also quantified. Outdoor activities impacted the daily inhaled dosage, and it was found to be higher on weekends than on weekdays. The smoke emitted from Mexican wildfires also clearly impacted the black carbon measurements in the region. Days with partial/complete smoke coverage were observed to have high BC concentrations compared to days with no coverage over the area. Findings from this study adds to the crucial body of BC air exposure patterns especially for the U.S.-Mexico border region.

## Funding

Graduate assistantship for S.D.P. was kindly provided by School of Earth, Environment, and Marine Sciences, UTRGV.

## Institutional Review Board Statement

Not applicable.

## Informed Consent Statement

Not applicable.

## CRediT authorship contribution statement

**Sai Deepak Pinakana:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Johnathan R. Gonzalez:** Methodology, Data curation. **Amit U. Raysoni:** Writing – review & editing, Supervision, Project administration, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

*Data Availability Statement*

Available on request.

*Acknowledgments*

The authors would like to express their gratitude to the administrators at the College of Science, UTRGV for their support during the duration of this study.

## Data availability

Data will be made available on request.

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