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Analysis of Black Carbon Concentrations in $PM_{2.5-10}$ and $PM_{2.5}$ Fractions by MABI Instrument in Two Urban Areas of Dakar, Senegal

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Abstract: Black carbon (BC) is a particular pollutant that absorbs visible light and can intervene in the climatic change with irradiance. The sources of BC emissions are known, such as incomplete combustion of fossil fuels and biomass burning. Our study focuses on two sites Hlm and Yoff in Dakar, Senegal in order to determine the mass absorption coefficient of BC in our polycarbonate nucleopore filters from November 2018 to October 2019 so as to collect $PM_{2.5}$ and $PM_{2.5-10}$ we face in our two study sites using MABI instrument. In addition, we investigate the source apportionment of black carbon in PM2.5 fraction. We observe that the mass absorption coefficient of $PM_{2.5}$ is higher than that of $PM_{2.5-10}$. The average concentration of BC at Hlm and Yoff were 1.85 ± 0.37 and 2.69 ± 0.54 $\mu g.m^{-3}$ respectively, whereas the average concentrations of BC_{BB} were 0.003 ± 0.0007 and 0.08 ± 0.01 $\mu g.m^{-3}$, respectively and for BC_{FF} were 1.85 ± 0.37 and 2.61 ± 0.53$\mu g.m^{-3}$. The BC from at Yoff has two compounds with 2.97% of Biomass burning and 97, 03% of Fossil fuels in contrast to Hlm site the black carbon was mainly composed of fossil fuels in Dakar, the fossil fuels are mainly source of the black carbon.

Keywords: BC, BC_{FF}, BC_{BB}, PM, MABI

1. Introduction

Air pollution has always been a topic of interest for researchers because of its adverse effects on health, the environment and the climate [1-4] Today, thanks to the research conducted on air pollution, we have become aware of the pollutants present in the air, namely heavy metals, chemical elements, organic and inorganic substances and particulate matters (PM). Particle matters have different aerodynamic diameters. In addition, we have elemental carbon (EC) and organic carbon (OC) which form carbonaceous aerosols and which are among the components of particle matters (PM).

Carbonaceous species, organic carbon (OC) and black carbon (BC) constitute a significant portion of fine particles [5]. Sources of BC emissions are known, such as incomplete combustion of fossil fuels and biomass burning [6, 7]. BC absorbs all wavelengths of solar radiation [8] and is considered one of the contributors to global warming in terms of direct impact [9, 10]. Organic carbon is adjective, but is responsible for the appearance of a brown haze and reduced visibility at a site [11]. Research on OC has been very fruitful in terms of the composition of the optical properties and morphology of the particle, so that it has been given several names in terminology. In the literature it is sometimes referred

to as "black carbon", for example: "soot", "light absorbing carbon", "elemental carbon", "refractory carbon", "graphitic carbon" has been used as terminologies [12].

In many studies on BC, several techniques for analysis and determination of its mass concentration have been used in urban and semi-rural areas [13-15] to determine the distribution of BC sources [16-19]. Some commonly used techniques are: the smoke stain reflectometer (such as an EEL (Evans Electroselenium 78 Ltd)) [20], Aethalometer (AE33) [21].

Dakar, the capital of Senegal, is the most developed city in the country, with a population of 5 million. There are many industrial activities in Dakar such as agri-food, automotive, wood and paper, plastics, textiles, oil and construction… We should also notice here there is an interesting agricultural sector in Dakar. In fact, it has been noticed a rapid increase in the number of cars and black carbon emissions. This has as result the change of the environment in Dakar. This is the reason why there is interest in a first study on BC sources in Dakar.

The objectives of this study were to determine the mass absorption coefficient of BC in our polycarbonate nucleopore filters during the period of our sampling campaign to collect $PM_{2.5}$ and $PM_{2.5-10}$ present in our two study sites namely Hlm an industrial location and Yoff, a coastal location. Measure the equivalent concentration of BC in each $PM_{2.5}$ filter, make the distribution of the BC sources contained in the $PM_{2.5}$ filters and last point, observe the temporal evolution between BC from incomplete biomass combustion and BC from fossil fuel combustion at the two sites studied.

2. Experiments

2.1. Sampling Sites

The measurement campaigns were carried out at two different urban sites (Hlm and Yoff) in Senegal. Particulate matters sampling was conducted using a low-volume sampler from the University of GENT, which collected $PM_{2.5}$ and $PM_{2.5-10}$ samples from the Hlm and Yoff sites. The measurement period was from November 2018 to October 2019. Samples of $PM_{2.5-10}$ and $PM_{2.5}$ were taken twice during a week (one business day and one weekend) at each site. Sampling, elemental sample analysis, and source distribution of the collected particulate matters (PM) were described by Kebe et al. [22].

2.2. Multi-Wavelength Absorption Black Carbon Instrument for Black Carbon Analysis

The samples were analyzed for Black Carbon by Multi-Wavelength Absorption Black Carbon (MABI). MABI was developed by ANSTO. It measures absorption light through unexposed filters (Io) and (I) exposed to sample particles at seven different fixed wavelengths: 405 nm, 465 nm, 525 nm, 639 nm, 870 nm, 940 nm, and 1050 nm. To disperse the light scattered through the filter towards the detector, the filter must face the detector and not the light source in our MABI unit [23]. Knowing the values (Io) and (I), the surface of the exposed area of the filters (A) and sampled air volume (V) for each 47mm nucleopore polycarbonate filter used, we can first calculate the light absorption coefficient b_{abs} $(M.m^{-1})$ according to the following equation:

$$b_{abs} = 10^2 * \frac{A}{V} \ln * \left[\frac{Io}{I}\right] \quad (1)$$

A = Filter collection area in cm²

V = Volume of air sampled through the filter in m³

I_o = Measured light transmission and reflection through blank (unexposed) filter

I = Measured light transmission and reflection through filter after particle sampling.

The black carbon (BC) mass concentration $(ng.m^{-3})$ was determined using a mass absorption coefficient ε $(m^2.g^{-1})$ at each wavelength according the following equation:

$$BC = 10^5 * \frac{A}{\varepsilon * V} \ln * \left[\frac{Io}{I}\right] \quad (2)$$

The values of the mass absorption coefficient ε vary between 4-9 $m^2.g^{-1}$ for $PM_{2.5}$ and 1 to 2 $m^2.g^{-1}$ for $PM_{2.5-10}$ [24].

The variability of the mass absorption coefficient with ε wavelength is [25, 26]:

$$\varepsilon(\lambda) = a.\lambda^{-\alpha} \quad (3)$$

3. Results

3.1. Measurements

To determine the mass absorption coefficient $\varepsilon(\lambda)$ for each wavelength, the first step is to use the wavelength $\lambda_1 = 639\ nm$ and assume $\varepsilon(\lambda_1) = 6.599$ $m^2.g^{-1}$ and 1.206 $m^2.g^{-1}$ for $PM_{2.5}$ and $PM_{2.5-10}$ respectively which were provided by the manufacturer for the 47 mm diameter nucleopore polycarbonate filters, at the last we plot ln (Io/I) for each wavelength λ against ln (Io/I) of the wavelength $\lambda_1 = 639\ nm$ and multiplying the gradient of these plots by the mass absorption coefficient $\varepsilon(\lambda_1)$.

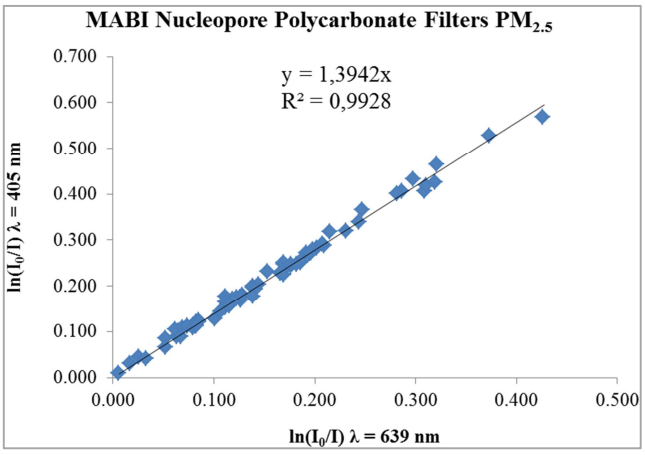

Figure 1. *The ln (Io/I) plot for λ=405nm against ln (Io/I) for λ=639nm for over 70 filters $PM_{2.5}$ from Hlm and Yoff sampling sites in Dakar between November 2018 and November 2019.*

Figure 1 shows that the adjusted coefficient called gradient is equal to 1.3942 and a correlation coefficient R^2 = 0.9928. Using equation (3) we obtain the mass absorption coefficients $\varepsilon(\lambda_{405nm})$ equals to 9.21 $m^2.g^{-1}$ for the $PM_{2.5}$ collected at Hlm and Yoff sites. Thus, to know the mass absorption coefficient $\varepsilon(\lambda)$ of each wavelength of the MABI instrument this process is repeated, always maintaining $\varepsilon(\lambda_1)$.

In addition, we want to determine the mass absorption coefficient of $PM_{2.5\text{-}10}$ by plotting ln (Io/I) plot for λ=1050nm against ln (Io/I) for λ=639nm while remaining in the same Hlm and Yoff sites with the same number of samples as $PM_{2.5}$ in figure 1.

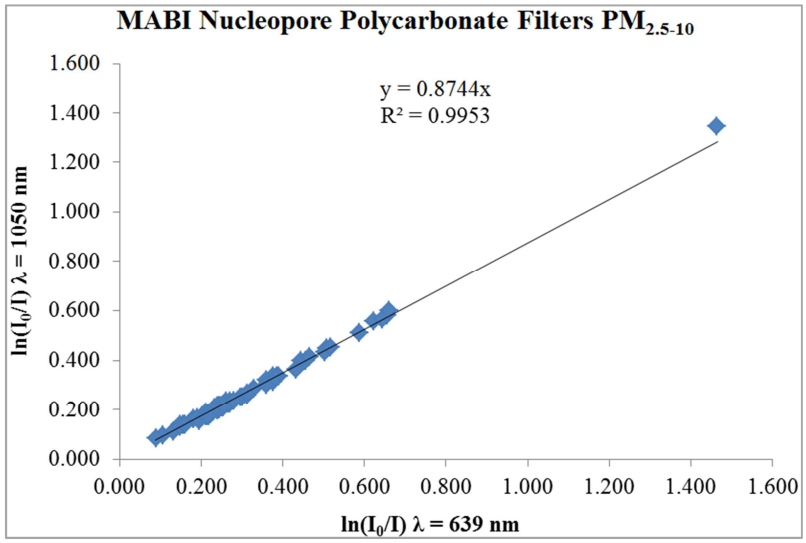

Figure 2. *The ln (Io/I) plot for λ=1050nm against ln (Io/I) for λ=639nm for over 70 filters $PM_{2.5\text{-}10}$ from Hlm and Yoff sampling sites in Dakar between November 2018 and October 2019.*

Figure 2 shows that the adjusted coefficient called gradient is equal to 0.8744 and a correlation coefficient R^2 = 0.9953. We obtain the mass absorption coefficients $\varepsilon(\lambda_{1050nm})$ equals to 1.054 $m^2.g^{-1}$ for the $PM_{2.5\text{-}10}$ collected at Hlm and Yoff sites.

In the same way as in Figures 1 and 2, we determine the variation of the mass absorption coefficient as a function of the seven wavelengths of the MABI instrument.

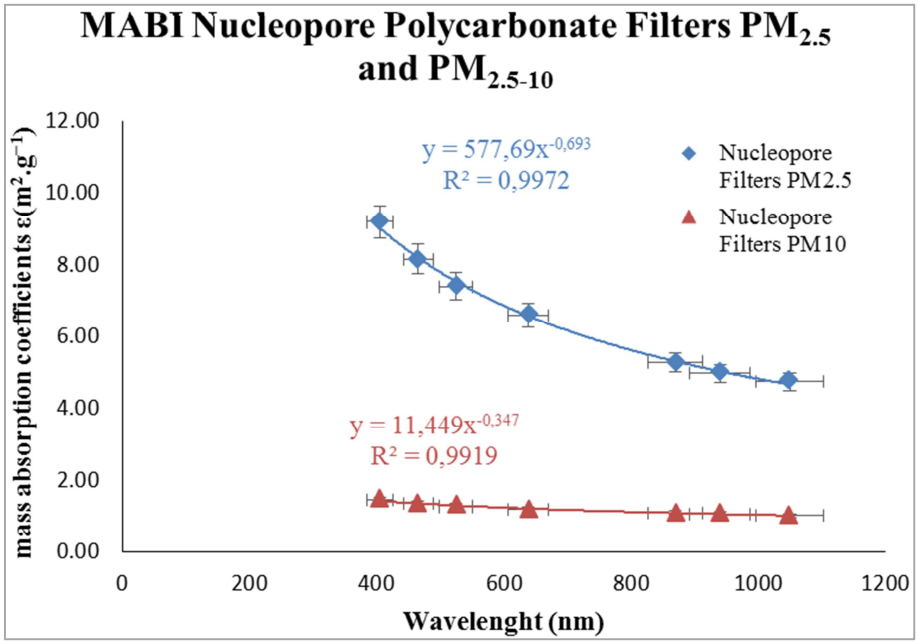

Figure 3. *Variation of the mass absorption coefficient as a function of wavelength for $PM_{2.5}$ and $PM_{2.5\text{-}10}$ from Hlm and Yoff sampling sites.*

Figure 3 shows the variations of the mass absorption coefficient ε(λ) with wavelength (nm) for 47 mm exposed Nucleopore polycarbonate filters $PM_{2.5}$ and $PM_{2.5\text{-}10}$ from Hlm and Yoff sampling sites. The powerful law (Theory of Mie) gives the mass absorption coefficient adjusted with with a = 577.69, α = 0.693 and an excellent correlation coefficient R^2

= 0.9972 for the $PM_{2.5}$ and for the $PM_{2.5-10}$ we obtain a = 11.449, α = 0.347 and correlation coefficient R^2 equals to 0.9919. We observe that the mass absorption coefficient of $PM_{2.5}$ is higher than that of $PM_{2.5-10}$. The exponent α called Angstrom exponent [27] in generally can be accepted around unity for BC from high temperature fossil fuel combustion [28]. Ours values α are fall within 0.4 <α<1 as indicated [23] using MABI systems.

3.2. Determination of Black Carbon Concentrations

To determine equivalent BC concentrations (eBC) with the MABI instrument we used Equation (2) with a mass absorption coefficient $\varepsilon(\lambda_{639nm})$ equals to 6.60 $m^2.g^{-1}$ as recommended in manual MABI.

The Black Carbon concentrations found in $PM_{2.5}$ fraction in Hlm and Yoff sites are presented in Table 1:

Table 1. *Equivalent BC concentrations of the collected $PM_{2.5}$ from November 2018 to October 2019 in µg.m^{-3}.*

	Hlm	Yoff
Mean	1.85 ± 0.37	2.69 ± 0.54
Median	1.6 ± 0.32	2.68 ± 0.54
Maximum	6.84 ± 1.37	4.98 ± 0.99
Minimum	0.1 ± 0.019	0.28 ± 0.06

The mean value for eBC concentrations at Hlm is 1.85 µg.m^{-3} and and 2.69 µg.m^{-3} at Yoff. The mean value concentration of eBC is more relevant in Yoff than in Hlm. The traffic related emissions contribute more than industrial activities in Dakar. This fact is a possible hypothesis due to the BC from fossil fuel combustion is more prevalent than the one from biomass combustion at the Yoff and Hlm sites. In this study, the mean values of eBC at Hlm and Yoff were similar to Italy [29], India [30] and Nanjing [31] respectively.

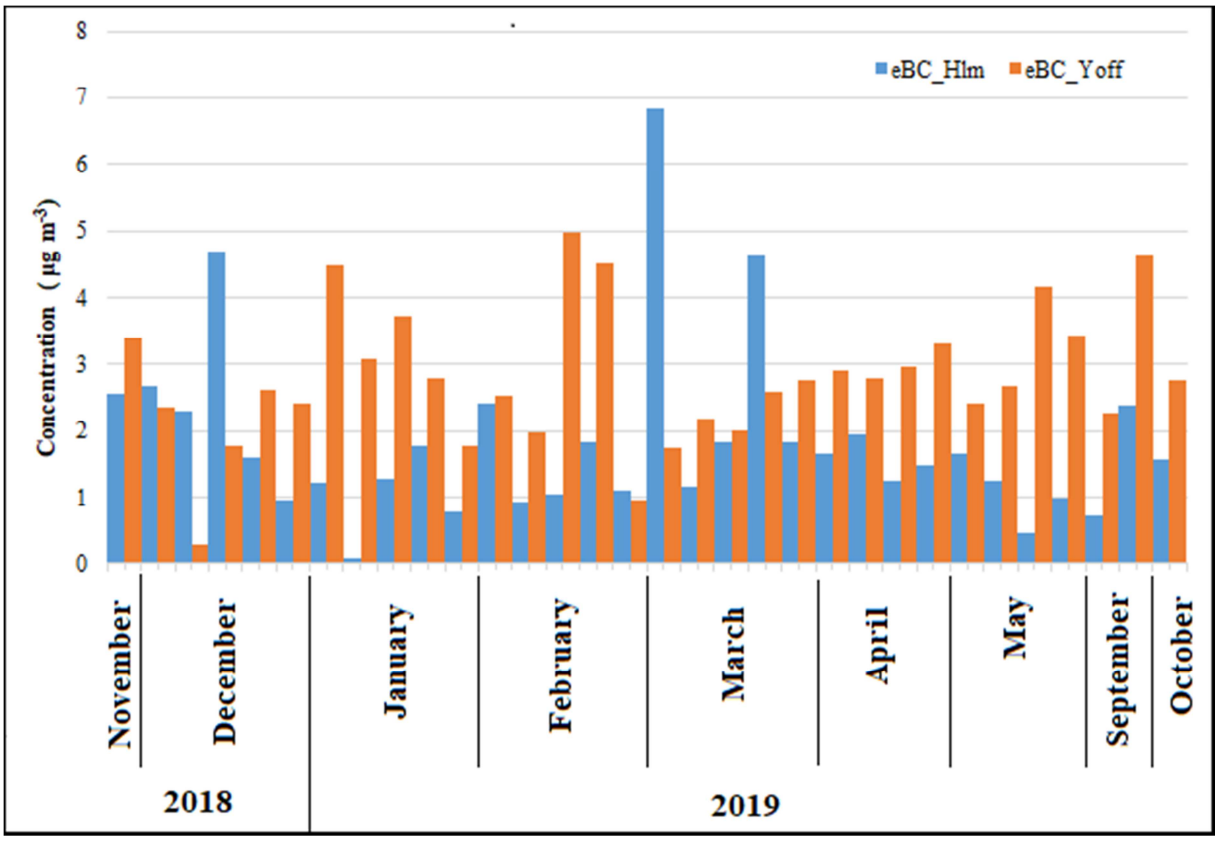

Figure 4. *Comparison daily eBC concentrations for 639 nm at Hlm and Yoff sites from November 2018 to October 2019 in µg m^{-3}.*

Figure 4 shows the variation of daily eBC concentrations with wavelength 639 nm at the two sites from November 2018 to October 2019 in µg.m^{-3}. In Figure 4, the blue vertical bar is the equivalent black carbon concentration at the Hlm site and the orange vertical bar is the equivalent black carbon concentration at the Yoff site. We have higher eBC concentrations at Hlm than Yoff only for a few days in December 2018 and March 2019. This can be explained by assuming that all plants were operating at that time. Previously, we know that industrial emissions and road traffic were sources of pollution at the Yoff and Hlm sites revealed in our previous study.

3.3. Source Apportionment of BC at Hlm and Yoff Sites

Black carbon (BC) particles come primarily from two sources: combustion of high temperature fossil fuels and combustion of low temperature biomass. By subtracting the BC data (1050 nm) from the BC data (450 nm), the BC from biomass combustion is obtained primarily. Black carbon particles formed at high temperatures are typically small, 100-300 nm in diameter, solid and spherical [32]. Carbon black from high temperature combustion absorbs more in infrared, while the low temperature absorbs at shorter

wavelengths (U. V) [33]. The mean values and standard deviations of the concentrations BC_{bb} and BC_{ff} in Hlm and Yoff cities are in Table 2.

Table 2. *Summary of the mean value, median, maximum (max) and minimum concentrations of BC_{FF} (fossil-fuel BC) and BC_{BB}, (biomass burning BC), Hlm and Yoff sites from November 2018 to October 2019 in µg.m^{-3}.*

	Hlm		Yoff	
	BC_{BB}	**BC_{FF}**	**BC_{BB}**	**BC_{FF}**
Mean	0.003 ± 0.0007	1.85 ± 0.37	0.08 ± 0.01	2.61 ± 0.53
Median	0.03 ± 0.005	1.63 ± 0.33	0.08 ± 0.01	2.6 ± 0.52
Maximum	0.48 ± 0.1	6.36 ± 1.28	0.45 ± 0.09	4.53 ± 0.91
Minimum	-0.46 ± -0.1	0.56 ± 0.12	-0.25 ± -0.05	0.53 ± 0.10

Biomass burning (BC_{BB}) and fossil fuels (BC_{FF}) mean values were 0.003 ± 0.0007 µg m^{-3} and 1.85 ± 0.37 µg.m^{-3} at Hlm site, 0.08 ± 0.01µg.m^{-3} and 2.61 ± 0.53 µg.m^{-3} at Yoff site respectively. BC_{BB} values can be negative but we expect its mean value to be zero and defined as a smoke diesel between ± 0.05 µg.m^{-3} [23]. From Hlm site it was expected the average value of BC_{BB} equals to zero because this location has characteristic industrial and there are no significant biomass burning event during the sampling period. The pollution come from traffic emission and fossil fuels combustion. Whereas at Yoff site mean percentage of biomass burning (%BB) was 2.97 ± 0.6. Fossil fuel burning activities are most predominant than biomass burning activities in Yoff. The source apportionment shows that BC are mainly emitted from fossil-fuel sources in Hlm site whereas a mean percentage of fossil fuels (%FF) equals to 97.03% ± 19.41 at Yoff site.

The determination for the fossil fuels concentrations at Hlm and Yoff sites was obtained by the following equation:

$$BC = BC_{BB} + BC_{FF} \quad (4)$$

Figures 5 and 6 show the distribution of BC (blue line), BC_{BB} (red line) and BC_{FF} (purple line) levels in Dakar using equation (6).

Figure 5 shows that BC ranges between 0.1 ± 0.019 µg.m^{-3} and 6.84 ± 1.37 µg.m^{-3}. The figure includes at both the variations of BC_{BB} and BC_{FF} concentrations over time. The maximum and minimum values BC_{BB} and BC_{FF} were 0.48 ± 0.1 µg.m^{-3} and 0.46 ± 0.1µg.m^{-3}; 6.36 ± 1.28 µg.m^{-3}; and 0.56 ± 0.12 µg.m^{-3} respectively. The negative value BC_{BB} is the fact we have the presence of diesel smoke at Hlm indeed it is an industrial area in addition to this, there is road traffic. The peaks of BC_{FF} above the equivalent BC concentration for some days in the Figure 5 are explained by the fact that the value for BC_{BB} was negative. We can conclude that the BC_{FF} concentrations are equal generally those BC concentrations at Hlm site.

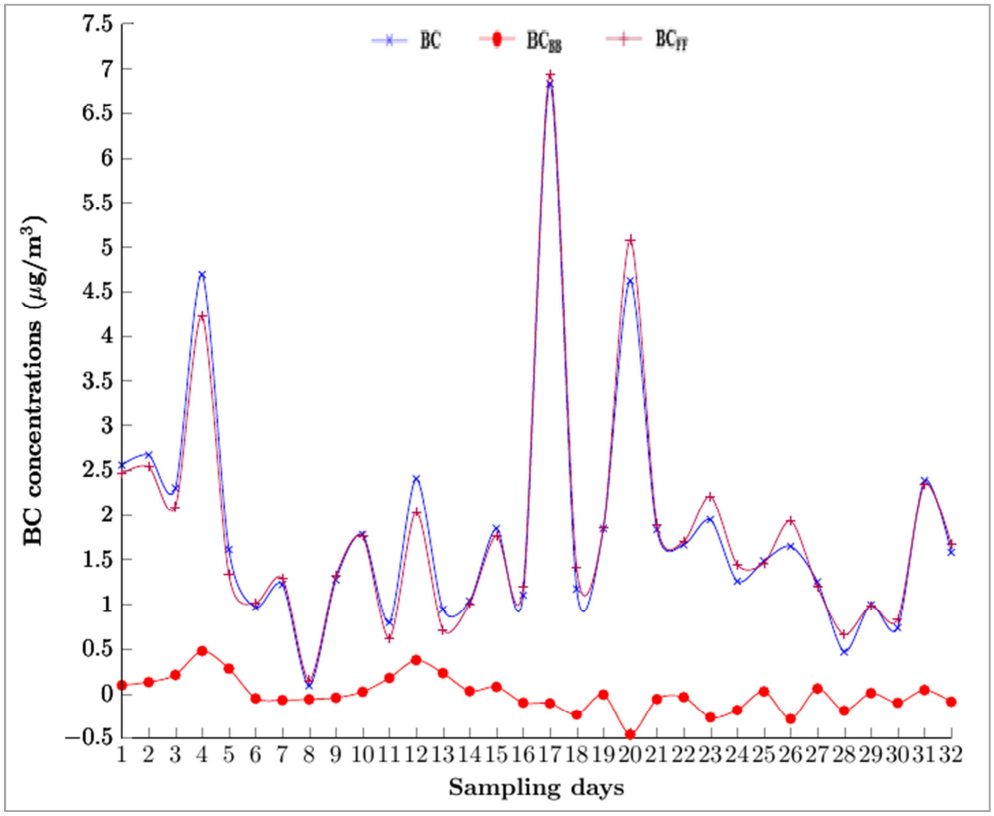

Figure 5. *Evolution of BC, BC_{BB} and BC_{FF} concentrations over time at Hlm site.*

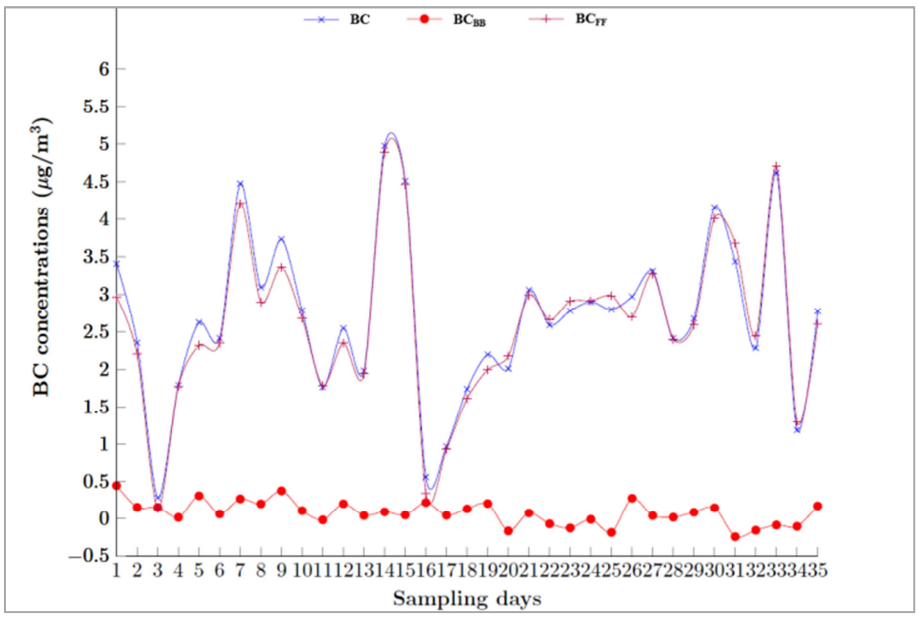

Figure 6. *Evolution of BC, BC_{BB} and BC_{FF} concentrations with time at Yoff site.*

In Figure 6, BC ranges between 0.28 ± 0.06 µg.m^{-3} and 4.98 ± 0.99 µg.m^{-3} whereas the variations of BC_{BB} concentrations with time were between the range 0.25 ± 0.05 µg.m^{-3} and 0.45 ± 0.09 µg.m^{-3}; and for BC_{FF} we have 0.53 ± 0.10 µg.m^{-3} to 4.53 ± 0.91 µg.m^{-3}. The black carbon from biomass burning at Yoff site is higher than Hlm site, with a percent of 2.97%.

4. Conclusion

The black carbon concentrations were determined by MABI instrument. The average concentration of BC at Hlm and Yoff were 1.85 ± 0.37 and 2.69 ± 0.54 µg.m^{-3} respectively, whereas the average concentrations of BC_{BB} were 0.003 ± 0.0007 and 0.08 ± 0.01 µg.m^{-3}, respectively and for BC_{FF} were 1.85 ± 0.37 and 2.61 ± 0.53 µg.m^{-3}. The BC from at Yoff has two compounds with 2.97% of Biomass burning and 97, 03% of Fossil fuels in contrast to Hlm site the black carbon was mainly composed of fossil fuels in Dakar, the fossil fuels are principally source of the black carbon.

The information obtained from this study has provided us with knowledge on the sources of BC and we will be able to restrict the number of diesel vehicles and reduce BC emissions from anthropogenic activities.

Authors Contributions

Conceptualization, A. T. and M. K.; methodology, A. T. and M. K.; validation, M. K. and A. T.; formal analysis, M. K. A. T. and V. V.; writing—original draft preparation, M. K. and A. T.; writing—review and editing, A. T. and M. K.; supervision, A. T.; Administrative issue, A. S. N. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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